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ZANDER Aufbereitungstechnik GmbH

Compressed Air: Filtration, Purification and Separation Technology

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Part 1

1.0 Atmospheric air

Planet earth is evenly surrounded by a layer of air. This layer of air is a mixture of different gases, the composition of which is fairly constant all over the surface of the earth.

At the boundary of the atmosphere at about 900 km and beyond, only solitary gas molecules will be found so that the air pressure can practically be equated with the absolute vacuum and the temperature with absolute zero.

The ionosphere starts at about 80 km height and is a zone consisting of electromagnetically charged layers of molecules which reflect emitted radio waves to the receiver.

Even in the stratosphere, which is below the ionosphere, there are no weather phenomena and the median temperature in this region amounts to only about -60°C.

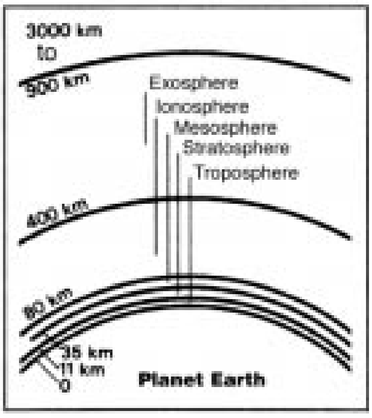


Fig. 1.0.1

The lowest layer of the air envelope, the troposphere, reaches a height of 10 km with its upper limit. The temperature at the extremes of the troposphere amounts to about -50°C. The temperature gradient from there to the earth's surface is 6.5°C per km on average.

Without atmospheric air, the daily temperature differences would be so large as to make life impossible. Atmospheric air permits the evening out between the heat of the day and the cold of night.

1.1 Gas mixture air

Geochemistry defines the earth’s living space as a unit consisting of the air and water envelope as well as the upper part of the solid earth crust. Within this range, a closed circuit of the elements which form this air envelope takes place. The subject of atmospheric air is governed by the elements contained in air, i.e. nitrogen, oxygen, carbon dioxide, and the rare gases argon, neon, helium, krypton and xenon.

Nitrogen forms part of the more widespread elements. By far the largest quantities are found in the air envelope, containing about 78.1 % by volume. Smaller quantities of nitrogen occur in the gases emitted by some springs and occlusions in rock.

Oxygen is the most widespread element of our living space and its weight share of the earth’s upper crust is estimated as being 49.5 % in this context. About 90 % of the available space of petrified rocks is occupied by oxygen. However, as oxygen is restricted to the outer crust of our earth, its weight share of the entire globe is reduced to 29 %. The atmosphere contains on average 1×10^{15} (metric) tonnes of oxygen i.e. a weight share of 23.1 %.

Carbon dioxide is contained in the air envelope of the earth with a weight of about 23×10^{12} tonnes. About 10×10^{11} tonnes of carbon dioxide per year emerge from the oceans into the atmosphere while the same quantity returns from air into the water. Assimilation by green plants annually extracts 6×10^{10} tonnes of carbon dioxide from the air but nearly the same quantity is released by the breathing of humans, animals, micro organisms and decay. Since the beginning of the 19th century, the carbon dioxide content has increased, this being caused mainly by the increasing use of fossil fuels and the clearing of forests. Assuming a continuing population growth of 2 % per annum and counting on a growth in consumption of 1% per year, doubling the carbon dioxide content of the atmosphere in the next 50 years can be expected.

Hydrogen makes up an estimated share of the upper earth crust including water and air envelope of about 0.88 weight percentage. At the height of 2000 - 20000 km the earth is surrounded by a layer of dilute hydrogen. In comparison, the sun consists of about 84 % by weight of hydrogen, the fuel for the generation of solar energy.

Argon is by far the most widespread of the rare gases. Air contains 0.93 % by volume on average and a human being breathes in and out 20 litres per day. Spring water, too, contains dissolved argon, particularly if the spring emerges from greater depths such as in the case of geysers.

Helium occurs most frequently in natural gases in concentrations of up to 7.5 % by volume. The major occurrences are in the USA and the former USSR. Percentage occurrence in the upper earth crust including the oceans and the atmosphere is estimated at 4.2 x 10^{-7} % and it is thus more rare than gold, silver or platinum.

Neon also belongs to the rare elements with an estimated share of 5 x 10^{-7} %. In outer space, however, neon forms the third most frequent element after hydrogen and helium. Krypton is contained in air to an amount of 0.000108 %. Content in the upper earth crust including the air and water envelope is estimated to be only 1.9 x 10^{-8} %, thus making it one of the most rare elements.

The share of xenon in the upper earth crust including air and water envelope is estimated to be about 2.4 x 10^{-9} % and the volume-wise share in air is 0.0000086 % = 86 parts per billion (ppb), thus extremely low.

Nitrogen, oxygen, carbon dioxide, hydrogen, in addition to the rare gases argon, neon, helium, krypton and xenon form the gas mixture which makes up our air in the lower regions of the atmosphere.

Air is ever present for us all. It surrounds all life at every step from the beginning to the end. Let us take a deep breath of air for new spectacular or vital aims. There is much to this medium: Air.

1.2 History of Air

Prehistoric men made use of air as an aid for driving windmills and sailing boats. The Romans used warm air systems for heating their villas and palaces.

In the year 210 BC, Archimedes discovered that a body is proportionately lighter, the more liquid, gas or respectively air, this body displaces.

Centuries passed without noteworthy progress being made in natural science with regard to gases. Up to the 17th century, one still regarded air as a uniform substance.

Carbon dioxide was discovered by J.B. van Helmont (1577-1644) as a product of combustion and fermentation. Carbon dioxide occurs in volcanic gases and many minerals, and reaches air through combustion of carbonates (salt of carbonic acid) but also respiration by humans and animals.

Evangelista Torricelli (1608-1647) was the first to recognise that the weight of air pressed against the earth’s surface. In the year 1644, Torricelli first succeeded in measuring air pressure. Torricelli filled a thin 1 m long tube with mercury and placed this tube, with the opening downwards, vertically into an open dish which had been filled with mercury. The mercury column inside the tube shrank from 1000 mm to 760 mm.

Otto von Guericke (1602-1686) pumped the air out of two hemispheres. Even 24 horses were unable to separate the hemispheres which were void of air (evacuated).

Guericke also constructed the first pressure gauge. A copper sphere was evacuated. The difference in weight between the copper sphere filled with air and the evacuated one corresponded to the weight of the air.

Edme Mariotte (1620-1684) carried out the same experiments with enclosed gas volumes independently of Robert Boyle and found the same interrelationships. This led posterity to deduce Boyle-Mariotte’s law :

The volume of gas is inversely proportional to the pressure

Blaise Pascal (1623-1662) established the proof of the correctness of Torricelli’s declaration. On the 19th September 1648, a barometer accompanied an ascent of the 1465 m high Puy de Dome. The difference in level of 85 mm water column (WC) provided the final proof of the existence of air.

Robert Boyle (1627-1691) used a bent glass tube which was sealed at one end. The air volume enclosed in this glass tube was subjected to the pressure of a mercury column of variable height. By this means, the relationship between volume and pressure in an enclosed quantity of air was established. This simple law consists of the fact that the product of the volume of an enclosed quantity of gas, multiplied by the pressure, always remains the same.

Gabriel D. Fahrenheit (1686-1736) made the first mercury thermometer, that is valid to this day in the English speaking world with its freezing point at 32°F and boiling point at 212°F.

Anders Celsius (1701-1744) proposed the introduction of the 100° temperature scale in the “Proceedings of the Royal Swedish Academy”.

Henry Cavendish (1731-1810) discovered hydrogen when dissolving metals in acid and also discovered that the combustion of hydrogen leads to the formation of water. In 1783 Lavoisier found that hot iron and water vapour generate iron oxide and hydrogen. He called the element HydrogËne, or hydrogen in English.

Because of its reactive inertia, nitrogen was recognised as an element relatively late in time. K.W. Scheele showed in his “Treatise on Air and Fire” that air contains a component which permits neither respiration nor combustion. He called this component “spoilt air”.

Antoine Lavoisier (1743-1794) determined this element, which can neither sustain combustion nor life, and called it Azote. J.A.C. Chaptal introduced the designation Nitrogenium for this element. The utilisation on a large scale of nitrogen from air followed only in the 20th century.

K.W. Scheele (1742-1786) obtained oxygen for the first time by heating silver carbonate and mercury oxide and called this fire gas in contrast to inert gas (nitrogen). Lavoisier is said to have given the former the name Oxygenium having recognised the correct explanation of the combustion processes. Oxygen is emitted by plants through the assimilation of carbon dioxide by a process known as photosynthesis. Air pollution considerably weakens solar radiation which is a precondition of assimilation. Deforestation of the earth’s surface has already reduced the generation of oxygen to two thirds of previous values.

John Dalton (1776-1844) established the theory that every element is composed of several atoms and that one or several atoms of the one element always combine with one or several atoms of another.

Joseph Gay-Lussac (1778-1850) transferred Dalton's theory of atoms to the chemistry of gases and formulated the general gas law as a combination of the laws of Boyle-Mariotte and Celsius. The relationship between pressure, temperature and volume of an enclosed quantity of gas was thus defined.

$$\boxed{\frac{p \times V}{T} = const}$$

Formula 1.2.1

Lord Kelvin (1824-1907) succeeded in abstracting objective temperature from the subjective feeling of warmth and thus created the technically correct scale division which starts at the point of absolute zero.

The existence of argon or other rare gases was suspected by Cavendish because there always remained a reaction-wise inert residue when he transmuted the components of air into chemical compounds. Argon was discovered in 1894 as a component of atmospheric air by the Englishmen Ramsay and Rayleigh, after these had been struck by the divergence in density between the residual gas, believed to be nitrogen (after extracting the oxygen from air) and that of chemically pure nitrogen obtained by decomposition.

The rare gas helium was discovered in the atmosphere of the sun by P. Jansen in 1868, in 1882 Palmieri found it in the course of the spectral analysis of Vesuvius lava.

In 1895 Ramsay succeeded in producing pure helium in larger quantities from the mineral cleveite. Later, proof of the presence of helium in air was also established by Kayser.

In 1897 neon was discovered by Ramsay due to its scarlet red spectral light and called it neon (from the Greek word “new”). The natural neon isotopes were already discovered by 1912 in the mass spectroscope by Thomson.

Krypton was produced for the first time by Ramsay in 1898, obtaining it from air by using Linde's process for air liquefaction.
It was again Ramsay who discovered and produced xenon in the year 1898

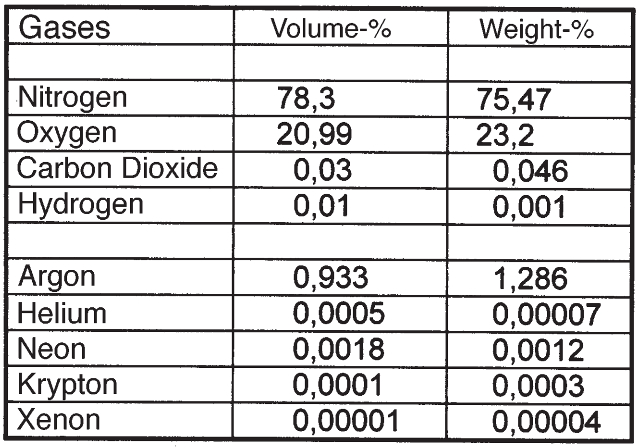
when he subjected the coarse argon obtained from air to a closer investigation and gave the name of Xenon (Greek word xenos = guest, foreigner) to this element.

1.3 Components of air

Atmospheric air is composed from gases of a widely diverging nature. On the surface of the earth, this composition is modified very little by changes in location or time, whereas, at great height, the lighter gases become prevalent.

Not only do the most diverse gases determine the composition of air but also a variety of liquid or solid components present in air. Looked at chemically, air is a mixture of different permanent gases amongst which nitrogen, oxygen, argon and carbon dioxide predominate.

Components of Air



Gases	Volume-%	Weight-%
Nitrogen	78,3	75,47
Oxygen	20,99	23,2
Carbon Dioxide	0,03	0,046
Hydrogen	0,01	0,001
Argon	0,933	1,286
Helium	0,0005	0,00007
Neon	0,0018	0,0012
Krypton	0,0001	0,0003
Xenon	0,00001	0,00004

Table 1.3.1

In addition to the permanent gases, air also contains water vapour in varying quantities.

1.3.1 Nitrogen N_2

Nitrogen is an inert gas, colourless, non combustible, non toxic, odourless and with suffocating effect. In its elemental state nitrogen forms very stable, bi-atomic molecules. Nitrogen is almost inert as a reagent and is used as a dilutent for oxygen. Suffocation in gas mixtures rich in nitrogen is a consequence of the lack of oxygen, but by no means a toxic effect of nitrogen. Nitrogen is an indispensable nutrient, it forms about 3 % of the body weight of a human being.

The technical generation of nitrogen takes place through the decomposition of air, i.e. through fractionating liquid air and it reaches the market in green coloured steel bottles at a pressure of about 200 bar.

The element nitrogen obtains its technical significance through its inertness in reaction i.e. as an inert or protective gas, as propellant for sprays, for diluting easily flammable gases. Approximately 85 % of the nitrogen produced is used in the fertiliser industry.

1.3.2 Oxygen O_2

Oxygen is a colourless, combustion promoting, odourless gas and is extraordinarily reactive in molecular form while forming compounds with nearly all elements. It is therefore, of biological importance. Oxygen forms an important nutritive substance and is essential for sustaining the life of the overwhelming majority of organisms. Only a few kinds of bacteria (anaerobes) can live entirely without oxygen.

An adult human consumes daily, about 900 g of oxygen, from the air. In addition, 225 g must be taken up from nourishment in chemically combined form. The human lung can just about utilise oxygen poor mixtures with 8-9 % oxygen, breathing in gas mixtures with only 7 % oxygen causes loss of consciousness after some time and an even lower content leads to inevitable suffocation.

In industry, oxygen is generated predominantly from liquid air through fractional distillation and condensation and is traded in blue coloured steel bottles at 200 bar.

Oxygen is frequently used instead of air for combustion and oxidation processes, likewise in metallurgy and metal working, as well as for autogenous welding and cutting. Oxygen is also used for manufacturing sulphur and sulphuric acid in the chemical industry.

1.3.3 Carbon dioxide CO_2

Carbon dioxide is colourless, non combustible with a faintly acid smell, has a suffocating effect and is heavier than air. Upon release to below sublimation temperature cooling causes dry ice formation. Carbon dioxide is not poisonous in the accepted sense (Occupational Exposure Standard limit 9000 mg/m^3). At a carbon dioxide content of 3%, a human being inhales 6.5 litres per minute. Relatively large quantities of carbon dioxide always circulate within the human body from which over 700 g (more than 350L) are exhaled. However, in larger quantities, carbon dioxide can have a suffocating effect through displacing oxygen.

Many industrial processes lead to the formation of large quantities of carbon dioxide. It is also found in the flue gases of fuels, when slaking lime, in the fermentation cellars of breweries and from the combustion gas of gas producers (generators).

Carbon dioxide is used in the beverage and refrigeration industry, in fire extinguishing devices, as inert gas in chemical processes, for the manufacture of fertilisers as well as for soda production.

1.3.4 Hydrogen H_2

Hydrogen is colourless, combustible, non poisonous, odourless and very much lighter than air. In conjunction with chlorine or oxygen, hydrogen forms highly detonating, explosive mixtures. Hydrogen burns with a barely visible light blue flame to form water vapour[1]. If it exudes at high speeds, there is a danger of autoignition.

Hydrogen is of extraordinary biological importance. By far the greater part of the muscle energy developed by organisms is derived from a step-by-step oxidation of the hydrogen linked to C-chains which amount to a share of 10 % of the total body weight in the human organism.

Hydrogen is obtained through the catalytic steam cracking of mineral gas and as a by-product from petrochemical processes in refineries and coking plants. Hydrogen is traded in red coloured steel bottles at a pressure of 200 bar.

For example about 19.1 thousand million m^3 of hydrogen is annually consumed in Germany. Of this, 33.5% is used as chemical raw material for ammonia, as well as methanol and in metallurgy, 47.5% is used as fuel gas for industrial processes and 19.0 % in the mineral oil industry for synthetic fuels. However, the world-wide hydrogen consumption amounts to about 500 000 million m^3 per year.

1.4 Rare gases

Rare gases do not enter chemical combinations or, if so, very rarely, in contrast to other gases.

1.4.1 Argon Ar

Argon (Greek word argos = inactive) is a gaseous, mono- atomic, zerovalent, chemical element belonging to the group of rare gases. No genuine rare gas compounds containing argon are known. Argon is heavier than air and has a suffocating effect. The gas is colourless, odourless and non toxic. In enclosed spaces the breathing air is displaced. There are no discernible warning symptoms.

Because of its low heat conductivity and chemical inertness, argon is used in a mixture with 10-20 % nitrogen for filling light bulbs and, in a mixture with other rare gases, for filling discharge tubes in order to achieve certain colour effects. Argon is also used as a protective gas when steel is electrically welded.

---

[1] $2H_2 + O_2 \rightarrow 2H_2O$

1.4.2 Helium He

Helium (Greek word helios = sun) is a mono-atomic gas, lighter than air, colourless, non combustible, odourless and non toxic. Helium is zerovalent and has no known chemical combinations.

Helium is obtained from helium containing natural gases. This takes place by cooling down the gas under partial condensation of the heavy fractions and coarse and fine purification of gas. Obtaining it from air through air decomposition is carried out only in areas which have little natural gas. Highly compressed, about 99 % pure helium is available in gaseous form in steel bottles and in liquid form in tank containers.

Helium is used for powder metallurgy as protective gas for avoiding oxide and nitride formation and also when manufacturing semiconductors and other electronic components. In refrigeration technology (cryogenics) liquid helium makes it possible to achieve low temperatures separated by only a few thousandths of a degree from absolute zero.

1.4.3 Neon Ne

Neon is lighter than air. The gas is colourless, odourless and non toxic. Neon asphyxiates. Upon fluorescent discharge, the reaction-wise very inert, zerovalent rare gas displays a typical scarlet red colouration.

Neon is used as a filling gas for fluorescent tubes, flash and stroboscope lights. Liquid neon possesses a 40 times bigger cooling power per unit of volume than liquid helium and about 3 times as much as liquid hydrogen.

1.4.4 Krypton Kr

Krypton (Greek word Kryptos = hidden) is heavier than air. The gas in colourless, odourless and non toxic. Krypton suffocates. It is obtained as a by-product of oxygen manufacture through fractionating and desorption with activated charcoal.

Krypton finds its principal technical application in the light bulb industry. One million litres of air contains about 1 litre of krypton, sufficient for filling 15 bulbs. In addition, krypton is a filling gas for Geiger counters.

1.4.5 Xenon Xe

Xenon is a gaseous mono-atomic element and is heavier than air. The rare gas is colourless and non toxic. Xenon has a suffocating and, when mixed with oxygen, an anaesthetising effect. In former times, xenon was regarded as a zerovalent inert rare gas but genuine rare gas combinations are known nowadays, in which it appears in differing stages of oxidation.

Xenon is obtained from air together with krypton, for which purpose more than 10 million m^3 of air have to be dissociated in order that one m^3 of xenon may be obtained.

The many possibilities of usefully applying xenon are handicapped by the high price. For instance, a mixture of xenon with 20 % oxygen could be used for narcosis during operation. Light bulbs filled with krypton/xenon could be heated to a higher temperature compared with those filled with argon, and this would improve the yield of white light.

1.5 Characteristic values

Air is composed from a mixture of the most varied gases. Table 1.5.1 lists the gases with their most important characteristic values compared to air.

Characteristic Values of Various Gases

Gas	Mol_v	ρ	$\frac{\rho}{\rho_{Luft}}$	ν	R	x
	$\frac{kg}{kmol}$	$\frac{kg}{m^3}$		$\frac{m^3}{kg}$	$\frac{mkp}{kg*K}$	$\frac{c_p}{c_v}$
Air	28,96	1,293	1,0	0,773	29,27	1,4
Nitrogen	28,02	1,25	0,967	0,8	30,26	1,425
Oxygen	32,0	1,429	1,105	0,7	26,5	1,4
Carbon dioxide	44,01	1,977	1,529	0,506	19,27	1,3
Hydrogen	2,02	0,09	0,07	11,127	420,58	1,415
Argon	39,94	1,784	1,378	0,561	21,23	1,665
Helium	4,0	0,179	0,138	5,602	211,81	1,665
Neon	20,18	0,9	0,696	1,111	41,99	
Krypton	83,8	3,74	2,9	0,344	10,09	
Xenon	131,3	5,9	4,56	0,169	6,42	

Table 1.5.1

1.6 Inclusions in air

Depending on locality, climate and season, atmospheric air contains inclusions to a larger or lesser extent. The most important gaseous inclusions are :

Ozone O_3, is formed from the oxygen of the air under the effect of electrical discharge or during evaporation. Ozone has a peculiar smell and is poisonous in high concentrations. Inclusion in air is about 0.02 - 0.1 mg/m^3.

Carbon monoxide CO, very poisonous, odourless gas, decomposes the red blood corpuscles and is generated by incomplete combustion, thus being contained in fuel gases as well as in tobacco smoke. Urban and industrial areas suffer CO pollution at an average of about 40 - 500 mg/m^3.

Sulphur dioxide SO_2 is created by the combustion of coal and fuel oil and has a negative effect on all forms of life if present in larger concentrations. Percentage in air is about 0.1 - 5 mg/m^3.

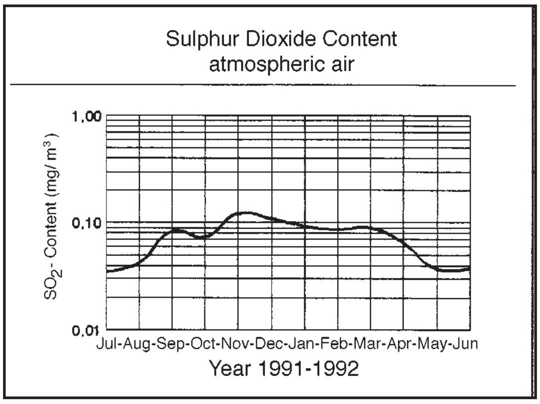


Diagram 1.6.1

Ammonia NH_3, a pungently smelling gas from coal combustion and putrefaction. In free air, ammonia is contained to an extent of about 0.02 - 0.05 mg/m^3.

Apart from heating and bituminous gases, residential areas contain few inclusions in air, contrary to industrial areas where considerable concentrations of gaseous impurities are contained in the air.

1.6.1 Solids

Spread in air, dust represents solids of various kinds, forms, structure and density and can be subdivided in accordance with particle size. In moving air, dust does not obey the laws of gravity but is precipitated slowly when the air comes to rest.

Soot is flocculated coal dust which arises from incomplete combustion and has a corrosive effect, particle size 2 - 6 micron.

Aerosols are solid or liquid substances very finely distributed in gas, particle size 0.01 - 0.1 micron.

Smog, arising from the accumulation of very fine particles in air, may lead ultimately to bad visibility.

Fog arises from finely distributed droplets of water in air, particle size
1 - 50 micron.

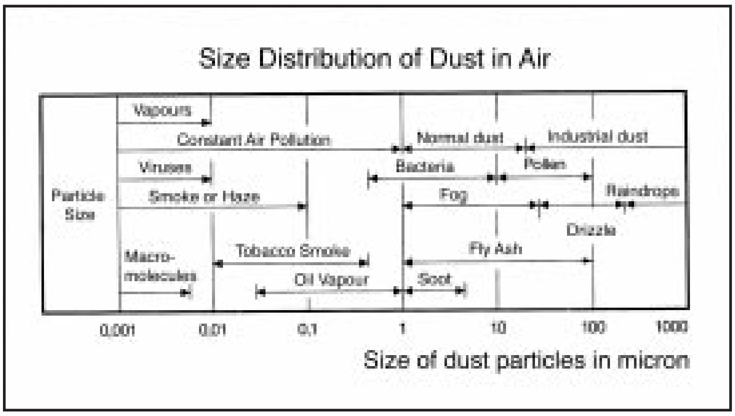


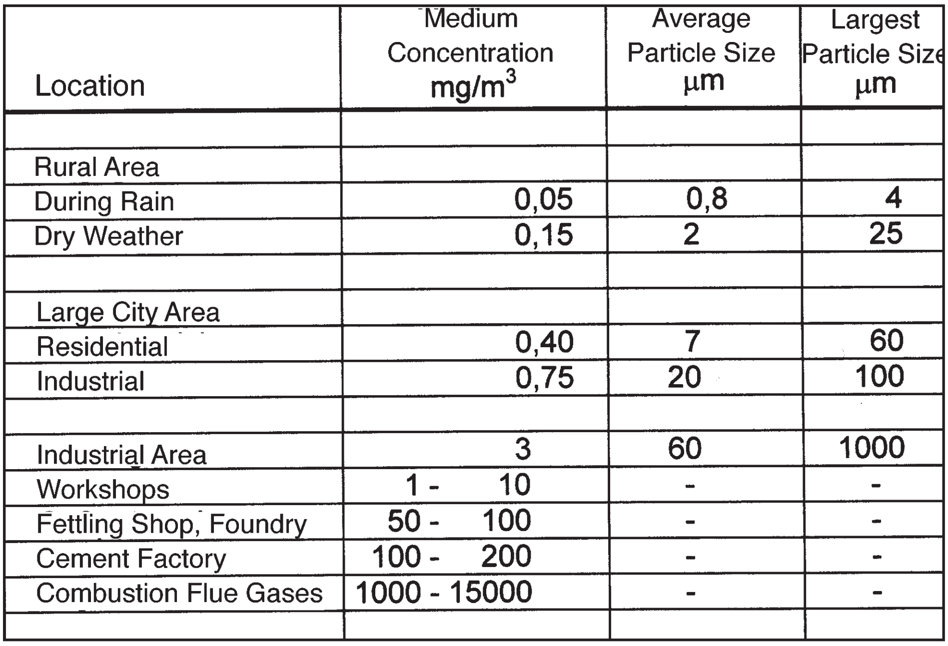
Diagram 1.6.1.1

These are only the most significant types of solid particles in air.

Dust is composed from organic constituents such as seeds, pollen, textile fibres or even flour, as well as from inorganic matter such as sand, soot, ash, chalk and stone dusts.

Dust is created in a natural manner through weathering and decay, putrefaction and fires, or through everyday human activities. Particularly also, through highway and railway traffic or from industrial activities in cement works or the chemical industry as well as through mining, to cite only a few examples.
The concentration of dust in air depends greatly on weather conditions such as wind and rain as well as the time of day and the season and, of course, differs from region to region.

Average Dust Content in Air



Location	Medium Concentration mg/m³	Average Particle Size µm	Largest Particle Siz µm
Rural Area			
During Rain	0,05	0,8	4
Dry Weather	0,15	2	25
Large City Area			
Residential	0,40	7	60
Industrial	0,75	20	100
Industrial Area	3	60	1000
Workshops	1 - 10	-	-
Fettling Shop, Foundry	50 - 100	-	-
Cement Factory	100 - 200	-	-
Combustion Flue Gases	1000 - 15000	-	-

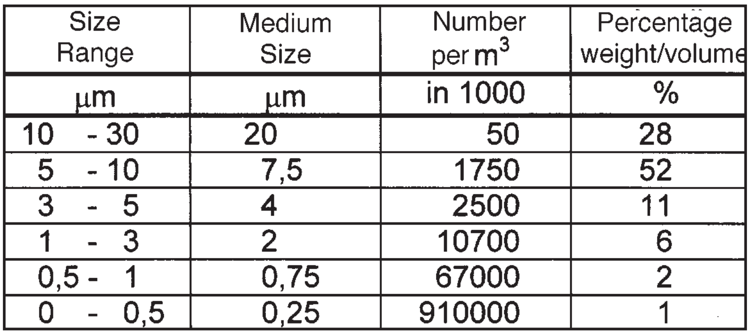
Table 1.6.1.1

The upper acceptable limit of dust deposition has been laid down :

in a Spa area	2 - 10 g/m^2 and more
in general	10 - 15 g/m^2 and more
in industrial areas	20 - 30 g/m^2 and more

When investigating the vertical distribution of dust, it was found in areas of high concentration that the first dust layer was about 3 - 4 m above the earth's surface in the form of traffic dust, with a second layer above which contained mainly heating dust. Apart from somewhat impairing breathing, the dust normally contained in air does not damage health because the mucus membranes in the respiratory ducts have a filtering effect.

Grain Sizes of Dust in an Industrial Area



Size Range	Medium Size	Number per m^3	Percentage weight/volume
µm	µm	in 1000	%
10 - 30	20	50	28
5 - 10	7,5	1750	52
3 - 5	4	2500	11
1 - 3	2	10700	6
0,5 - 1	0,75	67000	2
0 - 0,5	0,25	910000	1

Table 1.6.1.2

However, dust from production areas can be damaging or dangerous (such as silicosis) for living organisms and calls for targeted, effective reduction of the dust load in order to maintain viable living conditions. Dangerous dust impairs respiration, causes allergic reactions, impedes sunlight and, in conjunction with moisture and in the course of time, damages valuable buildings by decomposition.

1.6.2 Germs, viruses, bacteria

Bacteria count among the solid particles as well as the bacteriophage found in bacteria cultures, lastly viruses. All these germs can be present in compressed air either as floating particles or cling to solid or liquid particles. As a rule, germs adhere to dust particles.

Increase in dust particles leads to a higher germ content. In traffic arteries, an average enrichment in germs of up to 10 000/m^3 was noted.

Germs are living organisms of plant or animal origin, as well as microbes, bacteria and micro organisms in spherical, cylindrical, spiral or thread form, which propagate extremely fast through splitting. Some of these germs cause dangerous infections, others, on the other hand, cause putrefaction or fermentation.

Only a very small.portion of the germs cause infections. Most germs quickly die when drying and, therefore, infection through the air is relatively rare. Infection takes place almost exclusively through droplets which are finely spread in the air through coughing or sneezing.

Bacteriophage and viruses, both of approximately the same size, have a diameter of only 0.003 - 0.3 µm, they are thus 100 times smaller than bacteria. Foot and mouth disease virus belongs to the smallest viruses whereas the smallpox virus is among the largest.

Whereas bacteriophage can be found as parasites in bacteria cultures where they virtually devour the bacteria, viruses as a rule cause infections of more or less noxious character. Viruses cause illnesses such as influenza or measles in the human body.

Bacteria, on the other hand, are the cause of many infectious diseases such as diphtheria, tuberculosis or cholera. Bacteria in the widest sense have a size of about 0.2 - 30 µm.

Actinomyces (ray fungi) count among the bacteria, then the bacteria in the narrower sense known through propagation by splitting, furthermore the spore forming bacilli, the spherical cocci as well as the helical spirils and spirochetes, finally the comma shaped vibrios which move about through a whipping motion and which cause cholera.

Bacteria are omnipresent but must, at all cost, be kept away from certain products. For instance, when vaccines are produced, germs causing infection must not be present in the breathing air.

All these germs are very insensitive to cold and dryness. It is only heat, approaching boiling point, which they cannot withstand. If, at the same time, there is sufficient nutriment, germs multiply particularly fast in the presence of moisture. Anaerobic bacteria, however, only multiply and survive when there is no oxygen present. Viruses generally multiply only within the host body.

1.6.3 Nuclei of condensation

Small particles with a diameter of about 0.1 nanometres (nm) - 1 µm, on which oversaturated water vapour settles, are called nuclei of condensation.

Because of their small size, nuclei of condensation no longer obey Stokes’ law of precipitation. They are regarded as bodies dissolved in air and the result is described as a colloidal or divisible system. Nuclei of condensation are not formed as a result of mechanical break up but of chemical or physical processes.

Smoke and fog are such colloidal systems, where smoke is based upon the spread of solid particles in air, and fog on that of liquid ones.
Nuclei of condensation, which are charged either positively or negatively, are described as ions. The number of nuclei varies greatly from 0 - 4 x 10^2 nuclei per m^3.

1.7 Moisture in air

Moisture in air is essential for all forms of life. The water surfaces of brooks, rivers, lakes and seas evaporate and mix with air in the gaseous state.

Evaporation can also cause moisture to float in air as finely divided droplets of varying size. These droplets then form a stronger or weaker fog or mist.

Such floating droplets arise, on the one hand, when vapour of a liquid is being condensed, on the other, if they are picked up by the air current from an existing accumulation of liquid or are detached from a flowing liquid.

If liquids occur in the form of floating droplets, they are referred to as liquid aerosols.

Depending on droplet size, one can subdivide :

- Spray fog in droplets	from 100 µm and more
- Fine spray fog with droplets	from 10 µm and more
- Fog or mist with droplets	from 1- 10 µm
- Aerosols with droplets	from 0.1 - 1 µm

Droplets of less than 1 µm size count among floating substances. They can be either of a harmless or dangerous nature such as acid mist or petrol exudation or may simply cause a nuisance such as tobacco smoke for some non smokers, this consisting of microscopically fine droplets.

Atmospheric air always contains a larger or smaller quantity of moisture in invisible, unsaturated vapour form and this exerts a certain vapour pressure.

The quantity of vapour, which can be contained by 1 m^3 of air, is limited and depends solely on the temperature of the air. The water vapour mixes with the air as a gaseous component. At high air temperatures, a relatively large quantity of vapour, up to saturation point, can be carried.

Every kilogramme of air contains a certain quantity of water in grammes. This value x in g/kg is the absolute air humidity or also degree of humidity and is a result of the ratio of the quantity of water picked up to the mass of dry air.

To establish what quantity of gaseous water vapour is contained in 1 kg of air, and which part thereof is transformed into condensed water upon cooling, one uses formula 1.7.1. For air and water the following is valid :

RL= 29.27 mkg/kg °K
RD= 47.1 mkg/kg °K

$$\boxed{x = 0{,}622 \times \frac{p_D}{(p_D + p_L) - p_D}}$$

Formula 1.7.1

Here p_D is the saturation pressure obtained at a specific temperature referred to the barometric pressure $p_D + p_L$.

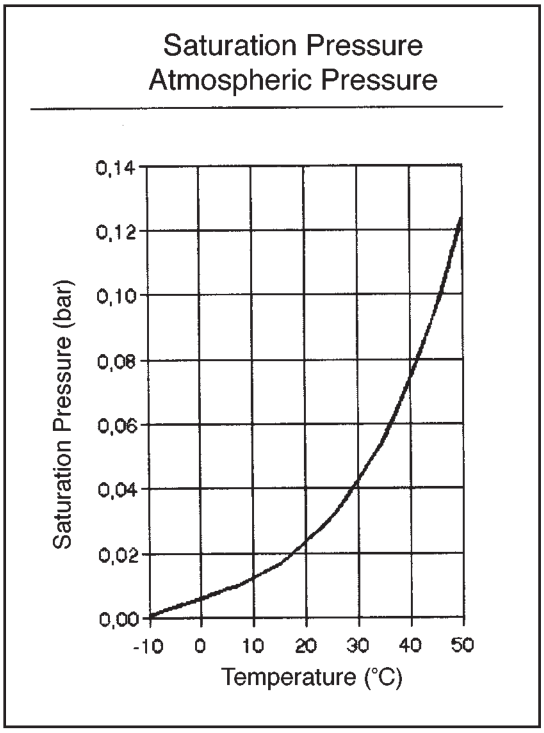


Diagram 1.7.1

Air with a maximum concentration of water vapour is saturated. If the air contains less vapour, it is unsaturated and can pick up further water vapour right up to the saturation limit.

If the air contains more water vapour than corresponds to the degree of saturation, the surplus vapour precipitates in the form of water mist.

The temperature at which a quantity of air is saturated by water vapour is described as saturation temperature or dewpoint temperature.

Thus the saturation quantity is the maximum quantity of water which can be carried by the air at a given temperature.

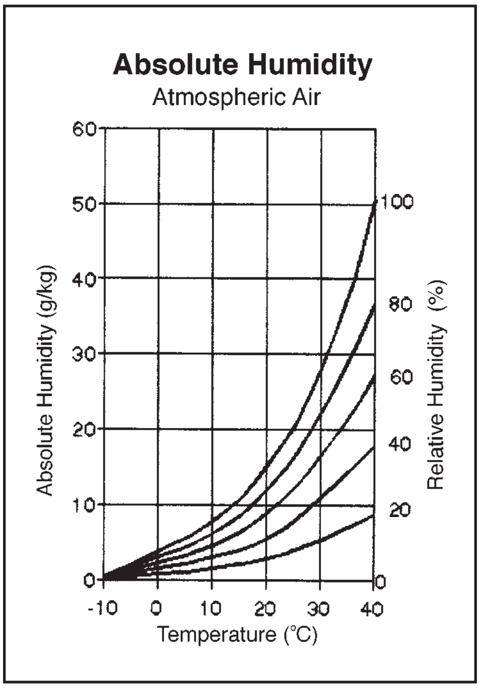


Diagram 1.7.2

The relative humidity is formed by the relationship between the water vapour pressure and the saturation pressure and is expressed as a percentage. If both pressures have the same value, the air is saturated with moisture. If the partial pressure of the vapour is higher, the latter liquifies, forming small droplets which precipitate as condensate. If, however, the partial pressure of the water vapour becomes smaller, the air is less than saturated with humidity.

The maximum quantity of water vapour in grammes which can be absorbed by the air, depends solely on temperature and volume but not on the pressure. With rising temperature, the volume expands, the space between the molecules is enlarged and the air can pick up more water vapour.

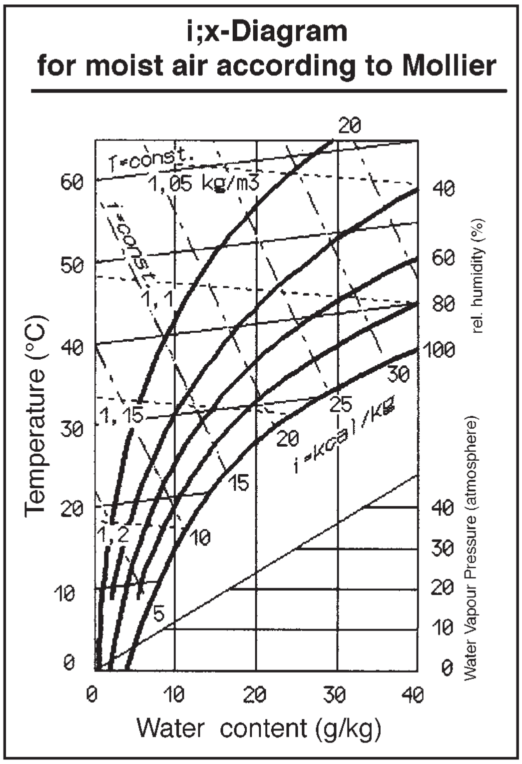
Absolute humidity of saturated air in g/m^3

°C	g/m^3	°C	g/m^3
1	5,15	26	24,38
2	5,52	27	25,78
3	5,92	28	27,22
4	6,35	29	28,77
5	6,80	30	30,36
6	7,28	31	32,02
7	7,77	32	33,78
8	8,29	33	35,64
9	8,84	34	37,57
10	9,40	35	39,60
11	9,99	36	41,72
12	10,65	37	43,91
13	11,35	38	46,20
14	12,07	39	48,62
15	12,82	40	51,14
16	13,63	41	53,76
17	14,48	42	56,49
18	15,37	43	59,35
19	16,32	44	62,34
20	17,29	45	65,44
21	18,31	46	68,63
22	19,38	47	71,92
23	20,53	48	75,40
24	21,74	49	79,08
25	23,04	50	82,98

Table 1.7.1

Table 1.7.1 shows the maximum quantity of moisture in the saturated state at 100 % relative humidity. The quantity of moisture is always referred to 1 m^3 of air.

To facilitate calculations with moist air and to demonstrate the changes of state in a clear manner, the following simplified ix-diagram by Mollier should serve. The diagram is an oblique angled co-ordinate system containing the x values on the abscissa sloping towards bottom right containing the enthalpy (1+x) kg.



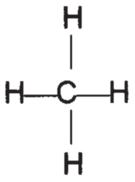
i;x-Diagram for moist air according to Mollier

Diagram 1.7.3

To facilitate the reading of the x values there is, in addition, a horizontal auxiliary axis. The saturation curve for the absolute pressure of 760 Torr (1 atmosphere) has been drawn in, as this separates the zone of unsaturated air from that of over- saturated air. Furthermore, the lines of equal relative humidity and equal density have been entered.

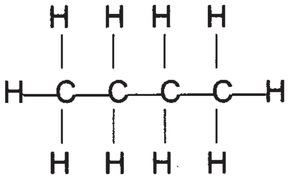
1.8 Hydrocarbons

Carbon is contained in all organic compounds and has the property that carbon atoms can form chains of any length with each other. Many compounds of organic chemistry consist of the elements carbon and hydrogen and are called hydrocarbons. One atom of carbon can for example link with four atoms of hydrogen to form CH_4 and is thus saturated.



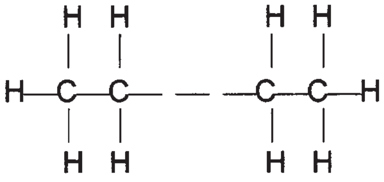
$$\begin{array}{ccccc} & & H & & \\ & & | & & \\ H & - & C & - & H \\ & & | & & \\ & & H & & \end{array}$$

Methane



$$\begin{array}{ccccccccccc} & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & \end{array}$$

Butane



$$\begin{array}{ccccccccccc} & & H & & H & & & H & & H & \\ & & | & & | & & & | & & | & \\ H & - & C & - & C & - & - & - & C & - & C & - H \\ & & | & & | & & & | & & | & \\ & & H & & H & & & H & & H & \end{array}$$

$C_nH_{2n}+2$

The crosslinking of the C atoms in conjunction with the H atoms can be continued indefinitely in line with the general formula of the alcanes. The first members of this series are gaseous, the ones in the middle in the range of C_5 - C_{16}, on the other hand, are liquid, the higher ones solid.

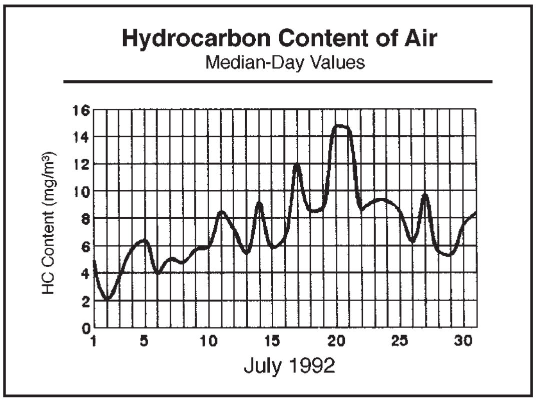


Diagram 1.8.1

Saturated hydrocarbons are primarily obtained from mineral oil. Crude oil is processed in refineries. Here, distillation is used to fractionate the crude oil into constituents of differing boiling points and drawn off separately, ranging from petrol via kerosene to lubricating oil.

When these substances are used, they are released into the environment. Diagram 1.8.1 shows the total hydrocarbon content.of atmospheric air, using a small town as an example.

It is not only motor traffic which loads up the air with hydrocarbons. For instance, the metal working industry uses compounds based on hydrocarbons as lubricants and coolants.

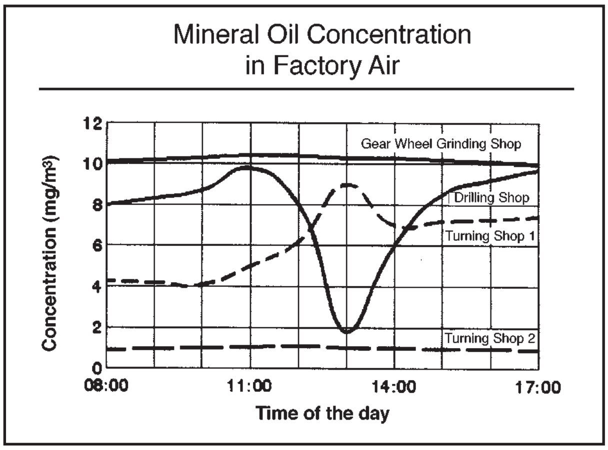


Diagram 1.8.2

The high temperatures generated by metal cutting cause the coolant to evaporate and separate out hydrocarbons. Oil fog concentrations in the most varied production areas with a widely differing and in part high level are shown over the course of a day in diagram 1.8.2.

The content of suspended dust in breathing air, which is relevant for assessing the oil content, amounts to average values of clearly less than typically 100 µm/m^3 of air. For instance, the 267 measuring stations of the environmental authorities in the Federal Länder found dust suspension levels in the air of only 38 - 51 µm/m^3 between the end of April and the beginning of May 1994, taking the average over the entire Federal Republic. However, these are only average mean values and can lead to false assessment when applied to particular compressed air stations.

1.9 Air pressure

The molecular forces which lead to more or less cohesion of solids and liquids, are so small in the case of gases that the gas particles are practically free to move. Gases spread over every available space and mix with gases already present there. The gas volume consists mainly of free volume and the net volume of the gas molecules, the latter being considerably smaller than their free volume. As a result, all gases and, of course, also air, can be compressed.

At atmospheric pressure and a temperature of 0°C, 1 m^3 of air contains approximately 27 x 10^{18} molecules which constantly enter into collisions, whereupon direction of motion and speed are altered in each case. In a closed vessel with 27 x 10^{18} molecules, each square millimetre of the inner surface of the vessel is exposed to about 3 x 10^{21} molecular impacts per second. The total effect of these 3 x 10^{21} impacts onto the walls is described as air pressure. The energy of motion of a gas particle is therefore solely dependent on the temperature. At -273°C every molecule of gas is totally devoid of motion.

Air pressure is measured by means of a barometer and is the current weight of the air column above the surface of the earth related to sea level. The pressure upon the surface of the earth caused by the weight of air amounts to 1.033 kg/cm^2.

If the air were of even density this would equate to a height of the atmosphere of

$$h = \frac{1.033 \times 10\,000}{1.293} = 7.991 \text{ m}$$

where 1.293 represents the density of air in kg/m^3 at 0°C. In reality, however, pressure decreases with height.

Meteorology uses the terms Torr for indicating pressure. 1 Torr corresponds here to 1 mm of mercury column. This denomination was introduced in honour of the Italian Professor Torricelli.

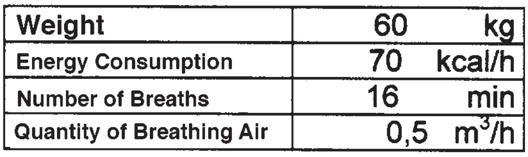
1.10 Human need for air

Breathing air is a precondition for human life, more accurately, the oxygen of the air which is essential for the combustion processes of the human body.

The air required by an adult human depends on various influences and can be indicated by way of example only.

The average bio-physical data of the human in a state of rest form a basis with the following values :

Human Bio-Physical Data

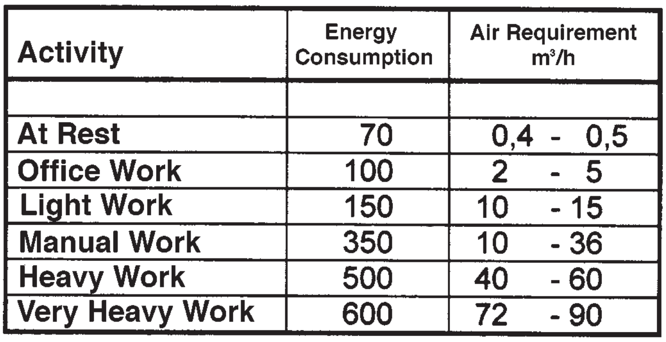


Weight	60 kg
Energy Consumption	70 kcal/h
Number of Breaths	16 min
Quantity of Breathing Air	0,5 m^3/h

Table 1.10.1

The air requirement of the human being at different activities, deduced from the above, is summarised in the following table.

Human Requirement of Air



Activity	Energy Consumption	Air Requirement m^3/h
At Rest	70	0,4 - 0,5
Office Work	100	2 - 5
Light Work	150	10 - 15
Manual Work	350	10 - 36
Heavy Work	500	40 - 60
Very Heavy Work	600	72 - 90

Table 1.10.2

The air inhaled by an adult human in the absence of bodily activity contains about 0.5 m^3/h where the air exhaled, on average, contains 17% O_2; 4% CO_2 and 79% N.

Part 2

2.0 Compressed air

Many technical applications of compressed air can be recalled from the early days of mankind.

In order to establish when compressed air was applied for the first time in order to carry out work, one has to look back to the day when hunters tried out blowpipes with arrows in order to shoot wild animals.

Considerably later in time, hand operated bellows were used when goldsmiths in ancient Egypt started to melt metals such as gold and copper. Copper and tin were alloyed to form bronze and this developed into an established method of production with the help of “air compression”.

Further development towards an air compressor proceeded through the blower cylinder, invented by John Smeaton, which was powered by a water wheel.

The first blower machine was built by Wilkinson around 1776. This blower provided compressed air with a pressure of about 1 bar gauge.

Only by the year 1800, was compressed air.seriously discussed as a carrier of energy. The first attempt failed, in 1820 in Wales. The blowing machines functioned as expected but the ducting system made from ceramic pipes was totally inadequate.

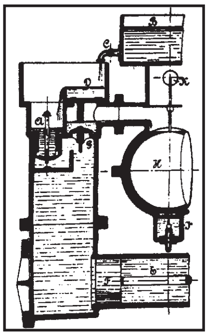


Fig. 2.0.1

The first successful transmission of energy by compressed air and on a large scale succeeded when the Mt. Cenis tunnel was built in the Swiss Alps.

When the 13.6 km long tunnel was built, compressors with a pressure of 6 bar were used. These worked according to the principle of the falling water column

(Fig. 2.0.1). The exemplary engineering achievements shown by the construction of the tunnel were acknowledged throughout the entire world.

The final break-through for compressed air succeeded in the year 1888, when the city of Paris installed a compressed air distribution system which supplied wide areas of the city with this form of energy. A 7 km long principal network with 50 km of auxiliary lines was supplied with compressed air generated by a 1500 kW compressor. This station was extended up to the year 1891 and reached a total compressor power of 18000 kW.

Thus compressed air stood at the threshold of great times. Technicians in many industrial countries became active with a view to utilising compressed air for the most varied applications.

Today, compressed air forms an essential supplement to electricity, and industry without it can no longer be imagined. The rapid development and spread of compressed air is due to the fact that it is both, carrier of energy and working medium, as opposed to electric current which can be used exclusively as a carrier of energy.

In addition to electric current and hydraulics, compressed air enjoys widespread use in present day technology and the fields of application are increasing all the time.

Compressed air is compressed atmospheric air. Air in the compressed state is a carrier of energy and offers the possibility of transmitting this energy over large distances and then utilising it upon release.

Particularly in medium size and large industrial works, we find machine and hand tools of all types which are powered by compressed air. To this have to be added pneumatic displacement and feed units, lifting tackle, blow guns, sand and shot blasting installations or, in paint shops, spray guns.

Furthermore, conveying appliances for bulk goods such as wheat, using pneumatic pressure or air suction power, are used in port installation or silos, also pneumatic or pneumatic/hydraulic control and activation equipment, and finally pneumatic logic elements are used in industry.

Mining forms another important field. Likewise the manufacture of pharmaceutical products such as with the production of vaccines or antibiotics, then numerous applications in the food and beverage industry and, last but not least, the hospitals, nursing homes and fire and rescue stations equipped with compressed air.

All these users of compressed air, of which are listed only the most important ones, do not only depend on compressed air but, in addition, compressed air must be fed to the operating process in a treated, i.e. filtered and dried, state.

2.1. Pressure

The air pump is the simplest example of the operating principle of the air compressor. A piston is moved inside a cylindrical housing. The forward stroke compresses the air. The return stroke motion sucks new air into the pumping space. Each compressing stroke movement thus increases the pressure of the enclosed air.

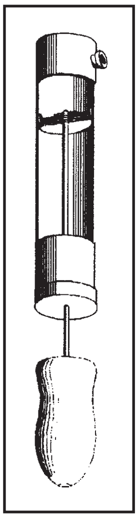


Fig. 2.1.1

An air pump is, of course, an unsuitable means for producing large quantities of compressed air for industrial purposes. However, if the piston is driven not manually but electro-mechanically, designed for high pressures and fitted with suitable control units, this principle can be utilised for industrial application. However fundamentally simple or complicated particular types of compressor are designed, all compressors compress the ambient air to reach a specified final pressure.

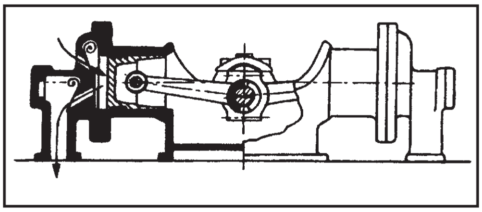


Fig. 2.1.2

Static pressure is the force effect per unit area of.a standard force FS.

$$\boxed{p = \frac{F_s}{A}}$$

Formula 2.1.1

Static pressure p or built up pressure results from the pressure exerted by a fluid at rest upon a wall lying parallel to the direction of flow.

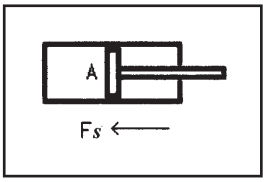


Fig. 2.1.3

On the other hand, dynamic pressure q or flow pressure, describes the force effect of a flowing mass of air onto a wall situated at a 90° angle to the direction of flow.

$$\boxed{q = \frac{\rho}{2} x\, w^2}$$

Formula 2.1.2

The sum of static and dynamic pressure is the total pressure of flowing compressed air exerting the required effect.

$$\boxed{p_t = p + q}$$

Formula 2.1.3

Referred to as free flow, differential pressure is the difference between flowing pressure and static pressure. The difference between two pressures, p_1 and p_2 is described as differential pressure delta p = $p_{1,2}$. For purposes of calculation, the static pressure should, as a rule, be given as absolute pressure (differential pressure compared with vacuum pressure).

In Fig. 2.1.4 pressure indications relative to barometric pressure p_b are shown graphically.

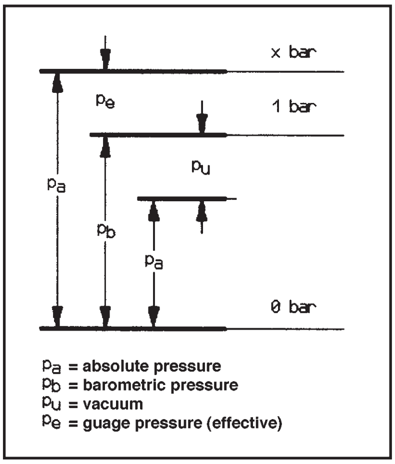


Fig. 2.1.4

For many practical applications, the term pressure is always understood as gauge pressure. Compared with atmospheric pressure, the numerical value of gauge or static pressure is less by 1 (bar). Static pressure is measured by means of a pressure gauge or with a manometer.

In accordance with DIN 1314, gauge pressure is given the formula symbol pe. Here, e means exceeding.

2.2 Gas laws

The parameters most important to a gas or air such as pressure, volume and temperature, determine the state of the gas at any particular time and are described as thermal state parameters.

The law of Boyle-Mariotte applies to ideal gases, i.e. at constant temperature the density (of a gas behaves like the accompanying pressure p.

$$\boxed{\frac{\delta_1}{\delta_2}=\frac{V_2}{V_1}=\frac{p_1}{p_2}}$$

Formula 2.2.1

Gay-Lussac’s law tells us that at constant pressure the densities σ of a gas behave in inverse proportion to the absolute temperatures T.

$$\boxed{\frac{\delta_1}{\delta_2}=\frac{V_2}{V_1}=\frac{T_2}{T_1}}$$

Formula 2.2.2

Formulae 2.2.1 and 2.2.2 enable us to form Boyle-Mariotte-Gay-Lussac’s law. If pressure and temperature of a gas change simultaneously, then the following applies taking into account the general gas laws :

$$\boxed{\frac{\delta_1}{\delta_2}=\frac{V_2}{V_1}=\frac{p_1 \times T_2}{p_2 \times T_1}}$$

Formula 2.2.3

If there is a change of state, individual state parameters assume different values. If pressure and temperature change simultaneously, then we deduce from the gas laws according to formula 2.2.3 and, leaving out the densities, that :

$$\boxed{\frac{V_2}{V_1}=\frac{p_1 \times T_2}{p_2 \times T_1}}$$

Formula 2.2.4

2.2.1 General gas equation

For the transition from state 1 to state 2 of an enclosed quantity of gas, Boyle-Mariotte's and Gay-Lussac's law then give us pressure, volume and temperature upon transition from state p_1, V_1, T_1 to state p_2, V_2, T_2

$$\boxed{\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2}}$$

Formula 2.2.1.1

It follows from formula 2.2.1.1 that the product of pressure and volume divided by the absolute temperature results in a constant value for all states of the gas.

$$\boxed{\frac{p \times V}{T} = const}$$

Formula 2.2.1.2

2.2.2 Specific gas constant

If the general gas equation is applied to $V = m/\sigma$, the gas equation assumes the following enlarged form :

$$\boxed{\frac{p \times V}{T} = \frac{p \times m}{T \times \delta} = m \times \frac{p}{T \times \delta} = m \times R}$$

Formula 2.2.2.1

It simplifies calculation with the gas equation if one operates with the specific volumes v, where $v = V/m$. If one substitutes $V = v \times m$ in equation 2.2.2.1, the physical state equation of gases related to 1 kg becomes :

$$\boxed{\frac{p \times V}{T} = R}$$

Formula 2.2.2.2

2.2.3 General gas constant

Gas constant R depends on the chemical characteristics of the ideal gas. This dependence is obviated if matters are expressed as a function of the kilomol. The term kmol is used for a quantity of mkg of a gas which has the same volume content V for all gases. At 0°C and 760 Torr, this is

molvolume v0 = 22.414 m^3/kmol

The density of air at 0°C is 1.293 kg/m^3. For air, expressing p in kg/m^3, this leads to

gas constant RL = 29.27 mkg/kg °K

If one refers the equation from formula 2.2.2.2 to 1 kmol, i.e. to mkg of a gas, the equation reads :

$$\boxed{V = \frac{m \times R \times T}{p}}$$

Formula 2.2.3.1

As, at constant pressure and constant temperature, the mol volume v0 for all ideal gases is the same, the multiplication of m x R must also have the same value for all gases. This expression is described as

general gas constant R_0 = m x R

and, expressed in figure[1], (101325 x 22,414 / 273.15), leading to a

universal constant of physics = 848 mkg/kmol°K.

2.2.4 Real gas factor

Gases which follow the above laws exactly are called perfect or ideal gases. Gases in reality follow these laws only approximately and the more closely the lower the pressures are.

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[1] p in Pascal = N/m^2

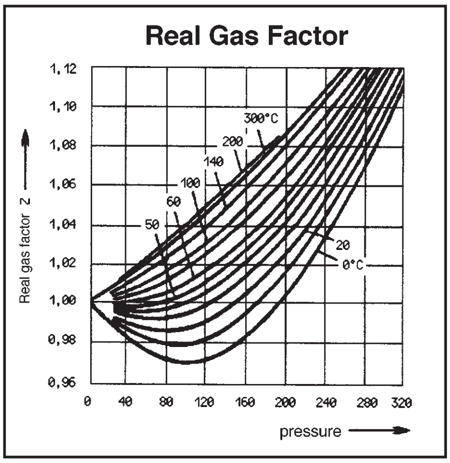


Diagram 2.2.4.1

If the gas approaches a vapour like state or if it contains a significant constituent of water vapour, one uses the introduction of a real gas factor Z (diagram 2.2.4.1) in order to effect a correction when calculating the volume. For pure air, and with absolute pressures lower than 40 bar and temperatures below 50°C, the real gas factor can be close to 1 and is, therefore, neglected in most cases.

Vapours and real gases only approximately obey the relation p x v = R x T. If steam tables or steam diagrams are available, the appropriate state parameters can be derived from these. These are based on measurements and interpolation calculations.

$$\boxed{V = Z \times \frac{R \times T}{p}}$$

Formula 2.2.4.1

Another possibility of establishing the real status parameters of gases, consists of supplementing the state equation with the correction factor Z from diagram 2.2.4.1 so that, at high pressures or temperatures, solely formula 2.2.4.1 is valid when an accurate determination of the volume is made.

2.3 Compression

It is logical to detect from the general gas equation (formula 2.2.1.1) that heat must, in principle, be generated when air is being compressed. In order to arrive at a theoretical calculation of the quantity of heat, one looks at the simplified case at which compression takes place theoretically without any heat being added or withdrawn.

$$\boxed{p_1 \times V_1 = p_2 \times V_2 = const}$$

Formula 2.3.1

As part of the heat of compression is conducted away from every compression chamber, compression in practice proceeds in between adiabatic[2] and isothermal[3], i.e. in a polytropic[4] mode.

The following interrelations can be deduced from the gas laws :

Temperature change as a function of pressure at constant volume as isochores[5]

$$\boxed{T_2 = T_1 \times \left(\frac{p_2}{p_1}\right)^{\frac{n}{n-1}}}$$

Formula 2.3.2

The volume change as a function of temperature at constant pressure as isobars[6].

$$\boxed{V_2 = V_1 \times \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}}}$$

Formula 2.3.3

Pressure change as a function of volume at constant temperature as isotherms

---

[2] Exponent x

[3] Exponent n = 1

[4] Exponent n > x

[5] Exponent n = ∞

[6] Exponent n = 0

$$\boxed{p_2 = p_1 \text{ x} \left(\frac{V_2}{V_1}\right)^{\frac{n}{n-1}}}$$

Formula 2.3.4

Supplementing the formulae indicated above, which are more of theoretical interest, there are the following equations which have greater practical importance. The adiabatic pressure change as a function of temperature at constant volume,

$$\boxed{p_2 = p_1 \text{ x} \left(\frac{T_2}{T_1}\right)^{\frac{x}{x-1}}}$$

Formula 2.3.5

respectively the adiabatic volume change as a function of pressure at constant temperature

$$\boxed{V_1 = V_2 \text{ x} \left(\frac{p_2}{p_1}\right)^{\frac{1}{x}}}$$

Formula 2.3.6

Polytropic change of pressure as a function of temperature at constant volume,

$$\boxed{p_2 = p_1 \text{ x} \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}}}$$

Formula 2.3.7

Respectively the polytropic change of volume as a function of pressure at constant temperature,

$$\boxed{V_2 = V_1 \text{ x} \left(\frac{p_2}{p_1}\right)^{\frac{1}{n}}}$$

Formula 2.3.8

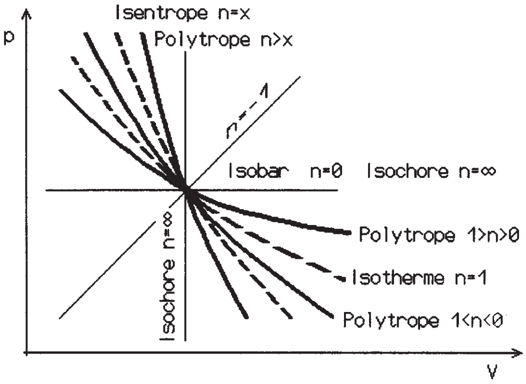
The change of state of a gas is established by taking into account the relationship of specific heat capacities exponent x. In doing so, one differentiates between :

c_p = specific heat at constant pressure respectively referred to 1 kg (kcal/kg°C)
c_V = specific heat at constant volume respectively referred to 1 kg (kcal/kg°C)

Based on experiments, the relationship of specific heats $x = c_p/c_V$ is :

with uniatomic gases	$x = 1.666 = 5/3$
with biatomic gases	$x = 1.400 = 7/5$
with triatomic gases	$x = 1.333 = 8/6$

The following illustration shows the interpretations of the various specific cases of the general polytropic law.



Changes of state as special cases of the general poly tropic law pVn

Fig. 2.3.1

The difference of the specific heat referred to 1 m³ at constant pressure and volume is a constant. For ideal gases, the following applies when applying the above x values:

With uniatomic gases

$$c_p = \frac{5}{22.4} = 0.22 \text{ kcal/m}^3\ °\text{C} \qquad cV = 0.13 \text{ kcal/m}^3\ °\text{C}$$

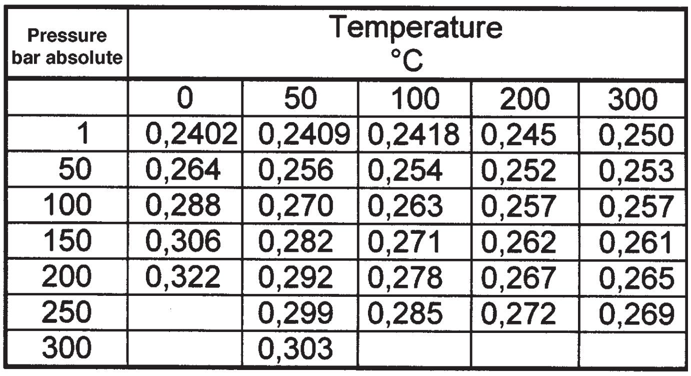
with biatomic gases

$$c_p = \frac{7}{22.4} = 0.31\ \text{kcal/m}^3\ ^\circ\text{C} \qquad c_V = 0.22\ \text{kcal/m}^3\ ^\circ\text{C}$$

with triatomic gases

$$c_p = \frac{8}{22.4} = 0.36\ \text{kcal/m}^3\ ^\circ\text{C} \qquad c_V = 0.27\ \text{kcal/m}^3\ ^\circ\text{C}$$

The specific heats of real gases deviate all the more from those of ideal gases, the higher their number of atoms. Furthermore, the specific heats, compared with the behaviour of ideal gases, increase with temperature and with pressure. For calculations involving a larger range of temperatures, the median specific heat cm must, therefore, be used instead of the true specific heat.



Pressure bar absolute	Temperature °C				
	0	50	100	200	300
1	0,2402	0,2409	0,2418	0,245	0,250
50	0,264	0,256	0,254	0,252	0,253
100	0,288	0,270	0,263	0,257	0,257
150	0,306	0,282	0,271	0,262	0,261
200	0,322	0,292	0,278	0,267	0,265
250		0,299	0,285	0,272	0,269
300		0,303			

Table 2.3.1

2.3.1 Normal state

As a consequence of the changing relationships between the state parameters and the high degree of compressibility, all data must, particularly in the case of gases, be referred to an accurately specified and agreed state. The normal state of solid, liquid and gaseous substances is laid down in DIN 1343 in a generally valid manner.

Normal volume Vn is the volume referred to at normal temperature and normal pressure. It is that state which is characterised by

- normal temperature T_n = 273.15 °K
- normal pressure P_n = 1.01325 bar

and is also defined as the standard physical volume

$$\boxed{V_n = V \times \frac{T_n}{T_n + t} \times \frac{p}{p_n}}$$

Formula 2.3.1.1

Differing from the above, ISO 2787 prescribed the following for indicating a volume of air

- reference temperature T_N = 293.15 °K
- reference pressure P_N = 1.00 bar

and this was accepted as the internationally valid normal state. This basic reference is generally used and known as “technical and atmospheric normal state”.

Unfortunately, in practical applications it is not always made clear to which definition reference is made.

In principle, the standard volume describes the state of air under normal temperature and normal (atmospheric) pressure.

2.3.2 Density of air

In practice, alternatively to the volume of air, its mass is also indicated. Volume is established by dividing the mass m by the density σ. for accurate specification, one should always indicate also the appropriate density when stating mass. The density of air, in turn, depends on the temperature and the relative humidity.

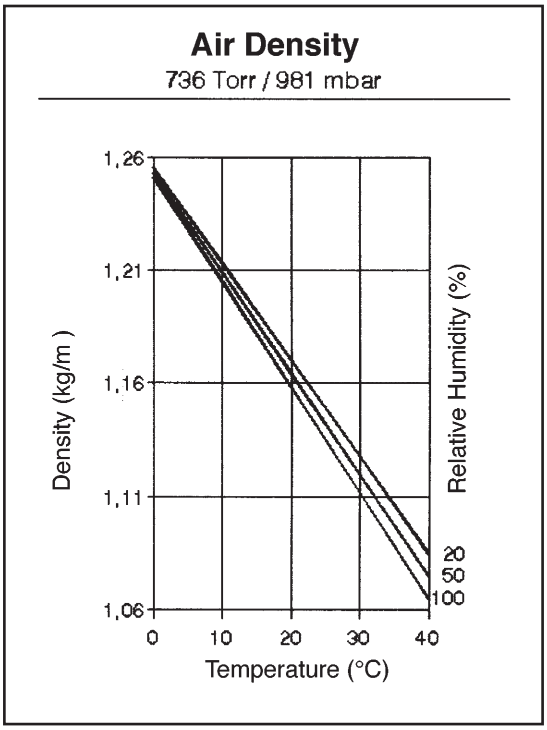


Diagram 2.3.2.1

Using the values of diagram 2.3.2.1, the volume is derived from the mass of air. The diagram is based on 1 atmosphere = 736 Torr.

2.3.3 Absolute temperature

There is no gas which follows the gas laws at the lowest temperatures, because every gas becomes liquid at a certain temperature. The laws, therefore, apply to so called ideal gases only. A gas approaches the ideal state as the pressure decreases and the temperature increases.

If one carries on cooling down a gas more and more at constant pressure, the volume at t = -273.15°C will be the $V_{(-273.15)} = V_0$ (1 - 273.15°C / 273.15°C) = 0, under the law of Gay-Lussac. A temperature below -273.15°C is therefore not possible.

Therefore the temperature of -273.15°C thus forms the point of absolute zero from which point only positive temperature values can be recorded. From this arises the scale of absolute temperature with the absolute temperatures T in degree Kelvin °K.

Temperature differences in °K and °C are the same. This applies also to temperature differences in °R and °F.

Temperature calculations

t_C	$= \frac{5}{9} [t_F - 32]$	$= T_K - 273,15$	$= \frac{5}{9} [T_R - 491,67]$
t_F	$= \frac{9}{5} t_C + 32$	$= \frac{9}{5} T_K - 459,67$	$= T_R - 459,67$
T_K	$= t_C + 273,15$	$= \frac{5}{9} T_F + 255,38$	$= \frac{5}{9} [T_R - 32]$
T_R	$= \frac{5}{9} t_C + 491,67$	$= T_R + 459,67$	$= \frac{5}{9} [T_K + 32]$

Table 2.3.3.1

2.4 Pollutants

Mainly three components, solids, water content and oil residues contaminate compressed air after compression to a considerable degree. One therefore finds all impurities of the ambient air in compressed form in the compressed air, unless they had been eliminated beforehand. These are joined by further substances originating from the compressor itself or from the piping and compressed air hoses.

Compressed air is used as a power medium in the most varied fields. These often differing manufacturing sectors also call for differentiated degrees of compressed air quality. It will be understood that normal working or factory air does not call for the refinement of quality of compressed air except where absolutely necessary in more select fields such as the food or beverage industries.

There are also other sensitive manufacturing processes, such as the manufacture of microchips for the electrical industry or the extraction of hygroscopic (adsorbent) materials in chemical factories, which confront compressed air users with widely differing requirements.

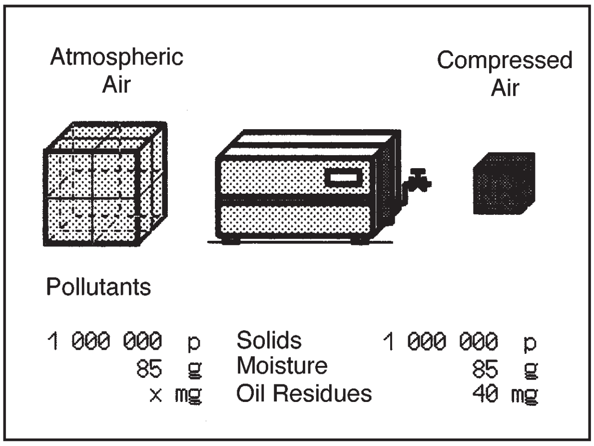


Fig. 2.4.1

If a compressor draws in 8 m^3 of air in order to covert this into 1 m^3 of compressed air at a pressure of 8 bar, then all contaminants present in atmospheric air (see table 1.6.1.1) likewise become compressed and are therefore present in the compressed air in 8-fold concentration.

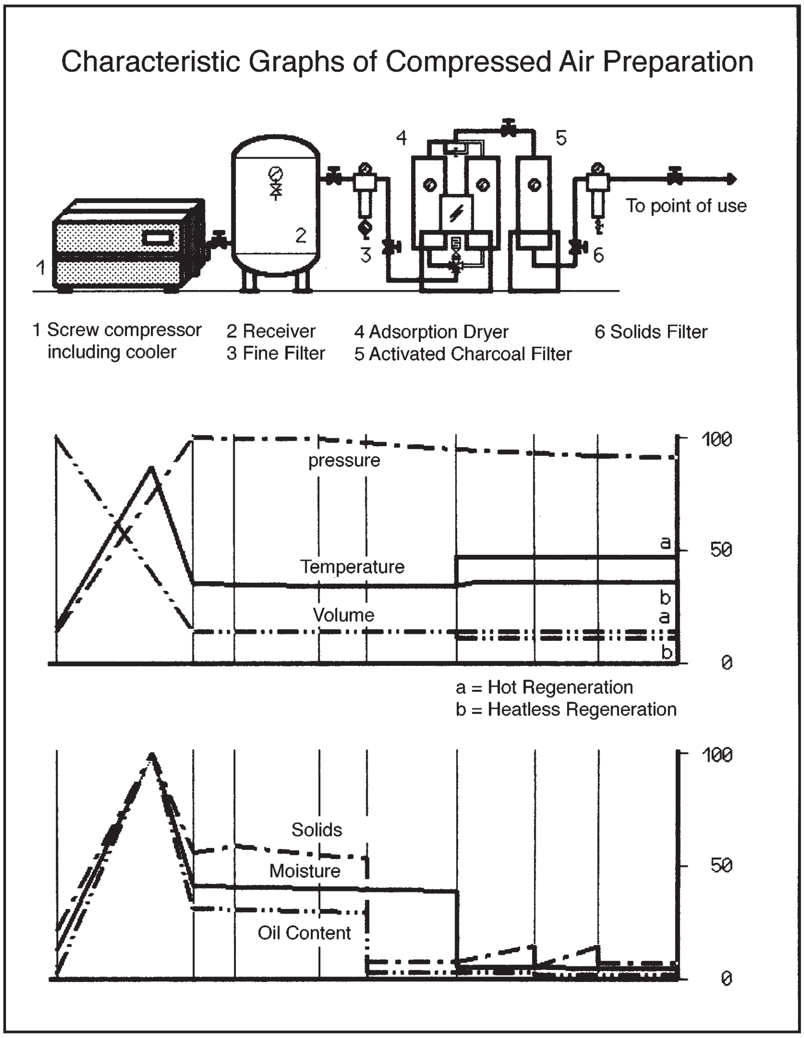


Fig. 2.4.2

The increasingly animated discussion in recent years concerning the subject of environmental pollution and of the problems raised by this do, of course, also apply to compressed air. Compressors convey the aspirated air with its impurities in heightened concentration to the point of use, where they are then released at the work place upon decompression. Drawbacks of this kind are in conflict with the requirements which are today demanded from compressed air quality.

Optimum conditions can be achieved only through targeted and consciously applied compressed air purification.

The solution to this problem is not restricted to the air purification chain after compression but affects all units of the compressed air system, starting with the compressor air intake right up to the point of use.

2.4.1 Solid contaminants

Solid particles floating in air are described as dust. In general, dust particles display widely varying sizes. Floating solid particles also include pollen, while bacteria and viruses must also be counted as solids.

Depending on particle size, dusts are subdivided into 3 classes :

- Coarse dust grain size >10 µm
- Fine dust grain size 1 - 10 µm
- Finest dust grain size <1µm

From amongst these three groups, it is essentially only the finest dusts which have to be counted among the floating substances.

Finest dust very often forms by far the largest share of the solids floating in air. These often form 80 - 90 % (by weight) of the contaminants in air. The majority of these particles is smaller than 1 mm. The sinking speed of dust depends on the grain size. If the air is at rest, the distance fallen may amount to fractions of a millimetre for very fine dust whereas, for very coarse dust, falling may take place at more than 1 m/s.

The dust content of air is influenced largely by the geographical situation and the location of the point of measurement, as well as by weather conditions such as wind, rain and snow.

The airborne dust concentration in large cities often amounts to more than 0.2 mg/m^3 of air. This content can be many times higher in industrial areas.

Meanwhile, dust contents of 5 - 10 mg/m^3 and more have been noted in relatively clean areas. This can be caused by high industrial chimneys and low precipitation speed of the released dust particles. In dusty workplaces, particularly on building sites or in quarries, the dust content may amount to some 100 mg/m^3 and even reach values of up about 250mg/m^3.

Further solid particles not originally forming part of air consist of oil soot, scale, rust as well as products of metal abrasion. These solid particles originate from the compressor or can be released from the internal walls of the pipework.

Solid particles and lubricating oil or grease act on pneumatic installations like an abrasive paste, causing particular trouble such as wear at sensitive points. Dust particles from castings, formed when cutting metal with machine tools, are particularly abrasive in their effect.

In addition, there are types of dust presenting a risk of explosion, particularly dust from aluminium and magnesium. Other dusts are injurious to health such as quartz or radioactive dust, others again have a toxic effect, are chemically aggressive or have pyrophoric (readily flammable) qualities. Some types of composite dust form encrustations in conjunction with water or moisture.

Solids of any kind and quantity in the intake area of the compressor frequently cause far reaching malfunctions in compressed air systems during or after compression. Depending on where the compressor is located, suitable steps have always to be taken at the intake end of the compressor as far as the suction filters are concerned.

The following examples of types of solids describe the possible sources of compressed air pollution:

Lignite, coal or anthracite mining result in increased coal dust content in the ambient air. To reduce wear and avoid explosion risk, special protective measures in the compressor system against these dusts are necessary.

Chemical production which results in aggressive substances such as sulphur compounds, calls for measures which also aim to reduce corrosion.

In the paper and wood industry, fine particles arising from sawing and cutting, often form the cause of.breakdowns in various manufacturing sections. This fine dust in the compressed air blocks the tools and machines installed downstream.

2.4.2 Water content

Ambient air always contains water vapour to varying degrees. This water content mixes with the compressed air in the form of invisible water vapour. More often than not, such air is unsaturated i.e. the temperature of the air is higher than the dewpoint in question at which condensation would take place.

Upon compression followed by cooling to approximate ambient temperature, also after isothermal compression, the dewpoint limit rises. This leads to the condensation of the surplus water from the compressed air, until the new saturation point is reached. The condensed water flows together and is collected at a suitable point at the aftercooler to be removed via automatically operating condensate drains.

Compression also causes finest fog droplets to form in the air. These can be retained in suitable filters (see Chapter 4), giving them the opportunity to coalesce. However, filters can solely remove droplets from the air current, not gaseous water vapour. In order to remove this water vapour as well, specially designed compressed air dryers have to be fitted.

The harmful effect of water on pneumatic installations is not limited solely to the formation of rust. In addition, the lubricating film is washed off rotating or linear drives, sliding parts jam or get eaten away, and a malfunction of the plant remains solely a question of time. Cost intensive maintenance work forms the logical consequence. Furthermore, there is the danger of freezing of equipment installed outside. At certain points of contact of differing types of metal, electro chemical micro elements may be formed, leading to surface corrosion.

2.4.3 Water vapour

Water vapour is always contained in the air and will, depending on the temperature, be drawn in, in larger or smaller quantities, whenever air is compressed. If the air is oversaturated with water vapour, the excess water vapour will condense. Oversaturation is possible when unsaturated air is cooled or when air is compressed while the temperature remains roughly the same. Heating due to compression initially prevents oversaturation. If this warm, moist air impinges upon a cold surface, the excess quantity of water vapour will again condense from the air.

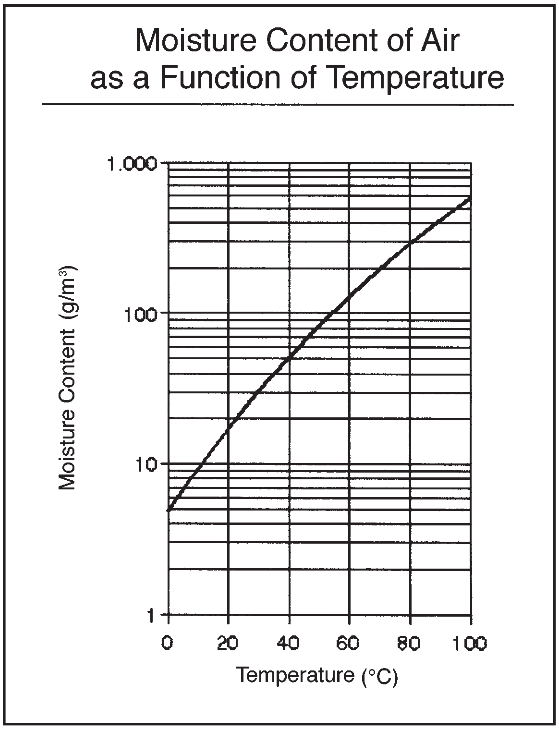


Diagram 2.4.3.1

Evaporation and condensation hold each other in balance, if the vapour pressure of the liquid is of the same magnitude as that part of the external pressure which is generated by the water vapour contained in the air. The dewpoint is that air temperature at which gaseous water vapour begins to condense in cooling air and is visibly precipitated as dew.

Diagram 2.4.3.1 establishes how much water is being condensed within the saturation limit, or how much water can still be picked up by the unsaturated compressed air, depending on the temperature. This can be demonstrated by means of an example :

Referred to an ambient temperature Tamb = 20°C and a relative humidity of 60 %, the moisture content in the ambient air amounts to 10.4 g/m^3. A compressor with 100 m^3/h intake capacity carries a total of 100 m^3/h x 10.4 g/m^3 = 1040 g/h of moisture. When compressing to p = 7 bar,.100 m^3/h intake air thus become 12.5 m^3/h of compressed air. However, this compressed air is no longer saturated to 60 % but, due to compression, saturated with water vapour to 100 %.

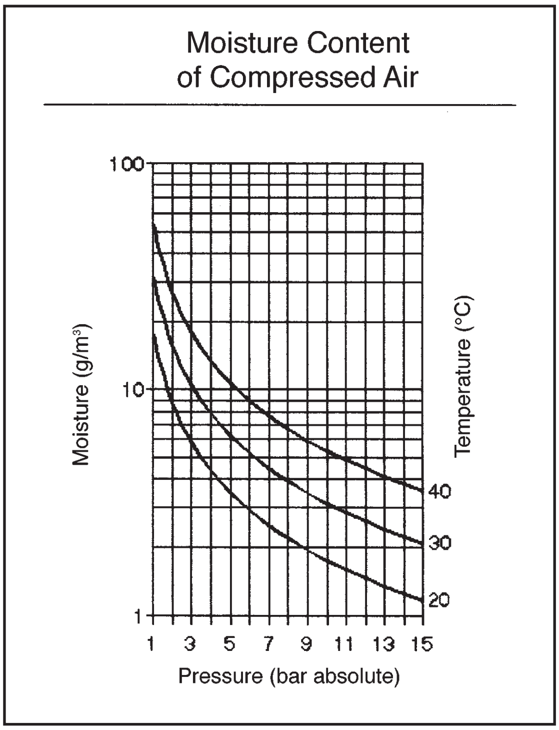


Diagram 2.4.3.2

With an ultimate compressed air temperature of Tult = 30°C, this compressed quantity of air hourly feeds a temperature dependent saturated water load of.12.5 m^3/h x 30.3 g/m^3 = 378 g/h into the compressed air system. The difference in moisture loading between intake and output quantity of 1040 g/h - 378 g/h = 824 g/h water load is separated out in the compressor’s after cooler.

The compressed air temperature following the aftercooler are very often much higher, so that the quantities of water load in the compressed air system will be higher than the values indicated by the example. Diagram 2.4.3.2 shows the influence of temperature on the moisture content of compressed air.

Pneumatic systems without air drying equipment, therefore, need not only water traps but also moisture separators. Separators and filters suitable for this task should, however, be fitted only just before the point of take-off, so there is little opportunity for the air downstream of the filter to cool further and thus precipitate further condensate.

The expansion of compressed air in a pneumatic device is accompanied by cooling. However, there is little danger of this causing the formation of condensed water because, with expansion, the dewpoint is lowered in proportion to the degree of expansion.

2.4.4 Oil residues

Sometimes a certain quantity of oil in the compressed air is desired or even prescribed. Pneumatic machines and tools receive their lubrication through a mixture of finely distributed oil added to the compressed air as an oil mist. However, there is other equipment which must remain totally free from oil as, otherwise, ducts could be blocked or deposits could form at critical points, which would endanger correct functioning.

In automatic conveying plants, oil content may cause caking of (powdery) bulk materials. Some substances such as food and beverage, but also pharmaceutical products which enter into contact with compressed air, must be kept free from even the smallest mixture of oil.

However, if oil mist is used for lubrication, the correct type of oil and the state of this oil are critical. Dirty, residue rich or resinous oil exerts a harmful effect on pneumatic components. The same applies to oil types which oxidise easily or form oil sludges.

Oils of the type and characteristics just described must be filtered out of the compressed air. This applies particularly to ordinary lubricating oils or heavy motor oils which have an undesirable effect on the properties of compressed air.

Being mineral oil products, the usual lubricating oils contain sulphur, albeit in small quantities. Added to this is a certain hydrogen content which will settle on metal surfaces. Under the influence of condensed water, this can lead to acid mixtures which attack seals or even cause corrosion damage on metal surfaces.

At the relatively high temperatures of compression, particularly with piston compressors, the effect of hydrogen and oxygen on oils susceptible to this, easily leads to the formation of solid residues which settle on the surfaces of sliding components of pneumatic devices leading to jamming. The presence of undesirable oils in compressed air is frequently the result of two causes :

1. The air drawn in by the compressor already contains some oil. This introduction of oil can be avoided or diminished by locating the intake filter into the open air, however protected against rain and dust, or finding an optimum location for the compressor itself.

2. The compressor passes oil into the compressed air, such as with piston

compressors where the lubricating oil helps to form a seal between piston and cylinder wall. This film of oil is subjected to a strong shearing effect, causing oil particles to be detached from the interface between piston and cylinder wall and to enter the compression space. On the other hand, with oil flooded rotary and screw compressors with oil injection cooling, it is the content of oil not caught by the oil separator which is thus withdrawn from oil circulation within the compressor but passed into the compressed air piping system.

This second cause does not arise with dry running compressors with oil free compression, i.e. with piston and screw compressors without oil lubrication as well as with diaphragm compressors. The same applies to blowers and ventilators which generate air of low pressure only.

In addition, and in most cases only small, oil or grease contamination arises from directional control valves, cylinders and regulators, which may have been greased or oiled before despatch.

By far the largest share of the oil contained in compressed air, sometimes 99% or more, occurs as floating droplets. Their diameter is usually less than 0.8 mm and even as low as 0.1 µm.

Whereas larger droplets occur only to a small extent and represent an aerosol, the smaller microdroplets form an oil mist or oil haze. These microdroplets can be removed from the compressed air only by means of high performance filters. Coarse filters or separators do not achieve this.

2.4.5 Oil vapour content

A certain oil content with the most varied structure of oil molecules is always contained in compressed air, whatever the design of compressor used.

Oil injected rotary screw compressors have conquered the compressor market and, given their many advantages over other systems of compression, now form an element without which compressed air generation can no longer be imagined.

With this type of compression system, oil is intentionally added to the drawn in ambient air when compression takes place. The residual oil content at the pressure outlet of screw compressors amounts, as a rule, to about
3 - 15 mg/m^3.

Not only with oil injected screw compressors but also with established types of piston or vane compressors, oil is used for cooling and lubrication.
Whereas oil injected screw compressors reach a maximum oil temperature of about 85 - 90°C, the oil of piston compressors or rotary vane types reaches far higher temperatures.

Even compressed air from non lubricated compressor systems is not always free from oil. For one thing, moving components (eg. sliding bearings) within the compressor are lubricated, for another, it is not impossible that hydrocarbons are drawn in from the surrounding air and thus conveyed into the pipe network in concentrated form. The vapour content of hydrocarbons diminishes with falling temperature.

Temperature (°C)	Vapour Pressure	Oil Vapour Content
10	0,000010	0,245
30	0,000037	0,801
60	0,000100	1,941
100	0,000298	5,170

Table 2.4.5.1

The values given in table 2.4.5.1 and otherwise referred to in this section are based on a particular compressor lubricating oil and can not be generally applied. The values indicated are derived from a compressor oil with the following technical data :

Ignition Point	250	250	°C
Equilibrium Temperature	60	150	°C
Vapour Pressure	0,0001	0,035	Torr
Density at 15°C	0,88	0,88	g/ml
Average Molecular Weight	520	520	
Oil Vapour Content	0,002	0,6	mg/l
	2	600	mg/m^3

Table 2.4.5.2

With lubricants based on mineral oil, it is often sufficient to estimate the vapour pressure on the basis of the ignition point. For every lubricating oil, the applicable vapour pressure diagram should be studied.

The oil vapour content of air can be estimated from knowledge of the average molecular weight of the oil. On the basis of the definition:

1 mol of a gas fills a volume of 22.4 litres
at 273°K and 760 Torr

The volume applying to 1 mg/L for oil vapour in air with 1.29 g/dm^3, 760 Torr and 273^{o}K can be deduced from the following formula:

$$\boxed{V = 22{,}4 \times \delta_L \times 10^{-3} \quad \frac{m}{M} \times \frac{760}{p} \times \frac{T}{273}}$$

Formula 2.4.5.1

And, after simplification through multiplying the constants, this leads to:

$$\boxed{V = 80{,}044 \times 10^{-3} \times \frac{m \times T}{M \times p}}$$

Formula 2.4.5.2

So that, after conversion, Formula 2.4.5.3 is available as a basis in order to determine the degree of saturation by oil vapour content in the volume of air, where the reciprocal value of 10^{-3} and the dimension m^3/dm^3 are taken into account through 10^3:

$$\boxed{V = 0{,}01243 \times 10^{-3} \times M \times \frac{p}{T}}$$

Formula 2.4.5.3

The result is displayed in the following diagram 2.4.5.1 and shows the oil vapour content for mineral oil[7] as a function of pressure and temperature.

For practical application one does, however, have to consider how far the gaseous phase is really saturated with the oil vapour and at what temperatures this takes place.

Furthermore, the question arises whether finest oil droplets are not floating as a mist in the air current, thereby causing a much higher content of oil than would correspond to the theoretical saturated vapour pressure.

It is also important to bear in mind that the compressor, depending on temperature, pressure and system of compression, can either promote or inhibit the occurrence of volatile decomposition products.

Being subjected to the effect of oxygen in the air and considerable heat, these decomposition products can falsify the oil vapour concentration in the air current strongly and sometimes lead to a far reaching scatter of values when it is attempted to measure the residual oil.

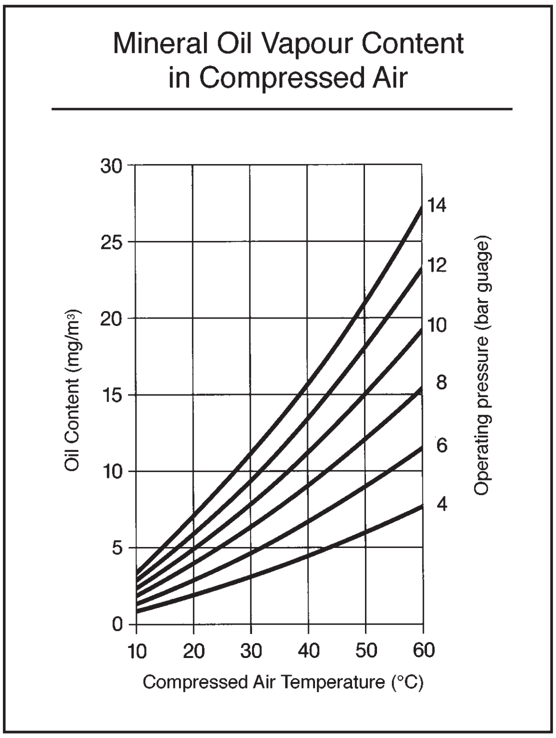

Mineral Oil Vapour Content in Compressed Air

Diagram 2.4.5.1

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[7] molecular weight = 520; vapour pressure = 0.0001 Torr

2.5 Gaseous mixtures

The gaseous impurities in compressed air consist, above all, of water vapour and, nearly always, of volatilised or evaporated oil. Other gaseous or vapour mixtures, which might potentially form.harmful sources, are normally contained in compressed air only to a very small extent, partly depending on where the compressor is installed, e.g. sulphur dioxide[8], carbon monoxide, hydrocarbons[9] and other trace gases.

The gas molecules involved have a size of around 0.0002 - 0.0005 mm. In order to eliminate harm arising from these as far as compression and subsequent compressed air treatment is concerned, the first step is to bear in mind possible negative influences of such gaseous mixtures when selecting the location of the compressor. For this reason, compressor manufacturers, in their operating instructions, advise to draw in only ‘clean’ air, which should also be as cool as possible.

Gaseous mixtures in air [10]

Compound	Formula	Moll wt. g/mol	Content ppm	Content mg/m^3
Nitrogen Oxide	N_2O	46,0055	0,5	1,03
Methane	CH_4	16,043	2	1,43
Carbon Monoxide	CO	28,0104	5	
Sulphur Dioxide	SO_2	64,063		
Ozone	O_3	47,99	0,01	0,02

Table 2.5.1

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[8] See diagram 1.6.1

[9] See diagram 1.8.1

[10] Source : Handbook of Physics and Chemistry

Part 3

3.0 Compressors

The state of a gas is specified by pressure, volume and temperature and can be changed in different ways.

- Isochoric	change of state :	Volume	remains constant
- Isobaric	change of state :	Pressure	remains constant
- Isothermal	change of state :	Temperature	remains constant
- Adiabatic	change of state :	Without exchanging heat with the surroundings	

Isothermal and adiabatic changes of state are of particular significance for compressors. Isothermal[1] calls for the lowest and adiabatic[2] for the highest expenditure of energy when compressing gases.

The true compression process takes place polytropically, i.e. the line of compression runs in between the adiabatic and the isothermal one. The closer compression, approaches the isothermal mode, the lower.the amount of work which has to be expended in order to compress the air or gas.

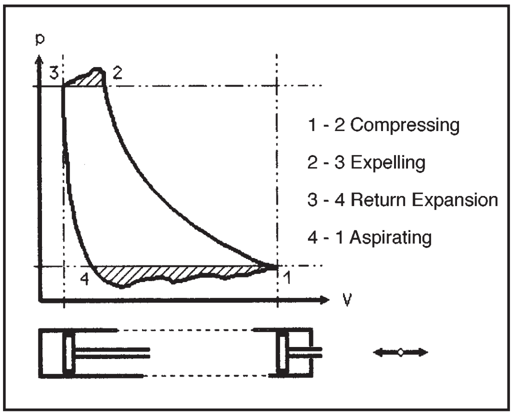

Fig. 3.0.1

Fig. 3.0.1 shows an idealised operating process of a displacement compressor in simplified form.

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[1] exponent $n = 1$

[2] exponent $x = 1.4$

As far as thermodynamic change of state is concerned, two principal theorems apply. The first principal theorem describes the effect of evolution of work and heat in accordance with enthalpy. The second principal theorem describes the heat exchange of enthropy. Using static thermodynamics, the first principal theorem can be incorporated into the second principal theorem.

When air is being compressed, a change of state with increasing enthropy is carried out. This change of state takes place polytropically. A special polytropic change of state used in compressors is the adiabatic change of state without change of heat content. The technical work needed to bring about the change of pressure arises from the difference between the enthalpies as between one state and the other. The different changes of state can be shown as an area (see Fig. 3.0.1) in the pxV diagram.

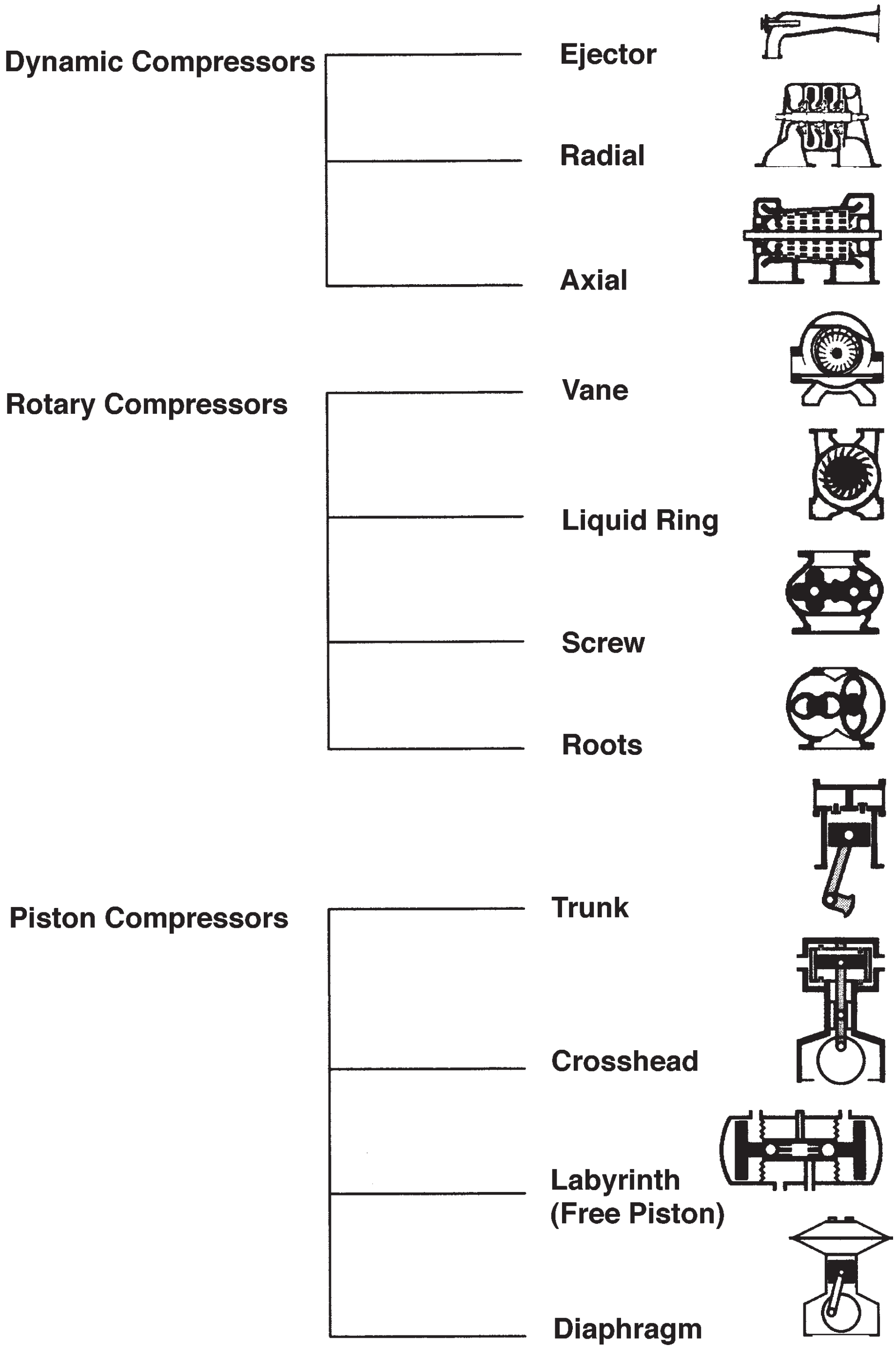
The approximation to isothermal single stage compression, the course of line 1-2, will be the closer, the more isobaric intermediate stages are used. Two and three stage compressor installations form part of present day technology. Work used for adiabatic or isothermal compression is necessary in order to compress the air to reach the higher pressure level. This work expenditure, therefore, represents no loss of energy. Isobaric intermediate and final cooling, as well as the cooling of the oil and water circuits, represent the energy loss element of the required expenditure of energy, if the heat, which has to be extracted, is passed on, unused, to the surroundings. Roughly estimated, about 94% of the energy fed to a compressor is lost as waste heat. Only about 6% is delivered with the compressed air.

Whether the necessary waste heat represents a real loss of energy is up to the operator of the installation. It is part of the present day state of the art to recover heat. The quantity of heat in question is hereby transmitted to cooling media and conveyed to the most varied points of use.

With an oil injected screw compressor, for instance, about 72% of the waste heat is given off via the oil cooler, 13% of waste heat through the aftercooler and 9% from the drive motor. This heat is available e.g. for heating water and/or generating hot air.

With oil free compressor systems, the heat of compression is used for the desorption of the adsorption dryer (see section 5).

3.1 Overview


Dynamic Compressors
Ejector
Radial
Axial
Rotary Compressors
Vane
Liquid Ring
Screw
Roots
Piston Compressors
Trunk
Crosshead
Labyrinth
(Free Piston)
Diaphragm

3.2 Types

Compressors can be subdivided into two groups :

The first group operates in accordance with the principle of dynamic compression, and these compressors are oil free compressing systems. The effective quantity delivered by a dynamic compressor depends on the operating pressure.

Examples of compressors using the dynamic compression principle are turbocompressors of axial or radial design. With dynamic compression, single or multi bladed wheels are used to impart a high speed of flow to the air drawn in, thus converting the kinetic energy of the flow velocity into pressure.

The second group consists of compressors which operate in accordance with the displacement principle. Here, static pressure is built up through a moving part which draws in, compresses and expels a volume of air into, inside and from an enclosed space.

The group of compressors operating in accordance with the displacement principle includes, e.g., piston compressors and rotary compressors. The quantity delivered by these compressors is not determined by the pressure, if internal leakage losses and delivery losses through limited volumetric efficiency are ignored. These compressor systems are supplied in oil free
(“non lubricated”), oil lubricated and oil flooded versions.

Displacement compressors represent by far the most widely used types:

Piston compressors, oil free and oil lubricated
Vane compressors, oil lubricated and oil flooded
Screw compressors, oil free and oil flooded

The following sections provide only a schematic sketch of these systems as there is sufficient literature available on the subject.

Compressors and compressed air treatment form one unit. Impurities such as water and dust are contained in the ambient air already.

In addition, compression introduces oil into the compressed air unless one operates with oil free compression systems. Using oil free compressors is, however, intimately linked with the ultimate purpose of the compressed air and is not required in each case.

It is not the purpose of this section to discuss the advantages or disadvantages of oil free compressors. It is sufficient to point out that the use of oil free compressors, where this is possible, keeps oil pollution away from the compressed air.

It would be quite incorrect to state that the use of oil free compressors makes it unnecessary to treat the compressed air or that compressed air purification could be completely ignored.

The assumption is correct however that the compressed air generated from oil lubricated compressors can be treated like any other compressed air right up to the standard of sterile air.

The statement that “compressor and compressed air treatment form one unit” is true, irrespective of the design of compressor. It is a statement of principle.

3.2.1 Piston compressors

In principle, the piston or reciprocal compressor consists of a crank case with crank shaft and connecting rod, piston and cylinder, as well as intake and pressure valve.

Through the rotary motion of the crank shaft and the reciprocating motion of the piston, the air is drawn from the atmosphere via the open intake valve into the cylinder space. When, in the course of its upward stroke movement, the piston compresses the drawn in ambient air inside the cylinder chamber, the intake valve is closed and the air in the cylinder undergoes compression.

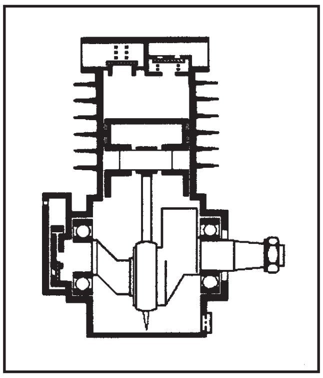


Fig. 3.2.1.1

The air is therefore compressed to take up only a fraction of its original volume while, at the same time, the pressure in the cylinder is increased to a multiple of the original. Once the pressure enclosed by the cylinder exceeds the spring force of the pressure valve, this valve opens and the compressed air is expelled from the cylinder.

There are different types of compression. Either the compressed air is immediately pushed into the compressed air system directly, thus representing single-stage compression, or further stages of compression follow the first stage and we then have a multi-stage compression of air.

A two-stage compressor in principle consists of two single-stage compressors mounted in series upon a common crank shaft casing. In the first one, the pressure of the ambient atmosphere is compressed to a pressure level corresponding to the square root of the absolute ultimate pressure. With two stage or multi-stage compression, the mechanical strain on the pressure bearing parts is thus diminished, achieving a longer service life of the piston compressor.

An intercooler is fitted between the first and the second stage of the compressor. Without an intercooler, the work of compression would, in the course of the second stage, continue to heat and expand the air volume and have an effect upon the compressor output temperature as though it was single-stage compression. Cooling by means of the intercooler permits compression towards the final pressure in the face of reduced air volume. It is a further advantage of two- stage compression that the final temperature of the air after compression is lower as a result of cooling after compression.

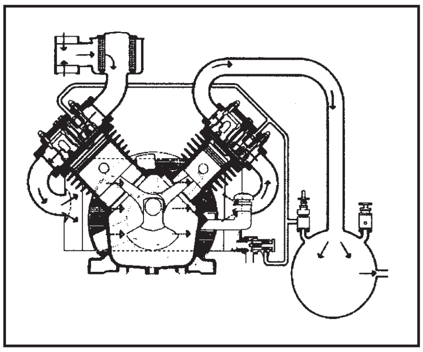


Fig. 3.2.1.2

Two-stage compression to $p = 9$ bar causes a delivery temperature of $T_2 = 110°C$ whereas, if the same pressure had been reached by single-stage compression, T_1 would be 240°C. Such a high temperature resulting from single-stage compression would naturally cause problems, regarding the lubrication of the compressor.

Piston compressors exist in various forms. The basis is the complete compressor assembly, fitted with an electric motor as a drive unit and the fundamental accessories such as intake filter, inter and aftercooler, automatic water drain and safety valves. An integrated control system forms an important factor, because this must be suitable for the cut-out and idle running of the compressor. Control depends on a signal provided by a pressure monitor set for the operating situation and with a lower and upper pressure limit value.

If the lower limit value is reached, the compressor automatically and continuously displaces compressed air into the system until the upper switching point has been reached, thus causing the switching off of the compressor.

Cut-off control switches off the compressor when the upper switching limit has been reached. This type of control is applied if the compressed air use is subject to great variations and is irregular. This type of control is the most economical, but the highest permitted switching frequency of the electric motor must not be exceeded in its application.

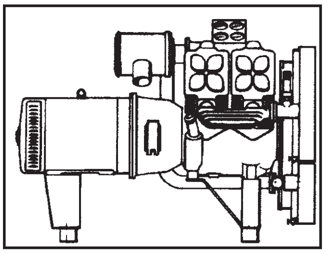


Fig. 3.2.1.3

Idle running control is used when short cut-out periods leading to high frequency of switching of the compressor is called for. When the upper switching limit is reached, the throughput is set to “zero”. The compressor then continues running idly, using little current.

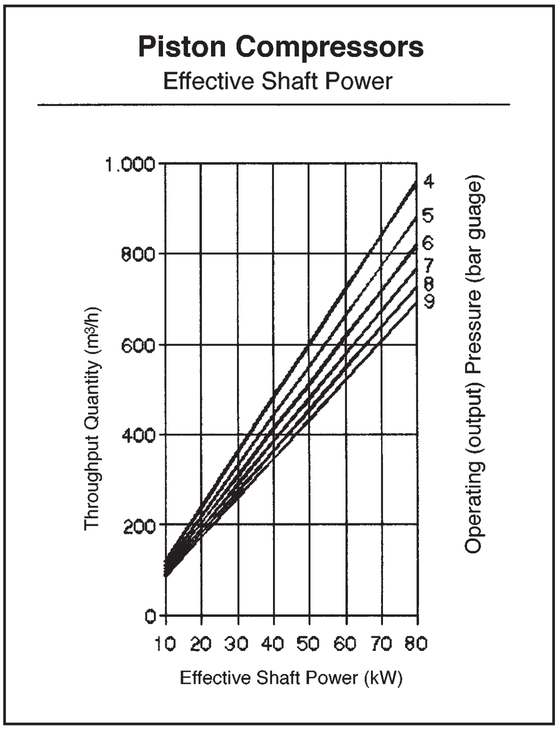
Present day standards provide the combination of cut-out and idle running control, with the additional refinement that the duration of the idle running period can be determined. This makes it possible to have an automatic adaptation to operating conditions when these involve elevated air consumption with a correspondingly high frequency of switching.

Today, nearly all manufacturers of compressors offer custom designed integrated control systems for particular operating conditions.

One usually comes across single stage compressors for the lower pressure ranges and small outputs. For higher pressures, two stage and multi stage compressors are usually installed.

Up to medium range output quantities, piston compressors are offered solely in the air cooled types, beyond this manufacturers offer the choice of air and also water cooled compressors.

Diagram 3.2.1.1 shows the shaft output power of piston compressors as a function of the throughput and the operational gauge (output) pressure. This diagram is based on typical piston compressors with a rotary speed of 1450 r.p.m.



Piston Compressors

Effective Shaft Power

Diagram 3.2.1.1

The shaft power levels given in the diagram do not refer to a particular type but are mean values based on a uniform design series.

3.2.2 Vane compressors

Vane or rotary compressors consist of a cylindrical housing in which the rotor is eccentrically mounted. Longitudinal slots for holding the vanes are cut into this rotor. Upon rotation, the centrifugal force presses the vanes against the internal wall of the housing.

Trailing rings contain the centrifugal forces of the vanes during rotation. The internal diameter of the trailing rings used, is made somewhat smaller than the internal cylinder or housing diameter. Vane compressors exist in oil lubricated and oil flooded designs. In both cases, the compressor oil serves not only for lubrication but also as a sealant between individual vanes and the housing inner wall.

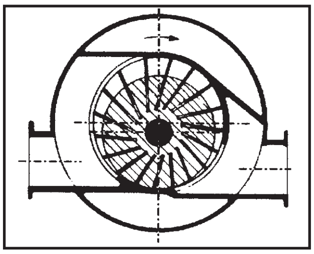


Fig. 3.2.2.1

For oil flooded vane compressors, a considerable quantity of oil is introduced into the compression chamber. This quantity of oil serves to conduct away the heat generated by compression so that the compressor output temperature amounts to only about T = 80-90°C. The injected oil is filtered through separators after compression and channelled back to the circuit after separation.

On the other hand, oil lubricated vane compressors reach very high temperatures in the compression chamber, depending on the final pressure. Compression causes the compressor oils to crack to such an extent that the oil residues in the compressed air may still be filtered out, however, only at the expense of reduced service life of the downstream filter elements.

The individual vanes, manufactured either from phenolic resin impregnated plastics or hardened steel, form cells within the rotor which, upon rotation, expand on one side and shrink on the other. On the intake side, the ambient air is drawn in through the enlargement of the cells and, through further rotation, conveyed to the pressure side. There, shrinking of the cells leads to continuous compression of the air.

Vane compressors are supplied as ready to connect compact units. These single-stage, single shaft compressors can be installed without foundations. This type of compressor is usually fully equipped with aftercooler, separator and all necessary safety devices. Compressors of this design have no valves but, are fitted with an output control adapted to the desired output pressure.

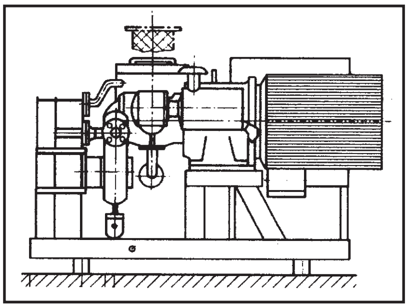


Fig. 3.2.2.2

Adaptation to the operating conditions takes place via intake regulation. If, at nominal operation of the compressor, the compressed air consumption falls, the pressure in the system rises. As soon as the pressure in the system reaches a preset value, a regulator causes an intake restrictor to become operative, thus reducing the volume drawn in, approximately in proportion to compressed air demand.

The power consumption of the drive motor is harmonised with the operating conditions. The smaller the compressed air consumption, the more the system pressure rises. Once the limit value to which the pressure monitor is set reaches the maximum switching point, the regulating system opens an integrated discharge valve and the pressure in the compressor falls to about 3 bar.

The compressor is separated from the network of points of use by a non return valve. On the intake side, the drawn in volume is set to the lowest value through restriction. The compressor now operates in a closed circuit or idle running, with minimum power consumption, which amounts to about 22% of the nominal consumption. Vane compressors, whether air or water cooled, find diminishing use for industrial applications. Maximum pressure is usually up to 10 bar gauge . The output is suitable for medium requirements.

3.2.3 Screw compressors

The operating principle of screw compressors has been known for more than 100 years. However, it took nearly 75 years until the wide ranging opportunities for this type of compressor were recognised, but this time was also needed to create the technological preconditions of its industrial manufacture. Today, the use of screw compressors is widespread and displaces to an increasing extent the established piston, rotary and other compressor systems. The first prototype of a screw compressor was built in 1943. This was an oil-free compressor with counter- rotating rotors not touching each other. The principal runner drove the auxiliary one via a synchronous transmission in this instance.

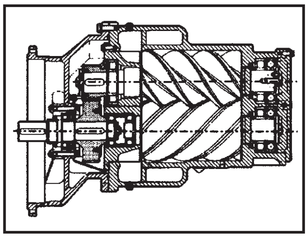


Fig. 3.2.3.1

The symmetrical circular profile was developed by SRM in 1946. This has been improved several times up to the asymmetrical profile version and is still known as the SRM profile today. In conjunction with the Holroyd company, the first screw compressors with economic application potential were manufactured in March 1955. Very soon the screw compressor acquired the reputation of a machine with reliable performance. However, the break-through did not occur until 1960, in conjunction with intensive tests to inject oil and other liquids into the compression spaces in order to be able to cope with the compression of impure and explosive gases.

Injection technology led to the development of the screw compressor without synchronous transmission but with oil injection cooling, where the rotors could counter rotate in a non-contacting manner because of the lubrication provided by the injected oil.

Screw compressors are equipped with two spindle shaped mutually engaging rotors. As a rule, the main rotor is made with four, the auxiliary rotor with six lobes, where the main rotor transforms about 85-90% of the energy received at the coupling from the drive motor into pressure and heat energy.

It is the sole task of the auxiliary rotors to seal the working space between suction and pressure side. In the course of rotation, main and auxiliary rotors generate a v-shaped space for the air drawn in, which becomes smaller and smaller right up to the end, between the rotor lobes and the cylinder walls. Before the leading chamber seals the outlet edge, the following chamber reaches this outlet edge.

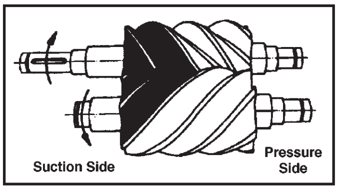


Fig. 3.2.3.2

Fig. 3.2.3.2 shows air intake by suction. The air enters through the inlet opening into the screw grooves of the rotor which are open towards the suction side.

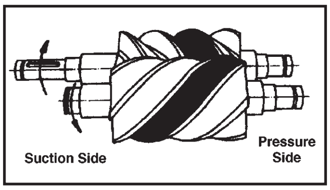


Fig. 3.2.3.3

In the course of compression, the continuing rotation of the rotors closes the air inlet opening and shrinks the volume at increasing pressure. Simultaneously with this process, oil is injected into the system.

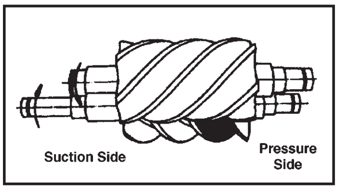


Fig. 3.2.3.4

In this manner, all chambers compress the air to the outlet pressure almost entirely without pulsation. The rapid sequence of.filling and evacuating the working spaces create the impression of a pulsation free flow.

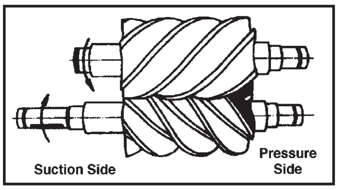


Fig. 3.2.3.5

With the outflow, compression is completed and simultaneously the final pressure is reached. The heat energy caused by this is absorbed by the injected oil and conducted to the oil cooler. The additional tasks of the injected oil consist of entraining the non driven rotor via a lubricating film and, through its sealing effect, preventing internal leakages. In single stage form, these screw compressors with oil injection cooling are used in the pressure range of up to 13 bar gauge.

These compressors are built as compact packages with closed loop oil circulation. During the early years, separating oil from the compressed air presented problems, as the quantity of injected oil was considerable. After many separation experiments with various separator designs, the breakthrough occurred through coarse separation via sufficiently large settling chambers and supplementary fine separation through glass fibre cartridges.

Screw compressors as in Fig. 3.2.3.6 draw in air via a suction filter (item 1) and contamination indicator (item 2). After passing through the intake regulator (item 3), the air reaches the compressor stage (item 4) and is compressed. Oil at about 55°C is continuously injected into the compression space in controlled quantities. This oil has the functions : Cooling, sealing and lubricating. The oil absorbs the heat of compression and reaches about 85°C. However, the oil also seals the gap between the pairs of runners and the housing, it lubricates bearings and screw flanks as well as the transmission. In the combined compressed air/oil reservoir (item 5), oil and compressed air are mechanically separated with a separation efficiency of more than 95%, using flow diversions. An oil separator (item 6) completes the remaining separation. With this system of compression, residual oil values are reduced to about 3-15 mg/m^3.

Via a minimum pressure non return valve (item 7), the compressed air then reaches the aftercooler (item 8) and is cooled down to a temperature of 10-15°C above inlet temperature. It is subsequently fed into.the compressed air system via the shut-off valve (item 9). The oil separated out in the oil separator is cooled down from 85°C to 55°C in an oil cooler (item 10) and returned. It passes through an oil filter (item 12) in order to protect the compression stage from contaminants. The oil circuit, in addition, contains a thermostatic oil regulation valve (item 11).

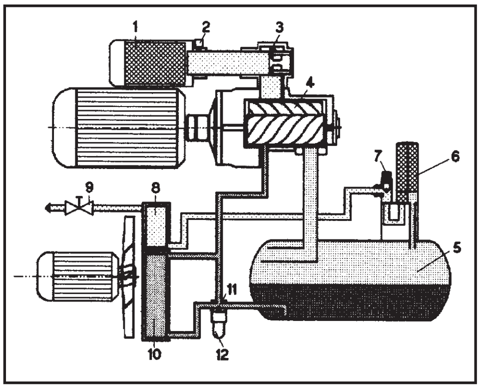


Fig. 3.2.3.6

At the present time, the oil injected screw compressor is the most popular representative of the compressor species in the world market and industry can no longer be imagined without it. The few moving parts of the screw compressor, which, moreover, solely rotate, have formed the basis for the reputation as a machine of utmost operational reliability. That is not yet all, if one reverses the direction of rotation, the screw machine is an expansion motor of remarkable efficiency. All these factors have contributed to making the screw system a firm part of compressed air generation.

Screw compressors are manufactured from small up to medium output volume ranges and thus overlap market areas which, until recently, were still reserved for turbo- compressors. The smaller ranges of screw compressors are supplied in air cooled form whereas the larger ones are constructed either in air cooled or in water cooled versions. All compressor units appearing on the market today, consist of :

A drive with the coupled transmission for adaptation to the compressor rotational speed.

Regulation and safety circuits in order to automate pressure monitoring.

Intercoolers between individual compression stages in the case of multi-stage compression.

An additional aftercooler for reducing the final temperature which will include a condensate separator and condensate drain in order to remove the precipitated condensate.
In addition, the compressors are mounted on a basic frame and fitted into a sound attenuating box. Today, systems are supplied complete with heat recirculating modules arranged in kit form, ready to connect.

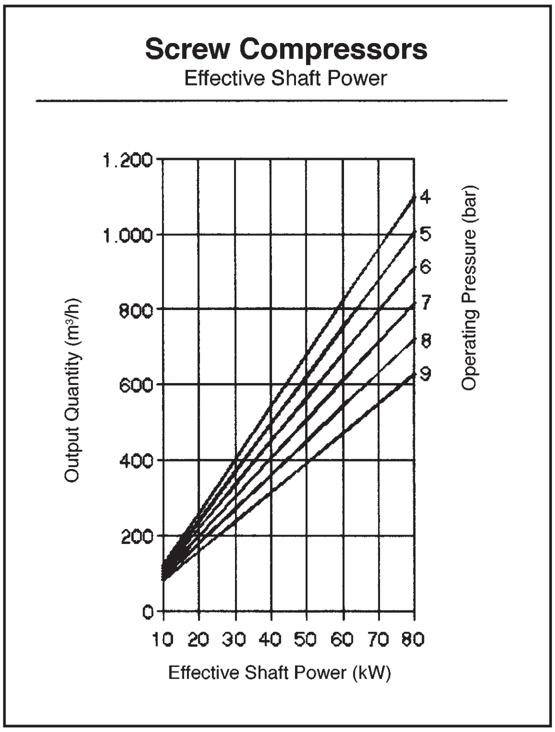


Diagram 3.2.3.1

Diagram 3.2.3.1 shows the relation between shaft power input, operating pressure and output quantity on the basis of a variety of performance curves from two national manufacturers of screw compressors systems.

3.3 Compressor accessories

Compressors draw in ambient air and compress it to the output pressure. In the course of this process the air is heated, enriched with oil, polluted by solids and permeated by moisture. Pollution and contamination will pass into the system unhindered, unless preliminary separation has already taken place at the compressor via intake filter and aftercooler complete with separator.

3.3.1 Intake filter

Every compressor is equipped with an air intake filter on the suction side, to prevent solid pollutants contained in the ambient air from entering the compressed air system. Air intake filters are largely adapted to the intended application and there are many differences in type, design and size. The most common air intake filters are constructed according to the following basic principles :

Cyclones, which hurl out the dust through centrifugal forces
Wet air filters, which bind the dust by means of a liquid
Dry filters, exercising a screening effect.

Filter efficiency, characterised by the degree of dust removal, indicates which percentage of the dust contained in the air is actually retained, and this by reference to an AFI test dust composition.

Test Dust Composition	Grain Sizes	Share
Street Dust	0 - 5 µm	28 %
	5 - 10 µm	13 %
	10 - 20 µm	11 %
	20 - 40 µm	13 %
	40 - 80 µm	7 %
Rust	0,08 µm	25 %
Cotton Linters		3 %

Table 3.3.1.1

3.3.2 Aftercoolers

The compressor types described in section 3.2 share oil lubrication as a common characteristic. For many users of compressed air, oil was not only undesirable but also dangerous under certain circumstances. While the number of fires and explosions which occurred in conjunction with air compression remained relatively small in relation to the number of compressors operated, consequences and previous accidents caused adequate safety measures to be introduced. [VGB (safety regulation) 16 and DIN 51506 and others] pay heed to this safety requirement.

For this reason, the compressor assembly is supplemented by an aftercooler in order to eliminate any negative consequences of the operation of the compressor and to ensure a safe application of the compressed air. Uncooled compressed air in the piping system would, through the naturally occurring drop in temperature, form an aggressive and dirty mixture containing condensed water emulsified with oil and solid particles. Corrosion, malfunction of applications, together with breakdown of production, would be the ultimate consequence.

The aftercooler integrated with the compressor therefore forms the first important step of compressed air treatment, as it significantly cools the hot compressed air flowing out of the compressor. This alone leads to the condensation of up to two thirds of the oil, water and other vapours contained in the compressed air. Effective water separation can be achieved only through cooling the compressed air, as this causes the precipitation of the water contained in vapour form in the compressed air. Oil/Water Separators alone cannot totally achieve effective water separation. Aftercoolers of water and air cooled designs reduce the temperature of the compressed air theoretically to about 25 - 40°C outlet temperature at the pressure outlet of the compressors, depending on the cooling medium. Compressed air is, in.principle, saturated at the pressure outlet of the compressor. This compressed air, at a pressure of 7 bar and an assumed temperature of 35°C, has a moisture content of about 40 g/m^3.

In practice, less favourable values, i.e. higher compressed air output temperatures are frequently observed, because, on one hand, the coolers are dirty and, on the other, of too small a size. Here, the so-called heat of condensation plays a decisive role. If a cooler is designed for an average condition of Tamb. = 15°C at a relative humidity of 60%, but is used during the summer at a temperature of Tamb = 25°C accompanied by the then higher relative humidity of e.g. 75%, one has to count on a compressed air outlet temperature augmented by 5°C, bearing in mind the changed heat content.which increases from 9.6 kgcal/m^3 to 18.7 kgcal/m^3 .

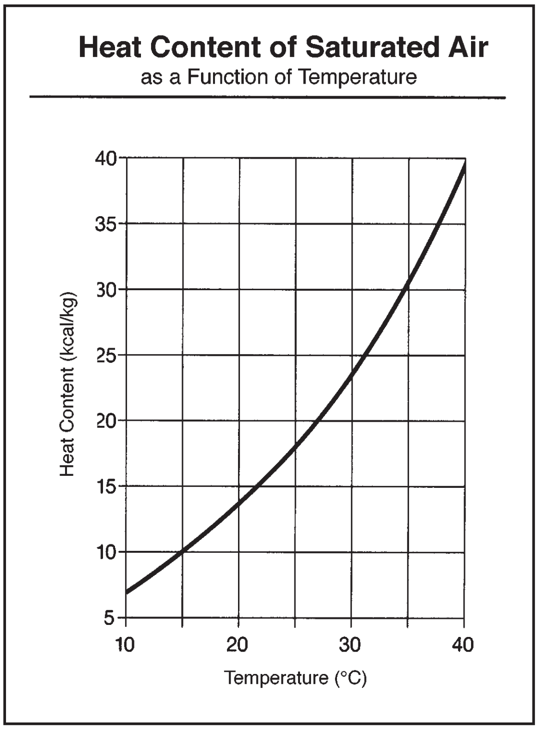


Diagram 3.3.2.1

An undersized aftercooler therefore fails to achieve the required cooling effect, just when this is most needed, but, on the contrary, creates additional problems for the units mounted downstream. Condensed water in piping and thus at the points of use leads forcibly to corrosion in pneumatic cylinders and compressed air motors, thus impairing the function of control and regulation equipment and finally causing operating malfunctions and loss of production.

High compressed air temperatures also mean a high concentration of moisture and oil residues, as is shown in a coherent manner by tables and diagrams.

3.3.3 Separators

The cooling of the compressed air in the aftercooler causes condensate to form and this must be removed from the air flow. By means of a vortex separator after the aftercooler, the condensate is separated from the compressed air and then periodically drained from the system, using a condensate drain.

The compressed air containing water droplets and aerosols flows into the separator passing through a spin impeller, the latter causing a rotating flow of air. The centrifugal force projects water and aerosol droplets against the separator wall from which they then flow downwards into the separator bowl..As with a natural cyclone, the compressed air in the bottom of the separator undergoes a centrally upward directed diversion to the outlet.

Vortex separators (see Part 4; paragraph 4.2.1) are effective and require no maintenance as they do not accumulate dirt.

3.3.4 Drains

Wherever condensate accumulates, this must also be drained to avoid it being picked up and drawn back into the air flow. In order to avoid the time consuming blow-down of separators and other condensate locations, which is, moreover, accompanied by a costly loss of compressed air, automatic condensate drainage systems have been developed. Electronic drainage systems represent the present state of the art.

Drains must be attuned to the special needs of compressed air condensate, as the latter is a mixture of water, oil and dirt particles, causing far more difficult operating conditions than, e.g., a pure water condensate from steam plants. Condensate from compressed air systems must be graded :

Oil lubricated compression systems generate a condensate mixture of oil and water as a by-product, its ph-value being in the neutral range.

Oil free compressing systems, on the other hand, cause a condensate with a ph-value in the acid range.

Drains do not always function reliably, for which reason the concept “automatic condensate drain” should be approached cautiously. Very viscous, highly contaminated oil/water mixtures are the cause of malfunctions, for which reasons regular checks form an essential element of maintenance.

Draining by means of solenoid valves, which remove the condensate at time controlled intervals, offer an alternative. The appropriate setting of the opening time of the solenoid valves presents a problem. This takes place as a function of pressure, however, the pressure level in the system is not permanently constant. For this reason, the draining of the condensate is always accompanied by the loss of more or less compressed air.

Electronic condensate drains have established themselves in the market. This system uses an integrated sensor to monitor the quantity of condensate in the collecting chamber and adapts the period of opening to the collected condensate quantity. Using this system, the loss of compressed air is reduced to a negligible minimum, or almost completely eliminated.

Photo 3.3.4.1

Part 4

4.0 Filtration

More widespread and demanding applications of compressed air have governed the requirements concerning compressed air quality to become more critical. Compressed air is applied in many sectors of technology, for example in the pharmaceutical industry, when manufacturing vaccines or antibiotics, in the food and beverage industry, in hospitals and also manufacturing in the electronic industry. All these compressed air users depend on purified compressed air.

The quality requirements are relative but differ considerably. Depending on the location of the installation, pollution can occur in many forms, namely as solid or liquid suspended particles or in a gaseous state. Depending on the purpose or application of the compressed air, one selects the filters in such a way that most closely matches the air quality required to prevent breakdown or low productivity.

In addition, the resistance of individual filter materials, plays an important part. The selection of the correct type of filter and filter material assumes greater importance if impurities in the air are dangerous such as, dust from insecticides, or bacteria and viruses. The same can apply to certain metallic compounds such as beryllium or lithium derivatives or radioactive substances.

The selection of the necessary air treatment measures are correspondingly specific. It is difficult to specify quality grades in this instance, because differing parameters have to be taken into consideration in each case such as:

- Dust/Dirt
- Moisture
- Oil
- Viruses and bacteria
- Gaseous constituents

When dry and dust free compressed air is used, it becomes more effective, efficient and ultimately more economical, because malfunctions are avoided. Water, oil, polluting gases and dusts lead to primary and secondary damage, as they cause corrosion in pipelines and fittings, bring about abrasive effects in conjunction with emulsions, as well as blocking and icing up. In order to eliminate these malfunction factors, treatment systems, i.e. dryers and filters are used.

Depending on the design of the compressor and the location where it is installed, compressed air may, as limiting values, contain up to :

- 250 mg/m^3 dust
- 85 g/m^3 water vapour
- 15 mg/m^3 oil

This being unsuitable for a compressed air system. The oil content in the compressed air consists of condensed, liquid oil, generally in aerosol form, and evaporated oil vapour.

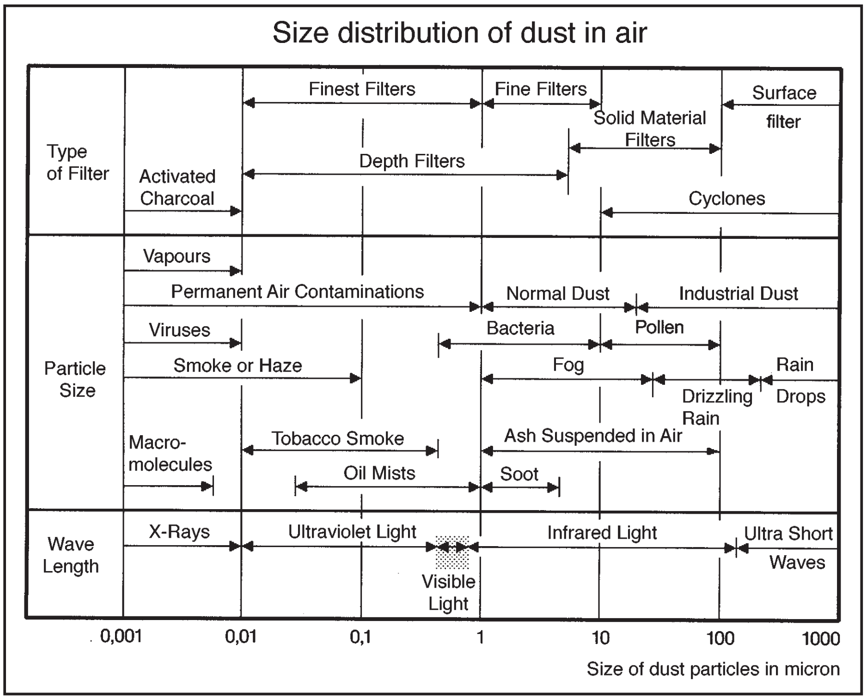


Diagram 4.0.1

Liquid droplets in gas or air can be of a widely different diameter size. For this reason, aerosols are divided into two groups :

Spray : Liquid particles with a diameter of 10 microns or more are referred to as spray. Spray can be relatively easily removed from compressed air by means of various mechanical separators.

Mist : Liquid particles with a diameter of 10 microns or less are described as mist. The term mist or aerosol is applied to droplets the mass of which is so small they can remain in suspension in the gas stream. Mist can only be removed from compressed air steam with great difficulty and calls for finer filter systems.

Mist or fog arises in the following manner :

Most often through cooling followed by condensation of the liquid particles from the medium.

Separation effect of mist

	Brownian Movement	Inertia Effect	Blocking Effect
Surface Speed m/min	5 - 12	120 - 150	120 - 150
Performance Particle > 3 µm	practically 100 %	practically 100 %	practically 100 %
Performance Particle > 3 µm	55 - 99 %	90 - 98 %	15 - 30 %
Pressure drop mm Water Column	125 - 400	150 - 200	25 - 50

Table 4.0.1

If a sufficiently large number of such mist droplets is present, mass attraction forces become effective and the mist droplets coalesce. In this manner, large droplets will, in the course of time, be formed, the mass of which is so large that the suspension forces in air are overcome by the weight of the droplet, causing the droplet to fall.

4.1 Separator systems

Separators and filters are basic requirements of a compressed air system. The question is, not therefore, why filter? But how should it be filtered.

The separation and filtration systems used today for compressed air purification are subdivided into four main groups :

- Gravity Separation
- (pre-filtration)
- Coalescing
- Adsorption

In the following, only a brief overview of these mechanisms is provided.
A more detailed explanation is provided in the subsequent sections.

4.1.1 Gravity Separation

The task of gravity separation is to direct the droplets in a motion relative to the compressed air to a solid surface in such a way that they collect there, and can finally be drained away.

4.1.2 Separation (Pre-filtration)

During the course of mechanical separation, the contaminated air is directed through several layers of filter paper consisting of microfibres, causing the aerosols to be collected on the fibres.

4.1.3 Coalescing

(Definition - come together and form one mass)

Fine oil and water aerosols collect within the microfibre filter media of the filter element and agglomorate (coalesce) to form drops of continuously increasing size which fall inside the filter bowl to be subsequently drained away. This process is called coalescence.

4.1.4 Adsorption

Depending on requirements, compressed air or gas can, in a further process, also be separated from gaseous impurities by passing it through a layer of activated charcoal or other adsorptive material. Activated charcoal adsorbs gas molecules which could cause odour, taste or subsequent condensation back into a liquid phase.

In general, there are two types of activated carbon filter element which are distinguished by the type of construction and the form by which the activated carbon takes.

The fist type is an impregnated paper or other substrate which may be wrapped or pleated, the second type being based upon granular carbon in the form of a deep bed. Both have odour removal capability, but care is required during selection of these types due to life versus pressure drop consideration.

4.2 Separators

By mist we understand the dispersion of a liquid within a carrier gas. Mist or fog consists of droplets with fairly widely differing diameters. The definition lays down that these droplets should have a diameter more than 1 micron. Mist droplets exist in compressed air

through condensation of water vapour
through condensation of oil vapour.

The size of the mist droplets is of great importance where separation is concerned. The droplet diameter, the viscosity of the liquid droplet and the density of the air determine the setting speed of the liquid droplets in the air at rest. The following guidance values apply:

0.1mm diameter	24 m/s
0.01mm diameter	0.3 m/s
0.001mm diameter	0.003 m/s

In order to force mist droplets into motion, considerable forces have to be applied. In order to achieve this, the mist laden air is caused to change direction, allowing strong inertial forces to affect the mist droplets. These forces drive the droplets through the air with elevated relative speed. The velocities so achieved are directly proportional to the forces, i.e. a force of

10 times the weight of the droplet increases the velocity to 10 times the setting speed. The high acceleration values needed for droplet separation from compressed air can, for instance, be achieved through a sharp diversion of fast flowing air, causing larger liquid particles to be projected out and separated.

Depending on the purpose of the compressed air application, the separator is selected to achieve optimum degree of purity in line with requirements. The most important mechanical separators used by industry are:

Cyclone or vortex separators
Impingement separators
Spin separators
Wire mesh

4.2.1 Cyclone or vortex separators

Cyclone separators are coarse separators fitted with a spinning device. The latter causes an extremely high radial acceleration with correspondingly high centrifugal force to arise, so that a rotating air current is formed inside the cyclone separator. These centrifugal forces can rise to a multiple of the weight of the droplet itself.

Through the centrifugal force thus created, solid particles as well as oil and water droplets are projected against the inner separator wall and, driven by gravity, flow downwards into the separator bowl.

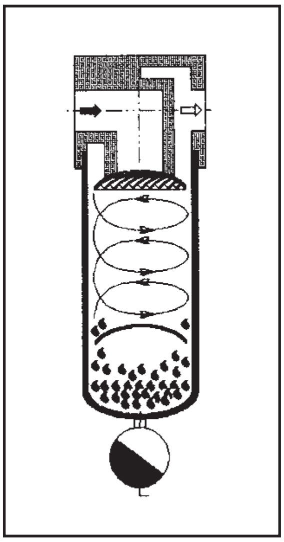


Fig. 4.2.1.1

A separating shield (vortex arrestor) prevents the deposited liquid from being re-entrained again by the air flow. A condensate drain, fitted to the lowest point of the separator bowl removes the condensate.

Cyclones of this design are used in similar applications to that of spin separators but are capable of separating droplets of a smaller limiting size. This is however, associated with higher compressed air losses. The separating efficiency of a cyclone amounts to about 98 - 99 %, the droplet limiting size is around 10 - 50 microns.

4.2.2 Impingement separators

Impingement separators with horizontal or vertical approach flows are normally used if liquid droplets with a very fine range of droplet size have to be separated from the air flow. Impingement separators tend to become blocked and must, therefore, be regularly flushed.

With impingement separation, the mist droplets are caused to change direction rapidly whereupon their inertia causes them to collide with a surface, thus separating them form the gas stream.

As is generally act or impingement separators represents the method of separation utilised by a very large number of mist separators. This operating principle is applied via e.g. wire mesh, columns filled with media, filters from cotton fibre, felt and many other materials.

Impingement separation separates out droplets from within a relatively narrow range of diameters. With vertical impingement, separation is effective for droplets of about 40 microns limiting size, with horizontal approach flow down to about 10 - 20 microns.

4.2.3 Cyclonic separators

Cyclonic separators are a particular design of cyclones. As axial cyclones without flow reversal, these separators are used for coarse operations, and tend to be employed when the disposal of considerable quantities of liquid in the form of large droplets from the compressed air system, if required and may also contain solid particles.

The separating efficiency of the cyclone separators is around 98 - 99%.

4.2.4 Wire mesh

The use of wire mesh has considerably reduced in recent years. Because of the danger of becoming blocked, separating systems of this type have to be flushed periodically. The pressure losses depend greatly on the degree of liquid loading.

Packages of wire mesh are capable of achieving a degree of separation of 99.9 %, given droplets of 6 - 20 microns limiting size.

4.2.5 Separating effect

The most diverse performances are declared for separation systems and percentage indications of up to 99.9999 % are not rare, but only an exact definition can bring about clarification.

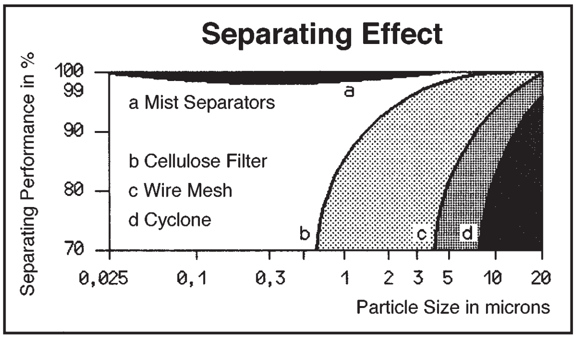


Fig. 4.2.5.1

These percentage ratings are often referred to on a total weight. If separating performance is stated in relation to particle size, a totally different picture of the separating effect emerges.

Fig. 4.2.5.1 shows the different separating systems in comparison with a depth filter element with a separating efficiency of 99 % at 3 microns. This diagram shows the areas in which individual filter designs show particular performance strengths.

The following tables show the difference in separating performance in numerical values, based on total weight on the one hand and particle size in the compressed air on the other.

Assumed particle weights and distribution

Particle Number	Size	Weight	Total Weight
50	20,0	29	145.000
1.750	7,5	60	300.000
10.700	2,0	8	40.000
67.500	0,75	3	15.000
∑ 80.000			∑ 500.000

Table 4.2.5.1

Separating performance based on particle weight and size

Separated Particles µ	Weight %	Total Weight %
20,0	$\frac{145.000}{500.000} = 29{,}0$	$\frac{50}{80.000} = 0{,}1$
7,5	$\frac{445.000}{500.000} = 89{,}0$	$\frac{1.800}{80.000} = 2{,}3$
2,0	$\frac{485.000}{500.000} = 97{,}0$	$\frac{12.500}{80.000} = 15{,}7$
0,75	$\frac{500.000}{500.000} = 100{,}0$	$\frac{80.000}{80.000} = 100{,}0$

Table 4.2.5.2

The numerical values indicated in the tables are based on the data from section 1.6.1.

4.3 Filtration

In the following section, the description of filtration and of the mechanisms occurring in the course of this, apply solely to liquid oil droplets except where solid matter particles are explicitly mentioned. In what follows, the oil droplets, are described as particles.

4.3.1 Particle science

In the case of a fog, the liquid oil phase is dispersed in the form of small particles. These are enclosed by a continuous phase, in this case compressed air. Such systems are referred to as dispersed systems.

An aerosol is defined as a quasi stable and quasi homogeneous system, in the sense of physical chemistry, in this case consisting of air and very many insoluble suspended particles. All of these particles form a relatively stable and identifiable system.

Whereas the dispersion medium compressed air is unambiguously specified by the physical parameters pressure, temperature and chemical composition, a complete description of the particles is not normally possible. Such a particle description is determined by

- the surface,
- the characteristics of the individual particles, a difficult matter because of the large number and complex shapes,
- the chemical composition,
- the description of the an agglomerate however, is not possible without knowledge of the individual particles.

Practical reasons, therefore, cause us to limit the description to certain characteristics, so that the selection and definition of parameters is guided by the questions need to characterising the aerosol. In practice, this means establishing the frequency of particle occurrence within the agglomerate.
For accurate specification of the dispersed phase, many practical problems and solutions require concentration C1 and relative frequency yf2 . For specifying particle diameter, the geometrical mean of diameter x is used, assuming particles which are by definition spherical.

4.3.2 Separation dynamics

The overwhelming number of known publications on the subject of particle separation in fibre filters assumes that the particles, separated in the fibre layers, do not cause any structural changes. This means the filters are envisaged on the basis of their unloaded state.
However, knowledge of this so-called stationary separation phase is, in practice, not sufficient in order to carry out an effective assessment and optimum design of the filters. To achieve this, the dynamic phase has to be taken into account. This includes all changes in the course of time because of permanent filter loading which, at the end of the elapsed time period, causes pressure loss and decrease of separating efficiency.

For these changes, questions of filter structure are important but the present state of the art offers no satisfactory answers. The following questions, therefore, remain open :

- Amount and intensity of the increase in pressure loss accompanied by simultaneous decrease of separating efficiency
- Assumed mutual influence of pressure loss and separation efficiency
- Structural changes, saturation behaviour and regeneration of the filter
- Degree of probability of particle adhesion

Particle separation at the fibre is, in the stationary phase, determined by two basic sub-phases:

- The particles must reach the sphere of influence of the fibre surface
- Adhere to this fibre surface

The dynamic separation phase required study of filter systems and leads to the following further occurrences:

- Agglomeration (accumulation) of the adhering particles at the fibre surface because of coalescing.
- Bridges and films of liquid between the fibres.
- By displacement of the liquid from the saturated fibre layer, the fibre is again available for particle/aerosol retention.

4.4 Filtration mechanisms

Filter elements, that separate solid and liquid particles from compressed air, function on the basis of a combination of differing physical mechanisms, depending on the mode and type of filtration. Filtration makes use of

- Brownian molecular motion (intermolecular forces)
- Forces of inertial
- Direct interception/sieving
- Electrostatic effects.

Should the particles settle on a fibre in the course of flowing past it, all the mechanisms described below may become effective simultaneously. To provide a universally valid mathematical relationship is very difficult. For this reason, only empirical solutions of individual mechanisms, or several of these in combination, are available.

The entire range of Reynolds numbers of interest to filter technology incorporates as well the range of viscous flow around cylinders ($Re < 1$) as the so-called transition range ($Re > 1\text{-}10^3$) ie. 0.001right up to potential flow ($Re > 10^3$).

An important range for depth filtration is among the smaller Reynolds numbers ($Re < 1$). Flow around a cylinder in the range of creeping flow is such that the speed in the immediate area of the fibre is significantly lower than the approach flow velocity in the undisturbed range of the fibre. This applies equally to fluid as well as to entrained particles.

It has to be added that particle impingement velocity onto the fibre surface depends on the point of impingement and thus on the boundary point of the undisturbed flow zone outside the cylinder, thus undergoing a range of velocities. This causes the effective speed of impingement in fact to be only a fraction of the approach flow and to increase evenly with growing distance from the point of contact.

The process of separation is explained here in an idealised manner, envisaging a circular cylinder being met by flow normal to its axis.

The separation of particles at the cylinder surface is a consequence of two continuously occurring phenomena in the course of the filtration effect :

The transport of particles to the cylinder surface.
The adhesion of these particles at the cylinder surface.

Essential transportation effects are based on inertia forces, sedimentation16, Brownian motion or electrical forces. Four conditions are necessary in order that a particle adheres to a fibre :

The elastic energy after impingement must be smaller or, at most, equal to the adhesion energy capable of bringing about retention.

There must be no break-up or atomising of the aerosol.

The drag forces of the gas acting upon the separated particles must not be stronger than the adhesion forces.

Particles already deposited must not be torn free again through the impact of subsequent aerosols collected.

4.4.1 Brownian motion

Brownian motion, also known as diffusion is the random movement of the aerosol in the gas stream caused by the collision of aerosols with atoms of the gas on a molecular scale.

In this, a particle of 1 micron diameter has 15 times the motion energy compared with a particle with a diameter of 5 micron. This means in practice that, the smaller the particle, the higher the probability that this particle will collide with a filter element fibre and thus be filtered out.

Filter elements making use of Brownian motion achieve an improved filtration performance in practice as far as the smallest particle sizes to be separated are concerned. For separating particles below 0.3 micron, filter elements are manufactured which filter out more than 99.99 % of all particles. Oil is stored in the fibre depth, the liquid particles add up to form droplets which flow as a cohesive film of liquid along the fibres to the lowest point of the filter. Suitable gas velocities prevent the separated liquid particles from following the airflow and being re-entrained .

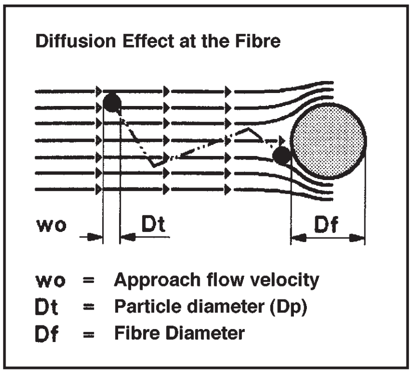


Fig. 4.4.1.1

Because of the Brownian motion, the aerosol particles do not follow the flow lines of the gases around the fibre. They deviate from the zone of these flow lines in the direction of the fibre surface, where they are deposited. The effect of Brownian motion grows with diminishing particle size and, with this, diffusion separation of smaller particles increase.

The diffusion effect of particle deposition applies particularly to particles smaller than 1 micron. It is caused by their motion. As a result, some particles adhere upon contact with the fibre. The concentration gradient created causes diffusion flow in the direction of the fibre surface. This effect depends mainly on the particle size Dt and the gas flow velocity wo.

The influence of temperature also affects the dynamic viscosity of the air. With small and very small aerosol particles, the diffusion coefficient is a function of the mean free path of the air molecules, which is inversely proportional to the air pressure.

4.4.2 Inertia effects

Particles larger than about 0.3 micron are caused by their inertia not to follow the air current in the fibre bed. These particles are caught by the fibres and filtered out.

For filtration with separating capacity down to 0.3 micron, filter systems acting on the basis of inertia effect are adequate.

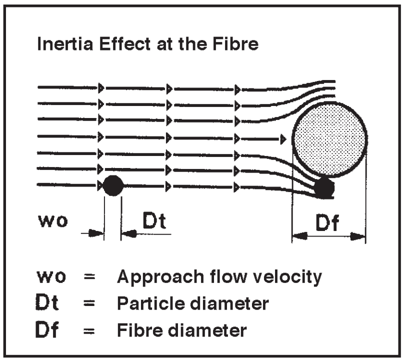


Fig. 4.4.2.1

During flow around the fibre, the line of gas flow circumvents the fibre in a curve and the heavy particle is caused by its inertia at higher speeds to proceed in a straight line so that, under favourable conditions, it can impinge upon the fibre.

This effect is proportional to the square of the particle size and flow velocity. Temperature effect is reflected in the viscosity of the gas.

4.4.3 Direct interception/sieving

Particles can follow a compressed air flow line and still be picked up without inertia effect if the flow takes place close to a fibre. If, for instance, a particle with a diameter of 1 micron flows in an air stream past a fibre at a distance of <0.5 micron, this particle will touch the fibre and thus be filtered out of the air stream.

With diffusional separation, it is presumed that the aerosol particles are simply points of mass possessing no envelope dimension. If, however, one considers that particles are a sphere with a definite diameter Dt, a further mechanism, the blocking effect, must be taken into consideration.

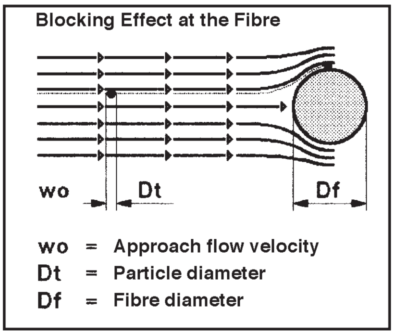


Fig. 4.4.3.1

A particle is caught if it approaches the fibre so that the distance is equal to or smaller than half its diameter 0.5 Dt. The effect is thus proportional to particle size Dt.

4.4.4 Electrostatic effect

The separating effect at the fibre within the filter is different from the separating efficiency of a fibre regarded in isolation. Fibres in a deep bed always have a higher separating efficiency than a single fibre. The filtering efficiency inside the deep bed is a function of the filter porosity, i.e. the packing coefficient.

The mean flow velocity is higher and changes in the speed distribution occur around individual fibres due to the influence of neighbouring fibres. The relative position of individual fibres in relation to each other within the bed are random.

Flow of the gas through this bed of fibres causes a permanent diversion of the gas current. The continuous friction of the fluid at the boundary layer of this fibre surface builds up an electrostatic charge on the fibre surface. Smallest particles up to 0.01 µm can be caught due to the electrostatic effect.

4.5 Characteristic values of filtration

The filtration of a dispersed system is a separation process, in the course of which the dispersed constituent is separated from the fluid dispersion medium by means of the filter. Compressed air ensures here that the fluid can flow through the filter.

According to the structure of the porous substances, filters are subdivided into

- fibre filters
- pore filters
- granular filters.

A fibre filter consists of a relatively thin layer of fibres, the fibres being of approximately equal thickness and arranged normal to the flow of gas roughly equidistant from each other. A pore filter is, e.g., a membrane filter; a granular filter consists of spherically shaped filtration elements, or granules.

An effective assessment of filtering performance can be carried out only if the characteristic values of filtration are used as criteria.

The most important characteristics are :

- Separation efficiency
- Pressure loss
- Penetration co-efficient

Separation efficiency and pressure loss are functionally interdependent in accordance with E = f (delta p).

For filtration efficiency it is important to select filters which combine maximum separation potential with minimum pressure loss and where these two parameters remain constant during the service life, i.e. do not change with time.

4.5.1 Separation efficiency

For describing separation, one defines a degree of separating efficiency E as the relation per unit time of the quantity of particles caught by the filter to the quantity of particles flowing into the filter during that time.

$$\boxed{E = \frac{\Sigma P \times \mathrm{L} - \Sigma P \times h}{\Sigma P \times \mathrm{L}}}$$

Formula 4.5.1.1

$$\boxed{E = 1 - \frac{\Sigma P \times h}{\Sigma P \times \mathrm{L}} \quad 100}$$

Formula 4.5.1.2

This expression is wrongly described as degree of effectiveness of a filter. But degree of effectiveness is really the relation of benefit to resources employed and does not, therefore, apply to filtration.

4.5.2 Pressure loss

The pressure loss, delta p = p1 - p2, occurring downstream from the filter, is the second most significant basic parameter of the filter, after separation efficiency E. The pressure loss is proportional to the gas flow velocity through the filter.

Should delta p be known for a certain velocity, it can, without difficulty, be recalculated for any other velocity. Pressure loss delta p is likewise proportional to filtering layer thickness.

When using a multi-layer filter, the total pressure loss is given by the sum of the partial pressure losses at the individual layers.

Furthermore, delta p depends on the value of the packing density coefficient. This increases with decreasing distance between the filter fibres. Lastly, delta p always depends on the temperature of the gas flowing through, as the viscosity of the gas increases with temperature.

In reality, the differential pressure of fibre filters are always smaller than those calculated theoretically. This is because of the random filter structure.

The differential pressure represents a pressure loss measured for the total filter and is of considerable significance as a source of performance loss. This pressure loss consists of:

- Pressure loss of the filter housing
- Pressure loss through the filter element
- Pressure loss through loading with liquid aerosols
- Pressure loss due to collected solid particles

Pressure loss rises more than proportionally with the throughflow quantity, mathematically described through Bernoulli’s energy theorem as :

$$\boxed{p_2 - p_1 = \frac{\rho}{2}\varpi_2^2 - \frac{\rho}{2}\omega_1^2}$$

Formula 4.5.2.1

If p = constant, the continuity equation runs

$$\boxed{V = \omega \times A}$$

Formula 4.5.2.2

The pressure loss thus being described by the expression

$$\boxed{\Delta p \;\alpha\; V^{2}}$$

Formula 4.5.2.3

Because density as well as cross-section are constant entities, the expression is supplemented with regard to the operational state by means of formula 4.5.2.4.

$$\boxed{\Delta p \;\alpha\; \frac{V}{p}^{2}}$$

Formula 4.5.2.4

This formula also determines the mutual dependence of throughflow quantity V and absolute pressure p in relation to pressure loss delta p.

4.5.3 Penetration coefficient

Penetration coefficient pF indicates the concentration relationship of aerosol particles before and after the filter. It is related to separation efficiency E according to

$$\boxed{p_F = 1 - E}$$

Formula 4.5.3.1

and can be determined experimentally. It depends on numerous parameters such as fibre diameter Df, particle diameter Dt, velocity of flow wo, concentration and filter thickness.

4.5.4 Filter quality coefficient

As the quality of the filter is determined by pressure loss and filtration efficiency, the filter quality coefficient Kv has been introduced, this being the relationship of the negative logarithm of the penetration coefficient pF to pressure loss delta p760.

$$\boxed{K_v = \frac{-\log p_F}{\Delta p_{760}}}$$

Formula 4.5.4.1

This value represents a material constant for a certain filtration material and depends on the gas throughflow velocity through the filter wo, fibre diameter Df, porosity and other values. Filtration layer thickness, however, remains without influence on this material constant which is determined experimentally.

4.5.5 Filtration kinetics

During the process of filtration, filtration efficiency E as well as pressure loss delta p change so that the overall process is not stationary. As soon as the filter structure is covered with a layer of deposited aerosols, the fibre diameter increases and thus the packing density coefficient, i.e. the permeability of the system for the dispersion medium is reduced.

This causes a disadvantageous rise of the pressure loss. At the same time, however, separation efficiency increases with the reduction in the open cross-section area, as now also particles with smaller diameters will be retained.

4.6 Filter classification

Filtration removes extraneous substances from the compressed air. Dust and fog is filtered out of the compressed air on the suction side of the compressor.

On the pressure side, filters are used to filter out dust, dirt particles, deposits, liquids and mist particles.

Filters achieve separation efficiencies of up to 100 % for particle sizes down to about 1 micron. In order not to overload these fine filters with coarse particles, mechanical coarse matter separators are fitted prior to the fine filters.

Depending on the mechanism of separation, one distinguishes between two types of
filter:

- Surface filters
- Depth filters.

With surface filtration, the screening or sieving effect plays the primary role as separating mechanism. Impurities, (as long as they are larger than the specified pores) are separated out on the surface of the filtering material and form a filter cake in the course of the service life. As a consequence of this, there is the side effect that, to a small extent, smaller particles than the effective pore width can also be separated.

As the impurities are deposited mainly on the surface, a simple regeneration of filter elements of this design is possible.

Depth filtration makes use of fibre beds consisting of a maze of the finest individual fibres. There are, therefore, no specific pore sizes. Such filter materials act not only as a sieve, mainly retaining particles corresponding to the pore size, but also separate impurities which are considerably smaller than the fibre maze structure. A combination of several separating mechanisms is responsible for this :

- Direct impingement
- Electrical charge
- Diffusion
- Sieve or screen effect
- Attachment through van der Waal’s forces.

4.6.1 Surface filters

With surface or sieve filter elements, separation of particles takes place on a surface positioned to the direction of flow.

In the ideal case, a surface filter element is endowed with a narrow pore size distribution, moreover, accurately equidistant from each other.

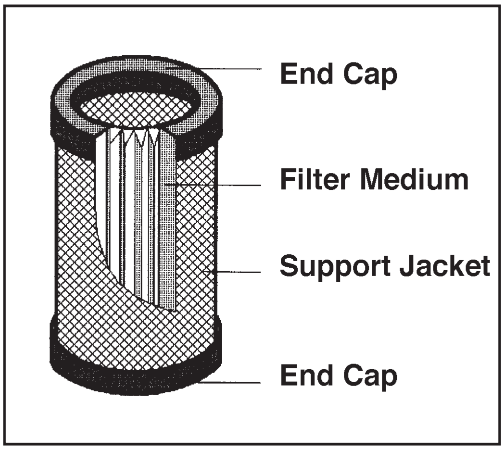


Fig. 4.6.1.1

Particles larger than the pores are screened off and retained on the surface. Separation and the rate of penetration is dependent on the pore size.

The surface has the effectiveness of a sieve which, due to its apertures, prevents the solid particles dispersed in the aerosol from passing through. As a result, the diameters of the flow channels are smaller than the diameters of the solid particles to be separated, so that the surface filter is penetrable solely by the dispersion medium.

It results from these characteristics that the use of a surface filter generally leads to a very high pressure loss which can be kept within tolerable limits only through reducing the flow velocity. Surface filtration has no significance as far as the separation of liquid particles is concerned. Thin walled sintered or cellulose acetate impregnated tubes, pleated in a star shaped pattern, are used as filter element materials.

Naturally, these surface filter elements are capable of achieving a filtering effect only if the matter to be separated is present in the form of solid particles or as droplets. Drying by means of such filter elements, i.e. removing the water vapour phase from the compressed air, is not possible.

As a rule, the complete filters consist of a two-part housing, in which the filter element and its sealing ‘o’ ring is fixed by means of a retaining device. Attachment by tie rod is preferred to all other forms of mounting as only in this way can a positive and strong filter element location be guaranteed.

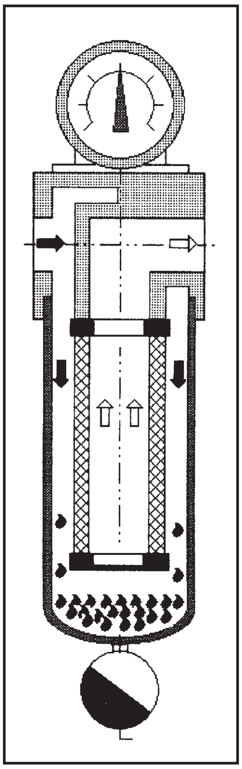


Fig. 4.6.1.2

The particles and condensate droplets removed by the filter element drop into the condensate collecting chamber due to gravity. When the maximum filling height is reached, the condensate is discharged by an automatically opening drain.

Surface filter elements inside a filter housing are, in principle, arranged for flow from the outside towards the inside. A reverse direction of flow would lead to a build-up of separated particles on the inside of the element, leading to degradation of the effective filtering surface through the accumulation of solid particles.

4.6.2 Depth filters

Depth filter elements generally consist of a layer of fibres of varying thickness. The structure of depth filter elements consist of individual fibres entwined with each other in a random pattern, resulting in a porous structure.

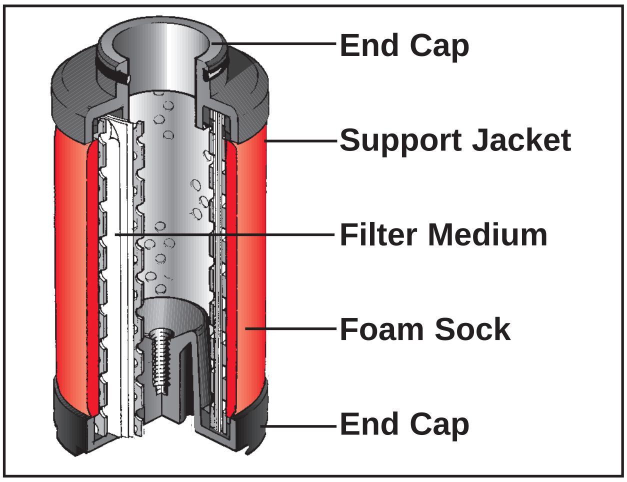


Figure 4.6.2.1

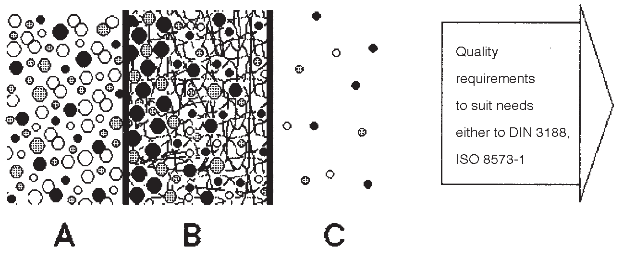
Labyrinth-like passages, are formed between the fibres and these are neither of uniform nor measurable size. The internal flow channels include diameters which, in part, represent a much coarser mesh than the diameters of the particles to be eliminated from a dispersed system. Separation takes place along the entire path followed by the aerosol through the depth filter element.

Filtration with depth filter elements is based essentially on the principle of random deposition of particles under the influence of the various cumulative physical effects. Depth filter elements separate out particles in the fibre bed near to the filter element surface. In this case, the direction of flow is from inside to outside. Such filters are used primarily in order to filter the water and oil condensate phase out of the compressed air.

In the course of flow from inside to outside, the wet phase is deposited on the filter element material. The accumulation of small particles, leading to bigger drops, causes these to flow into the condensate collecting chamber due to the direction of the gas flow from inside to outside and under the influence of gravity.

Deposition at the surface of the fibre takes place mainly through surface forces. As these are relatively small, care has to be taken that the deposited particles do not again become detached and re-entrained into the gas stream.

This requirement is most readily met through a low velocity of flow. In order to achieve a large separation performance, a large surface per unit volume is necessary. The unit for this volume is specified by m^2/m^3.



A Unfiltered gas from the system
B Depth filter stores pollutants
C Cleaned gas to suit applications

Fig. 4.6.2.2

Fig. 4.6.2.2 shows how classic depth filters function and why these, when filtering solid particles, can become loaded after a brief service life. The fluid to be purified penetrates the filter structure, the solid constituents to be removed are caught in the deepest layers of the filter. With increasing contamination, the resistance to flow limits the throughput gas, so that the differential pressure in the element increases.

When filtering liquid particles, they agglomorate to form larger drops and leave the filter structure. Solids trapped in the filter media cannot be removed and are held permanently.

Through the fibrous maze and the large storage capacity associated with this, these filter elements achieve a relatively long service life up to saturation, following which such elements are exchanged.

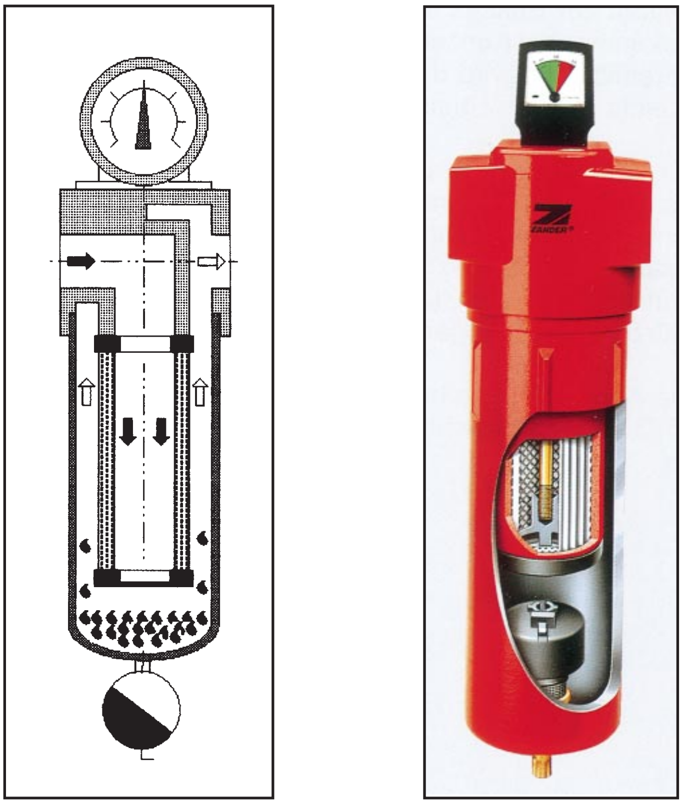


Fig. 4.6.2.3

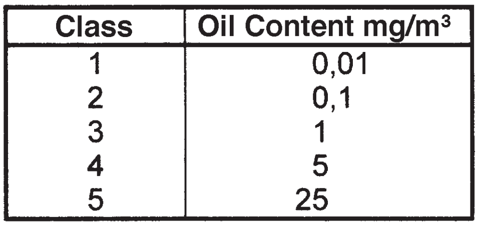
The materials for such depth filter elements are plastics, metal or glass fibres as well as woven or wound systems. Pleated filter elements offer a large surface, although the effective element depth is reduced to a few millimetres.

4.7 Oil separation

When using an oil lubricated compressor without filtration, oil enters the connected compressed air network with an assumed concentration of c = 10 mg/m^3. With an efficient depth filter, however, a residual oil concentration of 0.01 mg/m^3 is achieved, other conditions being equal.

Until recently, there were no standards covering the measurement of residual oil in compressed air. However, recent acceptance of ISO 8573.2 now gives the user a means of determining oil aerosol content.

Requirements regarding oil content in compressed air are indicated in ISO 8573.1



Class	Oil Content mg/m^3
1	0,01
2	0,1
3	1
4	5
5	25

Table 4.7.1.1

Technical oil free compressed air is defined by the values of

a residual oil content < 0.01 mg/m^3

The m^3 datum here refers to atmospheric air at a pressure of 1013 mbar and a temperature of 20°C.

On closer examination, even the use of oil free (non lubricated) compressors cannot guarantee absolute freedom from oil in the compressed air, for the compressor draws in ambient air of varying quality and concentrates hydrocarbon and other airborne impurities.

4.7.1 Oil droplet separation

Oil vapour is condensed by simple cooling only to the extent that the reduced residual oil value is only acceptable for a few fields of application. The condensed oil upon cooling, precipitates on the internal walls of the compressed air line, and is separated to nearly 100 % if the usual depth filters are fitted, and will flow into the bottom of the filter.

The portion of the condensed oil, forming fine oil droplets in the air stream, always totally reaches the filter material and is retained. When assessing filters, the oil content in aerosol form, the oil mist concentration, before and after the filter, is of primary significance.

The most penetrating particle size amounts to 0.15 - 0.45 µm even though an average value of 0.3 µm is stated in literature. This does, however, depend on type, viscosity, temperature and quantity of the oil particles fed to the filter.

Such filters which display a good separation behaviour faced with these particle sizes, are equally effective with other sizes :

Smaller particles are retained by fibre filters as a consequence of Brownian molecular motion,

Larger particles are removed mainly through inertial impaction and direct interception.

4.7.2 Oil mist separation

Oil fogs or mists comprise the very finest droplets in a system, and are visible as aerosols. As oil is a hydrocarbon compound, oil can also exist in the gaseous state. The gaseous or vapour like state refers in principle only to the hydrocarbons which are condensed from the liquid oil, depending on the temperature. The relative share of condensed hydrocarbons, oil fog or spray in the compressed air depends on the type of compressor oil used and the temperature generated by the compressor.

Modern compressors are usually fitted with air or water cooled aftercoolers. By means of the aftercoolers, the temperature of compression is reduced to a low operating temperature after the compressor. In the course of this cooling process, hydrocarbons are, condensed. The residual oil content varies as a rule between 5 - 20 mg/m^3, depending upon compressor design.

With compressed air filters, a distinction is made between two functions of the filter element : Filtering out and screening. The screen or sieve elements mainly retain coarse particles exclusively on the surface of the element (surface filtration). When filtering, also fine or oil particles are separated by the filter element (depth filtration), on the surface as well as in the course of flow through the filter element. Filter materials made from fine fibres separate fine particles in accordance with their fibre thickness. Modern technologies are capable of producing fibres with a diameter of less than 2 mm.

For the majority of compressed air users, the most important characteristic when assessing compressed air filters, is the retention capacity of these filters (separation efficiency) as far as the oil contained in the compressed air is concerned. The radial design of filter elements, with its flow always from inside to outside, has proved its value. Compactness, large throughflow surfaces at optimum layer thickness and favourable dynamic behaviour form outstanding attributes of these filter elements.

Fig. 4.7.2.1 shows the separation of oil mist. The compressed air initially enters through the inner layer of the filter element (item 4), which provides support for the filter medium and, moreover, has the effect of an integrated pre-filter.

Larger dust and liquid particles are retained, ensure a high separation efficiency. The smaller liquid particles are caught by the filter media (item 5) and form larger droplets after coalescing.

These droplets, found within compressed air as well as larger droplets, impinge against the outer layer of lower density (item 6) which gathers droplets when these become detached from the fibre. Within the cellular structure, these now larger drops gravitate down towards the lower end cap (item 1) and form the so-called wet band (item 9) in the lower region of the filter element.

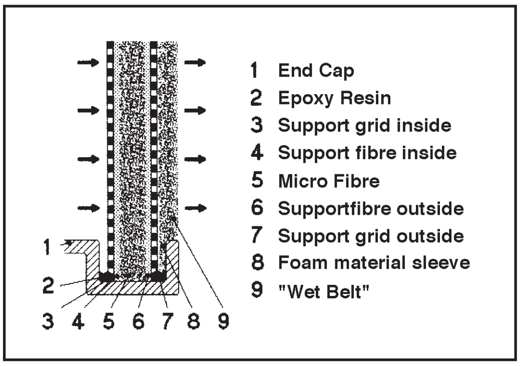


Fig. 4.7.2.1

The purified air passes above the wet band as the resistance to flow is less. This causes a quiet zone without air circulation in the lower region of the filter element. The separated drops fall from the lower part of the filter element through the quiet zone without being re-entrained by the air current. This condensate is collected in the bottom of the filter housing and discharged through a drain.

4.7.3 Oil vapour separation

In the vapour phase, the oil is present as a molecule in the compressed air and is thus not separated out by mechanical filters. The quantity of oil vapour, see Diagram 4.7.3.1, depends on the temperature and, under unfavourable circumstances, can amount to a larger quantity than the oil droplets or oil mist concentration.

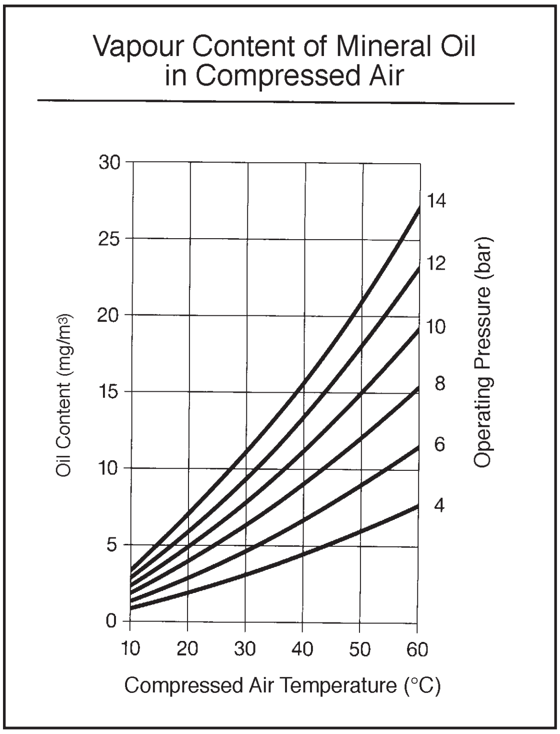


Diagram 4.7.3.1

The separating efficiency of a filter deteriorates with rising temperature due to an increase in oil vapour content. Thus, at a temperature of 20°C, up to ten times more oil passes through a filter than at 10°C. For this reason, care has to be taken, particularly with depth and high performance filters, to install at locations of low temperature. Oil vapour is condensed by cooling. Condensed oil can be filtered without problem from compressed air by means of depth filters.

The oil vapour remaining in compressed air is reduced by the use of activated charcoal adsorption filters mounted downstream. By means of such filters, residual oil contents down to 0.003 mg/m^3 can be achieved. Compressed air treated to this extent can be graded as technically oil free.

Activated charcoal filter elements are available in various constructions such as:

- Ground activated charcoals embedded on a deep filter bed manufactured from borosilicate - glass paper (Fig. 4.7.3.1A)
- Granular activated charcoal contained within a pleated element
- Moulded tubes of activated charcoal in the form of a hollow cylinder.
- Granular bed (Fig 4.7.3 1B)

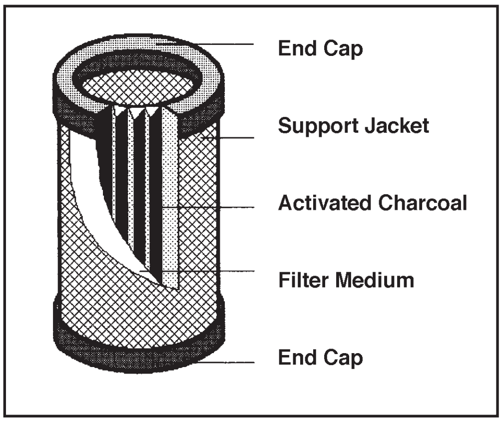


Fig. 4.7.3.1A

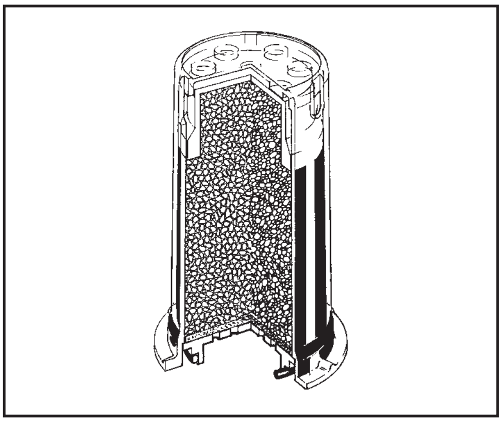


Fig. 4.7.3.1B

Activated charcoal is preferentially used if high quality of oil free compressed air is required for a particular application. The claimed residual oil content is, however, achieved only if the operating conditions are adhered to. Optimum separation requires:-

- A low inlet temperature to the adsorption filter
- Relative humidity of the compressed air of about 60 % maximum
- Pre-filtration with a depth filter.

The activated charcoal filter elements are fitted into standard filter housings to form a complete filter. Activated charcoal adsorbs the oil vapour from compressed air until it becomes saturated.

As the quantity of activated carbon in charcoal filters is relatively small, the service life of activated charcoal elements is limited, with regard to oil vapour adsorption. Depending on the geometry of the elements, service lives of

300 - 1000 operating hours are realistic, given optimum separation under normal conditions of use.

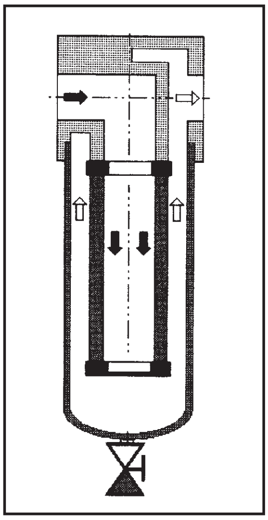


Fig. 4.7.3.2

As an alternative to activated charcoal filters, activated charcoal adsorbers are used. These adsorbers consist of a container filled with activated charcoal. Flow diffusion screens at the inlet and outlet of the vessel contain hold the activated charcoal.

Using an adsorber, a residual oil content down to 0.003 mg/m^3 is achieved. For this, the dwell time in the activated charcoal bed, itself determined by the adsorber’s geometry, is decisive. The specified quality is achieved from a relatively long contact time.

An activated charcoal adsorber is always used when the highest quality compressed air requirements are demanded and cannot be achieved by filters alone.

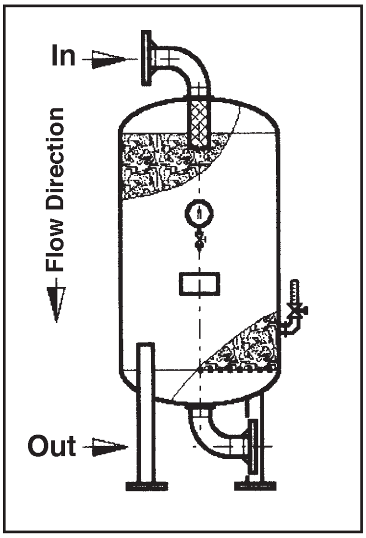


Fig. 4.7.3.3

The service life of the activated charcoal filling inside the adsorber reaches 8000 - 10000 hours of operation under normal loading conditions.

4.7.4 Residual oil determination

The usual methods of determining residual oil content are only capable of establishing the remaining oil aerosols after the filter. The residual oil content of oil in vapour form is therefore not indicated. The latter can be obtained on the basis of calculations(see Section 2.4.5) for the maximum oil vapour content in compressed air. The residual oil content after a filter is given by the oil vapour content of the oil, as a function of temperature. For this reason, comparison between filter elements is only valid for conditions of equal temperature.

With filter borosilicate-glass fibre material, residual oil contents down to 0.01 mg/m^3, given mineral based lubricants, at an operating pressure of p = 7 bar and a reference temperature of t = 20°C, can be achieved.

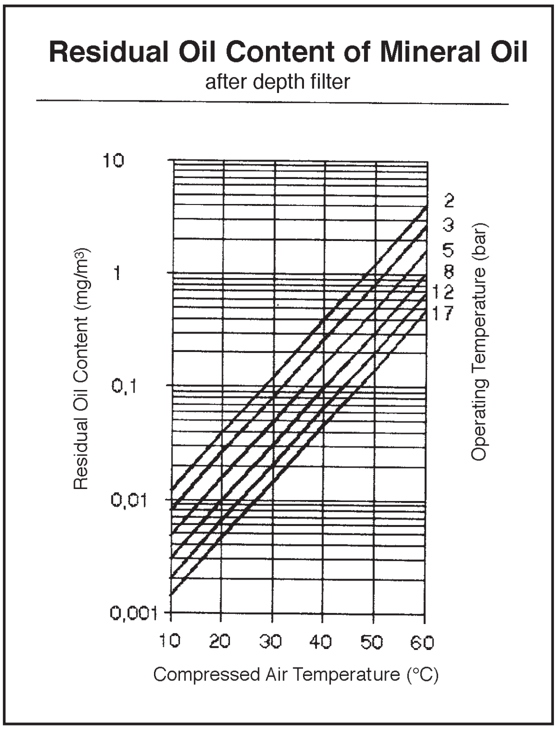


Diagram 4.7.4.1

The concentrations regarding the residual oil content are, according to ISO 554, based on the depressurised gas volume in m^3 and apply to an oil with a molecular weight of around 300. Deviating residual oil values at higher operating temperatures and different operating pressures are shown in Diagram 4.7.4.1 for mineral oil and in Diagram 4.7.4.2 for synthetic oil, for comparison purposes.

Using Dalton's Law of Partial Pressures, the saturated vapour content of compressed air at other conditions or alternative gases can be determined.

Synthetic oil, in contrast to mineral oil, has a much lower ability to evaporate. The respective partial pressure of the lubricant determines this.

An accurate determination of the residual oil value can be carried out only on the basis of knowledge of the type of oil used and of the parameters particular to this oil. For the quality of the compressed air, the residual oil content indicated in mg/m^3 or also ppm is the determining factor. Standards are set for various applications.

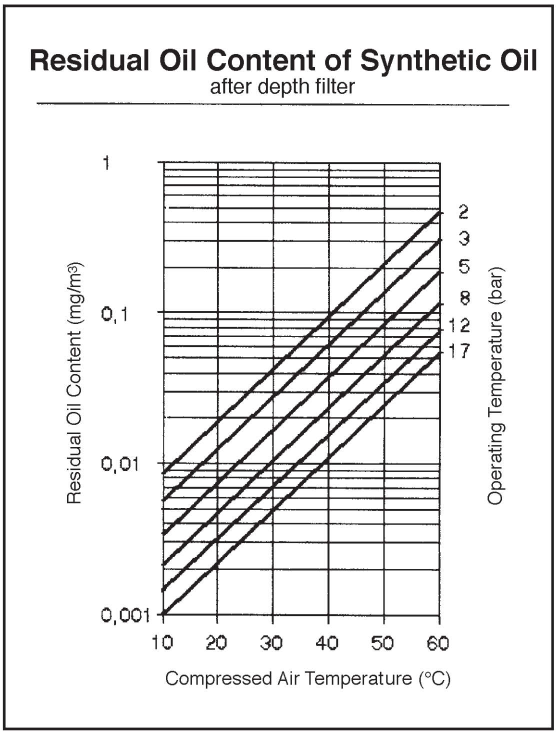


Diagram 4.7.4.2

At a given separating efficiency of the filter, the residual oil content in compressed air depends on the initial loading or content. Diagram 4.7.4.3 shows residual oil concentration as a function of initial content as far as a fine filter is concerned.

Reduction of loading or content leads to an exponential drop in residual oil concentration down to the theoretical value of 0.01 mg/m3. Below this value, the influence of the vapour phase is larger than the concentration present in droplet form.

In practice, a value of 0.001 mg/m^3 is regarded as the limiting value for residual oil concentration. In order to achieve a residual oil concentration of 0.01 mg/m^3, the original loading can amount to a maximum of 3 mg/m^3 at a given separating efficiency.

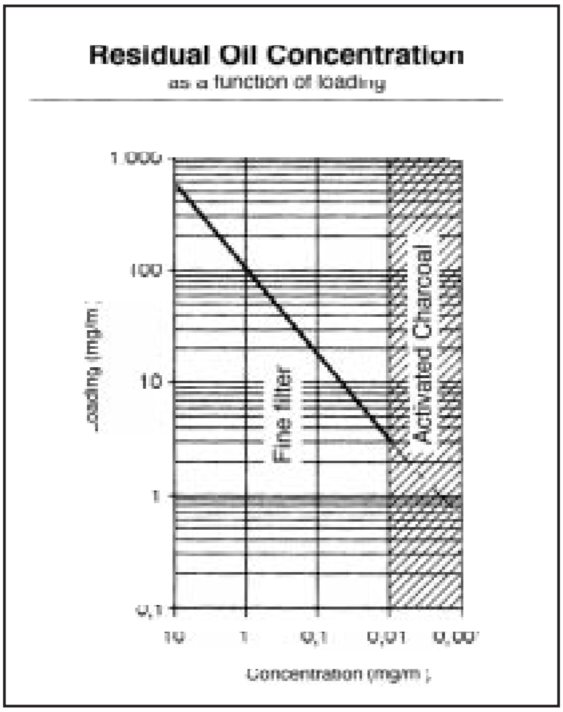


Diagram 4.7.4.3

A number of methods are used for determining the residual oil content of compressed air. ISO 8573.2 is the preferred Standard.

In the majority of cases, the following filter integrity test methods are presently used, but are only preferred for operation of the filter at atmospheric pressure

- Methylene blue test
- Sodium flame test
- D.O.P. test (Dioctyl Pthalate)

Different methods of measurement inevitably lead to differing results, so that the residual oil contents established in the compressed air cannot be compared with each other, or with reservations only. This is why an International Standard has been produced.

ISO 8573.2 contains a method for determining the residual oil content in compressed air, and also offers the possibility of obtaining reproducible results to the filter manufacturer as well as the compressed air user. In the course of this, the compressed air is filtered and then led to an aerosol generator via a pressure regulator. The constant oil/air mixture formed in the generator flows through a filter, the pressure loss of which is monitored by means of a differential pressure gauge. Following the filter, the compressed air is divided into a main and a test flow.

The test flow is conducted through a high -efficiency collection membrane with the aim of completely filtering out the oil droplets contained in the compressed air. Parameters such as temperature and pressure have to be monitored with appropriate instruments during the test, so that the operating state can be established and subsequently converted to the standard conditions by calculation.

4.8 Filter selection

Filter design is mainly empirical, experience and experiment are the determining considerations when designing new equipment. The question arises, to what extent this approach takes adequate account of all influencing parameters and relationships and how far technical theorems could offer a design aid. This implies the consideration as to what degree an analytical calculation is permissible.

The following data, forms part of the material specification of a filter:

- Type of material
- Weight per unit area
- Thickness of layer
- Volume flow per unit of surface
- Pressure loss at nominal volume flow
- Permissible static pressure difference.

4.8.1 Selection criteria

Filtering materials should, above all, excel in the following :

- Low pressure loss
- Good separating capability
- Homogeneous, stable pressure build-up
- Favourable retention capacity.

In certain cases, however, other qualities may play a determining role, such as chemical and thermal resistance. For this reason, the selection of filters in relation to optimum requirements is likely to cause a compromise.

When selecting the filtering material, overcoming the secondary effects (see Section 4.3.2) caused by the dynamic phase represent a task of primary importance. This ability, therefore, determines the underlying concept of the filter.

Given the characteristic values of the oil particles to be separated, thought must be given to filter structure and fibre surface. Here, fibres from different materials are available.

With the selection of suitable filtering material, the question of stability of the package arises. The solution lies as much in the construction of the filter as in the robustness of the fibrous layer. The latter can be significantly influenced when determining optimum filter parameters and inlet flow velocities.

In fibrous layers which are subjected to high velocity, compression of the filter material becomes noticeable from a certain load onwards, and this can falsify the appearance of the filter behaviour but can be compensated for through appropriately high packing densities.

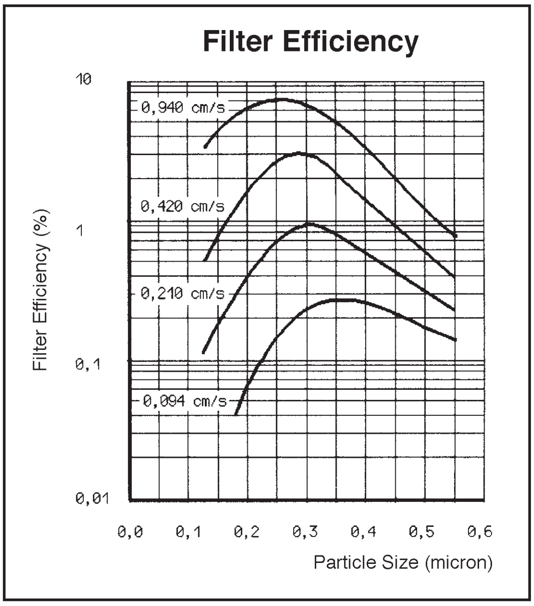


Diagram 4.8.1.1

For good separation performance, adequate layer thicknesses of more than 1 mm are necessary. To prevent re-entrainment, fitting a foam sleeve around the supporting grid offers a useful solution. At the usual inlet velocities, this highly porous layer prevents bubble formation and leads to an improved drainage of

the emerging liquid.
The foam material exerts no influence concerning secondary generation of particles smaller than 6 microns. In this range, fitting a fibrous material complementing the main drainage layer immediately downstream has proved to be advantageous. Diagram 4.8.1.2 shows the effectiveness of the foam material given an inlet velocity of 0.1 m/s.

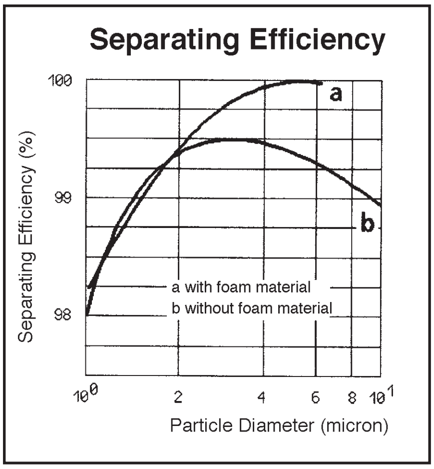


Diagram 4.8.1.2

Graded density filter combinations, the individual filter layers of which display diminishing fibre diameter in the direction of flow, offer a higher degree of separation at relatively low pressure loss in comparison to a single layer. Such variations offer improvements in the stationary phase, i.e. when all parameters are constant.

4.9 Fibrous materials

Filters are used for varied applications and using element materials of a wide ranging nature such as sintered bronze, ceramics, fibre, felt, cloth, glass wool, PTFE, metal and many more. The materials most important for oil filtration are described in the following sections.

4.9.1 Needle felts

Based on the structure of the filter medium, needle felts offer an even distribution of the air stream flowing through the filtering material, as the fibres of needle felts with a mean diameter between 10 - 30 microns are evenly distributed throughout the entire filter volume.

4.9.2 Microfibre

In order to achieve the smallest residual oil content in compressed air, filters with stepped separating qualities were developed. For this, microfibre has proved of value, particularly in the range of fine separators. With 95% porosity (voids volume), this offers not only adequate space for the air flowing through and, therefore, a low pressure loss, but also voids of the largest possible size for the oil droplets to be retained.

The relatively unstable microfibre is supported on the inside and outside through perforated stainless steel cylinders. A coarser fibre layer fitted immediately upstream protects the microfibre from gross pollution and therefore preserves the filtering qualities. For filtration and for the analysis of systems dispersed in air, filters from fine organic and inorganic fibres can now be regarded as the most effective filtering material. They are characterised by high separating efficiency at low differential pressure.

The individual fibres of a are mutually arranged in a labyrinth and thus subject the continuous carrying phase of throughflow to innumerable subdivisions. In contrast to a woven filter with systematic structure, the dispersed particles impinge much more frequently on a fibre so that the probability of retention is higher. Moreover, microfibre filters display a 30 % lower pressure loss than woven filters at the same efficiency of separation.

4.9.3 Filter service life

It is mainly from the economic point of view that the service life of fibrous layers is of interest.

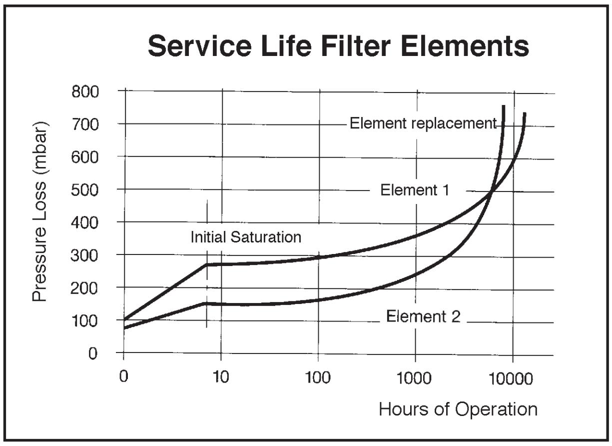


Diagram 4.9.3.1

Assessment criteria are influenced largely by the interaction between the design and construction of the filter and the conditions of operation. If the content of solid particles in air can be ignored, the service life of the fibrous layer may amount to several years. In practice, however, these solid particles exercise a decisive influence on the deformation of the fibrous structure, and, therefore, on the service life of the fibrous layer.

The displacement of liquid from the fibrous layer causes only a portion of the solid particles to be washed out of this layer. The remainder settles within the filter medium, causing an increase in pressure loss.

The resulting strain on the fibres may, under certain circumstances, cause the functioning of the filter to be impaired. In order to reduce the solid matter pollution of depth filters, these are preceded by a surface filter in the circuit to separate coarse solid particles and liquid droplets.

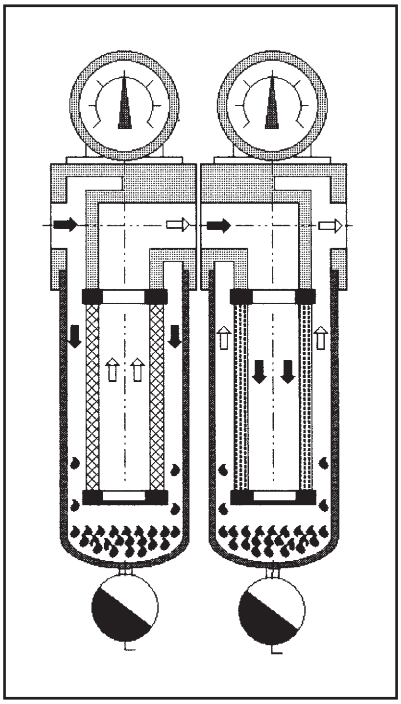


Fig. 4.9.3.1

It is advisable to install a differential pressure gauge to enable a continuous optical check of filter element performance.

Despite of all measures taken to obtain the most suitable filter for a given operating situation, the effective service life of filter elements cannot be predicted, as the differential pressure builds up only slowly in the course of operating time and the content of solid matter in the compressed air differs from case to case.

The operator of a filtration system must determine the period of element replacement with optimum operating economy in mind. Knowledge of the relevant data enables such a period to be estimated.

Differential pressure measurement indicates the pressure loss across the filter. This establishes two values, pressure before the filter p1 and pressure after the filter p2. These values offer means of estimating the performance loss along the lines of Pv = 1 - p22/p12.

The installed motor power Pi of the compressor is a further basic indicator. The power loss through the temporary pressure loss of the filter can be deduced from the motor performance as a numerical value. Multiplied by the cost of electric current Cp, a mathematical relation between operating costs and pressure loss can be deduced.

The investment costs CE for a new filter element must be compared with the operating costs. Formula 4.9.3.1 encompasses these specified criteria and determines the period of element replacement tEr.

(Note : Anglicisation of some symbols)

$$\boxed{t_{Ew} = \frac{C_E}{\left(1 - \frac{p_2{}^2}{p_1{}^2}\right) \times P_i \times C_p}}$$

Formula 4.9.3.1

Degrees of efficiency are not contained in this formula. These should, however, be taken into account. In the first instance, the relationship between installed motor power and effective shaft performance of the compressor should be observed. In addition, the characteristics of the service life of the filter elements in accordance with Diagram 4.3.9.1.

Alternatively, one could lay down a maximum operational pressure loss linked to the use of the element and, when this is reached, element replacement should be effected.

4.10 Filter accessories

Effective use of filters and separators in compressed air systems can only be monitored with suitable and supplementary accessories. Filter elements are loaded with various substances. During the operating life, liquid substances (condensate) must be continuously drained out of the system. For this, automatic condensate drains form the appropriate equipment. Solid matter is retained in the filter element and influences the service life of such elements. Differential pressure gauges form an expedient means of monitoring this service life.

4.10.1 Condensate drains

Wherever condensate precipitates, this must also be disposed of. For this purpose, automatic condensate draining systems have been developed. These can be divided into mechanical float valves and electrical or electronic condensate drains.

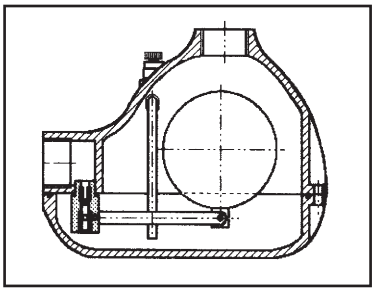


Fig. 4.10.1.1

Float valves, Fig. 4.10.1.1, must be specially adapted for the requirements of compressed air condensate, as this is an emulsion of water, oil and dirt particles, representing a much more critical operating problem than steam condensate. Precipitated condensate is collected and the buoyancy force of a float used in order to open up the valve seating.

Because the buoyancy force is limited by the envelope size of the float, valve diameters of 0.5 - 2 mm can be designed. The stroke length of the valve stem is about 25 - 50 % of the seating diameter. While system conditioned problems are pre-programmed, it cannot be denied that float valves do not always function.

The causes can be:

- Viscous emulsion,
- Accumulation of dirt or resinous material or stiction.

Draining by means of solenoid valves offers an alternative. Via a time control, these are opened for 1 - 10 seconds at specific intervals to dispose of the condensate. However, condensate accumulation in compressed air stations is not always constant and changes continuously. In contrast to float valves, each opening operation causes the unnecessary loss of compressed air.

Apart from the fact that malfunctions are not indicated, another aspect has to be taken into account. Through the high velocities arising inside the solenoid valve, combined with several changes in the direction of flow, the oil particles contained in the condensate are broken up into micro particles and charged negatively through friction with the air. As a consequence of this, stable emulsions are formed, the processing of which is costly.

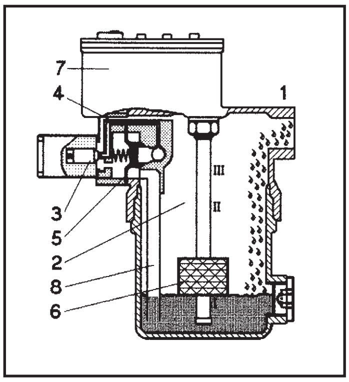


Fig. 4.10.1.2

An optimum, reliable solution of condensate draining problems is provided by the use of level controlled electronic drains (Fig. 4.10.1.2). With this separator, the condensate is detected by a level sensor system fitted with contactors.

As soon as the condensate level, reaches a contact, the electrical control system of the drain will open the solenoid valve (item 3) and direct the condensate away via a riser tube without loss of air. The condensate level is lowered and reaches a sensor, causing the solenoid valve to close. If sensor is not reached in a preset time, the controller sends signals causing repeat cycles of fixed duration. This ensures that the condensate collecting chamber is emptied completely. A sensor causes the control system to emit the principal alarm if opening intervals remain constant. This prevents any possibility of flooding of the system. As this level controlled drain operates with a time dependent cleaning cycle, there is no danger of “dried up” condensate, even if there has been a long period of non operation.

4.10.2 Differential pressure gauges

Differential pressure gauges are fitted to monitor filters and their elements continuously. The degree of pollution of a filter is linked to the rise of the differential pressure across the filter element. A typical differential pressure gauge in a compressed air installation has the following features:

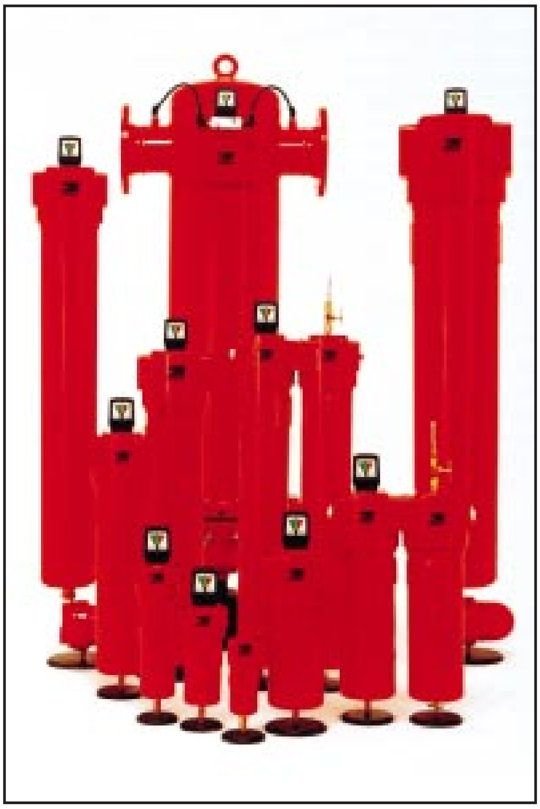


Fig. 4.10.2.1

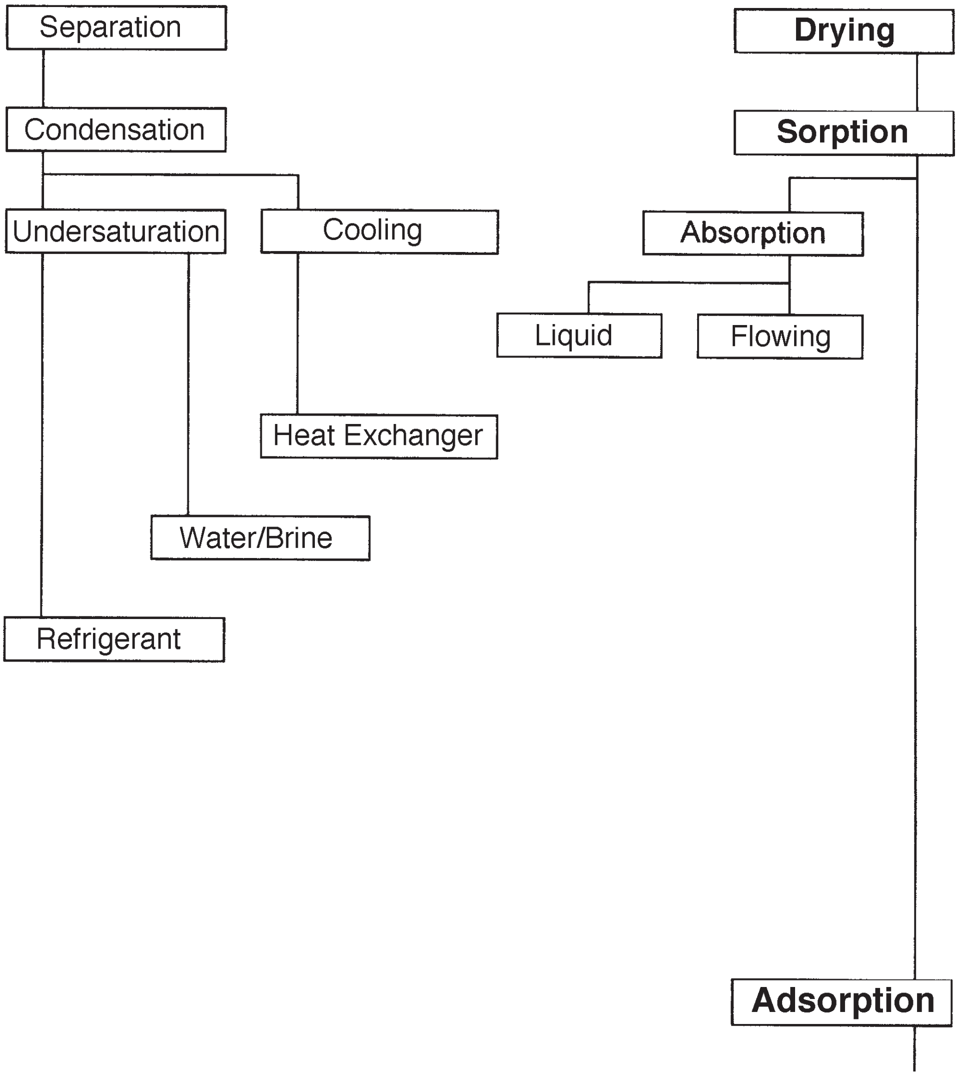
- Simple operation
- No pressure in the dial area
- Pressure surge indication
- No condensate in the dial area

The pressure loss across the filter element during operation is reflected in the differentiated pressure level at filter inlet and outlet. The diaphragm is moved in proportion to the difference in pressure level and also the magnet.
The movement is transmitted to the pointer mechanism and made visible.

Part 5

5.0 Compressed air dryers

The drying of compressed air is carried out by a variety of processes. Compressed air drying, working on the principle of cooling and condensation, makes use of refrigeration systems. Pressure dew points of down to 2°C are achieved by these methods. Pressure dewpoints below the limit value 0°C cannot be reached by the principle of condensation, as such systems freeze as soon as the condenser temperature drops below 0°C.



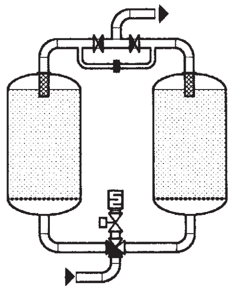
Compressed air dryers operating on the principle of adsorption can achieve pressure dewpoints below 0°C. Compressed air drying by adsorption for pressure dewpoints down to -110°C (state of the art) differ according to the mode of regeneration:

1) Heatless regeneration 2) Heat regeneration

Adsorption

Heatless Regeneration

Regeneration without heat supply, using a branched off flow of dry compressed air

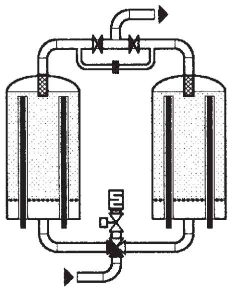


Warm Regeneration

Regeneration with heat supply

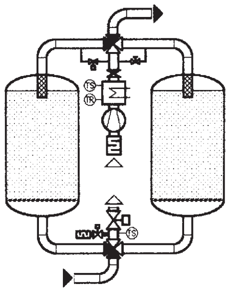
Internal

Regeneration using a branched-off flow of dried compressed air plus internal electrical heating



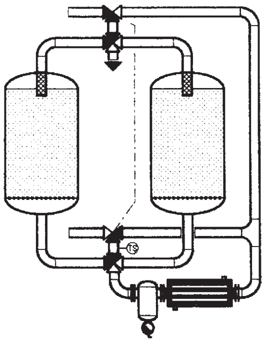
External

Regeneration with ambient air, drawn in by blower, heated by external electrical heating



Compressor Heat

Regeneration using energy from the compressor system, full flow, Partial flow



Many of the compressed air dryers in use are refrigeration dryers. The physical principle of refrigeration drying consists of cooling the compressed air down to a few degrees above 0°C, then separating the condensate from the compressed air flow and disposing of it externally.

Cooling is carried out almost exclusively by means of two heat exchangers, the first one of which is an air/air heat exchanger and the second one an air/refrigerant heat exchanger. The refrigerant, usually freon, is conducted through a closed refrigerant circuit

In principle, the cooling process is arranged in such a way that the cooling temperature in the air/refrigerant heat exchangers amounts to 1 - 3°C. At lower temperatures, the precipitated water would freeze, thus icing up the heat exchanger and integrated separator. Refrigeration dryers are capable of achieving pressure dewpoint temperatures between 2 - 10°C.

The mode of operation of a refrigeration dryer falls under the generic heading of separators while being subject to thermodynamic concepts.

The purpose of the following text is an explanation of adsorptive compressed air drying. For this reason, other types of drying are intentionally not dealt with.

5.1 Adsorption drying

Drying compressed air through adsorption represents a purely physical process in the course of which water vapour (adsorbate) is bound to the drying medium (adsorbent) through binding forces of molecular adhesion. Adsorbents are solids in spherical or granular form which are permeated by a multiplicity of pores. The water vapour is deposited onto the internal and external surface of the adsorption medium, without the formation of a chemical compound taking place, therefore the adsorption medium does not have to be replenished but only regenerated periodically. The adsorption process can achieve compressed air pressure dewpoints of down to -110°C.

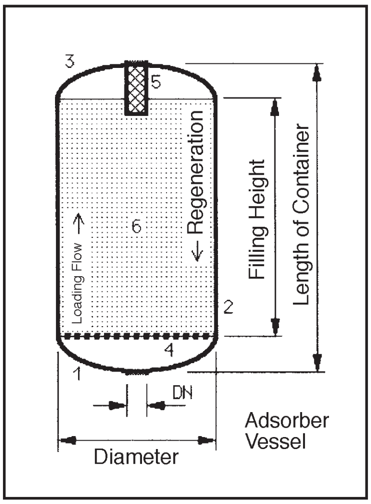


Fig. 5.1.1

For drying compressed air, the adsorption medium is packed into a container. The size of the adsorber depends on the required quantity of drying agent which has to store the introduced moisture from the compressed air to be dried.

Adsorptive drying takes place in a two (or more) chamber system and is made up from adsorption1 and desorption[2].

Adsorption makes use of the ability of porous solids with large surfaces such as

Silica gel	SiO_2
Activated alumina	Al_2O_3
Molecular sieve	$Na\ AlO_2\ SiO_2$

to selectively accumulate gases and vapours contained in low concentration from gas mixtures and thus separate them from the mixture.

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[1] deposition of a material onto the surface of a solid

[2] release of the deposited material to the surrounding medium

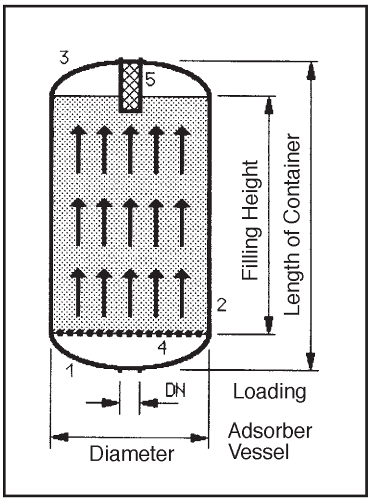

Fig. 5.1.2

For adsorption to take place, moist air is directed through the adsorber at operating pressure. In order to achieve effective drying, there must be a sufficiently long contact time between the compressed air and the bed of drying medium. The contact time depends on the flow velocity and the filling height. A typical twin tower adsorber is dimensioned in the proportion of about 1:2 of container diameter to filling height .

Loading up the drying medium with moisture from the compressed air system takes place from bottom to top. Correct dimensioning of the drying chamber prevents swirling or lifting-off of the drying material in the adsorber through the upwardly directed movement of flow. In this, it is assumed that the prescribed flow velocity in relation to the operating pressure is adhered to. This direction of flow has the advantage that, should the operation of the installation be interrupted, the entering moisture does not overload the bed of drying medium but is caught, through the force of gravity, in the lower zone, free from drying material (fig. 5.1.2 item. 4), of the adsorber. A dust filter (item. 5) at the outlet of the adsorber, protects the equipment installed downstream from abraded particles of drying medium.

Too low a flow velocity causes an undesirable channel formation within the desiccant bed. Such a formation of channels is caused, when the effective speed of flow velocity in the adsorber is less than 10-15 % of the nominal flow velocity (see Diagram 7.1.1.2).

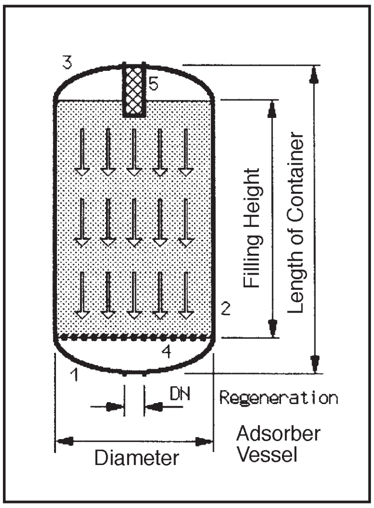

Fig. 5.1.3

Two adsorbers are required for the continuous operation of an adsorption dryer, each filled with adsorption medium. Drying the air under pressure takes place in the first adsorber whereas, in the second adsorber connected in parallel, desorption of the drying material is effected in the unpressurised state. Each of the two adsorbers is connected to the other at the inlet and outlet by piping. The valves required for the switching over of the adsorption dryer from adsorption to desorption are integrated into the piping.

During desorption, the direction of flow takes place from top to bottom, i.e. in the opposite direction to that used during adsorption. At the beginning of desorption the adsorber, which is pressurised, is discharged to atmospheric pressure. This discharge momentarily causes a “blow-like” high flow velocity in the adsorber. However, with direction of flow from top to bottom, the drying medium is not swirled but pressed against the lower sieve (item. 4) in the adsorber.

On the other hand, a pressure release directed from bottom to top gives the drying material an extremely strong swirl in the upper drying medium zone. A consequence of this would be an excessive mechanical stressing of the drying medium, shortening the service life. As with adsorption, the flow velocity of the regeneration air must not lead to the formation of channels in the adsorber. If channels are formed, pockets of moisture stay behind in “dead corners” and these exert a negative influence on the number of cycles of which the drying medium is capable. Desorption is carried out by means of differing processes.

In one case, desorption is achieved by purging the adsorption medium using a branched off current of dried and depressurised air with an appropriately low water vapour pressure and without adding heat (Heat Regeneration).

Alternatively, the drying medium is regenerated by being subjected to heat, whereupon the vapour pressure of the water related to the adsorption medium rises correspondingly (Heat Regeneration).

The regeneration air removes moisture from the adsorber. These processes, heatless and heat regeneration, form the basic types of regeneration with adsorption drying.

Adsorbers are designed in order to remove the humidity contained in the compressed air in the form of vapour. Additional condensed moisture forms a supplementary load on the drying medium and, therefore, amounts to an overloading of the adsorption dryer.

Adsorption drying must always be applied in conjunction with filtration.   A filter should be installed upstream of the dryer in order to eliminate condensate, oil droplets and solid particles, a filter downstream from the dryer to remove any abraded matter from the adsorber.

5.2 Heatless regeneration

Adsorption dryers regenerating without heat input, i.e. cold, are known as Heatless Dryers and are based on the principle of Pressure Swing Adsorption (PSA), thus permitting desorption to take place without an external heat supply. The principle of heatless regeneration uses a current of dry air typically 8-18%, expanded to atmospheric pressure and purged through the adsorbent bed to bring about regeneration. The strong undersaturation of the purge flow and the heat of adsorption arising through the adsorption process are utilised to bring about desorption.

5.2.1 Layout

The layout of adsorption dryers, using the principle of heatless regeneration, is clearly structured. For continuous operation, the adsorption dryer based on heatless regeneration (Fig. 5.2.1.1) consists of two vessels filled with drying medium.

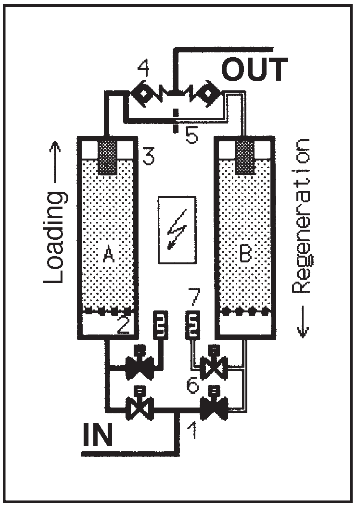

Fig. 5.2.1.1

Flat sieve bases (item 2) are used at the inlet side of the adsorber, whereas cylindrical wire mesh (item 3) is fitted at the outlet side in order to retain the drying medium in the adsorbers. Both adsorbers are interconnected at the inlet and outlet by piping. In order to switch over from adsorption to desorption, i.e. from adsorber A to adsorber B, interconnecting piping is fitted with valves.

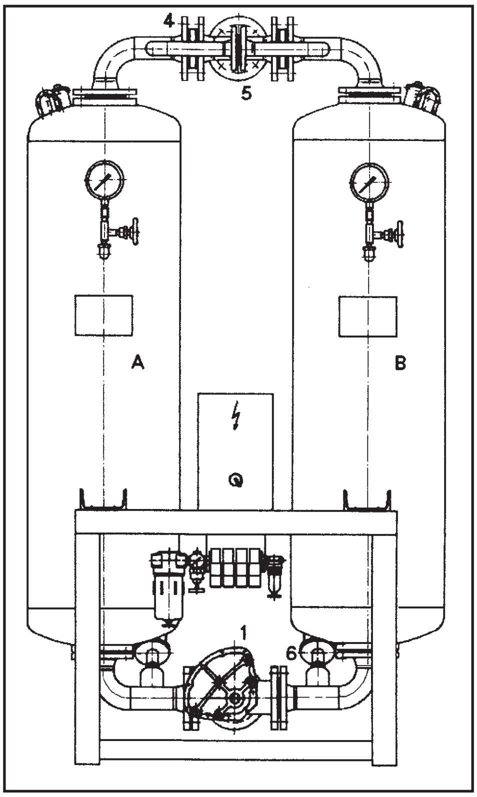

Fig. 5.2.1.2

Dryers for smaller outputs (Fig. 5.2.1.1) have direct controlled 2/2-way directional control solenoid valves (item 1 and item 6) on the inlet side. Main valves switch the dryer to adsorption or desorption respectively, via exhaust valves and silencers (item 7), leading to desorption and the pressure build-up. Adsorption dryers in the higher performance ranges (Fig. 5.2.1.2), on the other hand, are fitted on the inlet side with a 4/2-way pneumatically piloted directional control valve as main control element (item 1). A 2/2-way pneumatically piloted directional control valve is fitted after the main valve as exhaust valve.

At the outlet side of the adsorption dryer, the flow of dried air is fed into the compressed air piping via non-return valves (item 4). In parallel to the piping at the outlet of the dryer, a purge flow of dried compressed air is directed via a by-pass line with perforated screen (item 5) for desorption. The diameter of the perforated screen is determined by the quantity of air for desorption and the pressure difference at the perforated screen. Adsorption takes place at operating or line pressure, desorption at atmospheric pressure.

Heatless regenerated adsorption dryers achieve operating pressure dewpoints of -25°C given a dwell time of about 4 seconds. Different dewpoints call for a corresponding dwell times. For example, for a pressure dewpoint of -70°C, a dwell time of about 7.5 seconds is necessary. Differing pressure dewpoints, moreover, also require different quantities of regenerating air.

The heatless regenerated adsorption dryer is filled with activated alumina drying medium for normal operating conditions. Molecular sieves are utilised for even lower pressure dewpoints.

Heatless regenerated adsorption dryers need few valves. These valves are controlled directly or indirectly with reference to time. For this reason, the control of cold regenerated adsorption dryers calls for only a few control functions per cycle. These control systems are thus arranged to contain few complications. Using an appropriate time relay or switch system, the changeover from adsorption to desorption is brought about. Fully automatic operation makes demands on the control system, calling, for instance, for a programmable logic controller in combination with a dewpoint measuring gauge.

5.2.2. Adsorption

In order to dry the moisture laden compressed air, it is fed through the adsorber. The partial pressure gradient from the drying medium to the moist compressed air causes the deposition of moisture from the compressed air onto the receptive drying medium. With adsorption based on the principle of heatless regeneration, moisture from the compressed air is deposited onto the external surface of the drying medium. With this drying system, the capacity of the drying medium is used up to 0.5 % because only the external surface of the drying medium can be used for the deposition of moisture.

In order not to overload drying materials with moisture during adsorption, relatively short cycles between adsorption and desorption have to be chosen.

Economical adsorption is achieved in a period of a few minutes only. Longer periods call for a larger adsorber with the correspondingly larger quantity of drying medium, shorter periods lead to an unfavourable relationship of the desorption and pressure build up time which runs in parallel.

The loading of the drying medium with moisture from the volume of air takes place in the mass transfer zone (see paragraph 6.3.3) of the drying medium. The moisture introduced into the adsorber passes through the distance between inlet and outlet in increasing concentration. Before the break-through

point of moisture reaches the outlet, the system switches over, time controlled, from adsorption to desorption.
For heatless regenerated adsorption dryers, activated alumina or a molecular sieve are utilised as adsorbents. Activated alumina is suitable for entry temperatures up to 35°C and pressure dewpoints as low as -40°C. Molecular sieves as drying medium find application for higher inlet temperatures of up to 55°C and lower pressure dew points of down to -90°C. Whereas the pressure dewpoint of -25°C is achieved in operation relatively quickly, theoretically lower pressure dewpoints, as low as -90°C are achieved only after days of continuous operation.

A rise in temperature through adsorption in the bed of drying medium is relatively small with heatless regenerated adsorption dryers because the loading up with moisture is quantitatively low. The compressed air temperature at the outlet of the dryer is thus about 2-6°C higher than at the inlet, given normal operating conditions.

The service life of the adsorbents in heatless regenerated adsorption dryers amounts to about 4-5 years, if correct operating conditions are adhered to and assuming one shift operation.

5.2.3 Desorption

The desorption of the drying medium of adsorption dryers with heatless regeneration takes place in a counter current direction, in parallel and simultaneously with adsorption, making use of a purge of dried compressed air. The mode of operation of pressure change desorption corresponds to almost isothermal desorption through partial pressure drop in the adsorbing component by means of pure purge gas.

In parallel to the outflow side of the adsorption dryer (Fig. 5.2.3.1), there is a by-pass line with integrated perforated screen (item 5). As soon as the exhaust valve (item 6) is opened, the part-current of dried compressed air, restricted by the perforated screen, flows from the pressure side of the system, through the adsorber to be desorbed, to the atmosphere. The part-current used for desorption, which is depressurised down to atmospheric pressure, is approximately equal to the volumetric flow with which the moisture is fed into the adsorber during adsorption. The moisture content of the air always depends on the effective temperature.

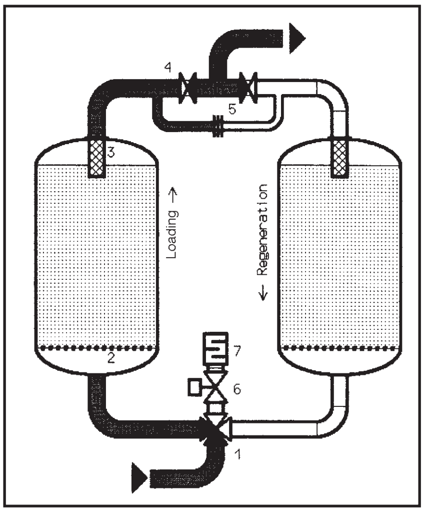

Fig 5.2.3.1

At constant temperature, equal volumes of air, if saturated, contain equal quantities of moisture. The volume flow of atmospheric air needed for desorption is, therefore, about equal to the volumetric flow during adsorption. The bigger the difference between operating and atmospheric pressure, the smaller is the regeneration volume flow in proportion to the total. Upon pressure release, the total humidity in the dried part-current remains constant, however, the air volume change after depressurisation leads to a reduction of relative humidity in proportion to the pressure drop then extremely dry part-current or regeneration air current has a very steep gradient of partial pressure drop in relation to the bed of drying medium. The moisture from the bed of drying medium is re-entrained by the regeneration air current and carried into the open air via the opened exhaust valve and silencer (item 7).

5.2.4 Pressure build-up

Right up to the end of desorption, moisture is removed from the adsorber, thus making the desorbed unit ready to accomplish adsorption again . However, switching over from desorption to adsorption cannot take place while there is the pressure difference between atmospheric regeneration pressure and the required operating pressure. This would lead to a pressure surge when switching over, leading to high mechanical strain. For this reason, pressure equalisation starts following desorption, as soon as the exhaust valve (item 6) is closed. Switch over from desorption to adsorption takes place while the pressure level in both adsorbers is identical.

5.2.5 Control system

Controlling adsorption dryers with heatless regeneration presents no problems. One or two main and exhaust valves, depending on the design, are actuated either directly or indirectly by means of a time controlled cycle timer. The main valves are required for switching over from adsorption to desorption and back, the exhaust valves for the functions of desorption and pressure build-up. The installed electrical capacity is thus low. Two valves, simultaneously actuated, and the time control need an electrical power of about 30 - 40 Watt.

Using this control system, an effective running time harmonisation between the adsorption dryer with heatless regeneration and a discontinuously operating compressor can be achieved fairly simply.

The on/off contact of the main switch of the dryer is linked to the signal emitter (pressure switch) of the compressor control. The synchronisation between compressor and adsorption dryer, therefore, brings about adaptation of the regenerative output of the dryer to the running time of the compressor. This switching system cannot, however, achieve adaptation to differences in pressure or moisture load.

Fully pneumatic control systems, as an alternative to standard electrical controls, are utilised when there is a risk of explosion or where mobile application means no availability of an electrical supply. Fully pneumatic control systems are expedient only under conditions of continuous running. With discontinuous operation, harmonisation between the dryer output and the desorption performance via synchronisation of dryer and compressor can only be achieved with difficulty.

5.2.6 Variable cycle

Purified compressed air is not a low cost item. It cannot be tolerated that unused compressed air is blown into the atmosphere upon regeneration. Adsorption dryers are designed for maximum full load operation. Deviating operating conditions thus, in principle, mean underutilisation of the adsorption dryer. If this is not corrected, it will always consume desorption energy as though it was running on full load. Adapting the adsorption dryer with heatless regeneration to differing operating situations therefore makes sense from the point of view of good housekeeping and energy efficiency.

Load dependent control systems lead to a variable cycle whenever the demand for compressed air fluctuates, inlet temperature with corresponding humidity load varies strongly between summer and winter operation but also if the take-off depending pressure range is scattered over a wide band of levels. The differing moisture load at the inlet to the adsorption dryer, caused by volume, pressure or temperature fluctuations, leads to a change in the pressure dewpoint at the outlet of the dryer in the course of time.

Depending on what level of residual humidity is acceptable, the pressure dewpoint of the compressed air is specified as a limiting value which forms the basis for regulation in face of a variable load situation.

Electronic systems in conjunction with a humidity measuring instrument (see part 9) are capable of detecting changes in operating conditions, evaluating these and passing on the result as reliable signals. Every part load of the adsorption dryer is thus consistently converted into prolonging the adsorption period while keeping the desorption time constant.

When part load running, the adsorption period is extended proportionately in line with the moisture load and converted into a full load situation. The desorption time is not variably adapted with a correspondingly reduced desorption air quantity, as a part load can, at any time, be followed by full load and the required desorption must have been completed at this point in time. The saving in desorption energy results from the difference between variable adsorption time and constant desorption time. Compensating for overloading the adsorption dryer by means of load depending control systems is impossible in principle.

When using a load dependent control system, one special feature has to be observed. Assuming a 70 % loading of the dryer with time dependent control and at full compressor output, the quantity of air for desorption is set for just this 70 % of dryer capacity. On the other hand, when using the load dependent control system, this will be 100 % because the dryer is utilised to 100 % capacity per cycle via the load dependent control system.

5.2.7 Range of application

The layout of adsorption dryers with heatless regeneration is clear and simple. Compared with other adsorption dryer systems, pressure dewpoints down to -90°C can be achieved without additional effort.

Use in the higher pressure ranges and at low inlet temperatures causes the quantity of air needed for desorption to be reduced to an economical value.

At low operating pressure the demand for already dried compressed air for purposes of desorption is increased. This causes a large proportion of the prepared compressed air to be no longer available for productive purposes. This system for drying compressed air should thus not be utilised for operating pressures of less than 5 bar.

Higher inlet temperatures exert no influence on the load factor, so that solely the degree of humidity at the inlet determines the size of dryer required.

Photo 5.2.7.1

Depending on the cycle, the quantity of air enclosed in the adsorber expands upon release at regular intervals with an emission noise level of about 90 - 95 dB(A). Given suitable noise attenuation measures, a reduction of the noise emission level to the region of 10 - 15 dB(A) can be accomplished.

The use of adsorption dryers with heatless regeneration is given preference

in the capacity range of up to 3000 m^3/h
in the higher pressure ranges
at high inlet temperatures
for installation in explosion proof areas
for use under ground
on frequently changing locations with fully pneumatic control

5.3 Heat regeneration

The adsorption dryer regenerated by means of heat undergoes this regeneration with the help of a purge of already dried air accompanied by a simultaneous supply of heat. The external layout is roughly similar to that of adsorption dryers with heatless regeneration, but a direct acting electrical source of heat is utilised and this supports the regeneration to optimum effect. This decisive characteristic calls for differentiating considerations from the process technology point of view.

With heat regenerated adsorption dryers, possessing a regeneration air system complete with a heater built into the adsorber, the heat of regeneration is fed directly into the drying medium by the heater. Optimum heat transfer efficiency depends on the system, as only small losses occur in the course of the transfer of heat from the heating system to the drying material.

In contrast to the dryer with heatless regeneration, the charging process does not have to be interrupted at brief intervals for secondary reasons of process balance. Corresponding to thermal separating processes, the following knowledge is required in order to design an adsorption system :

- Adsorbate/adsorbent balance in the light of thermal adsorption processes
- Kinetics of adsorption and desorption
- Mass and energy requirements of adsorption
- Permissible flow velocities and pressure losses
- Dimensioning of the adsorbent layers

Adsorption media must fulfil the following requirements:

- High selectivity for the component to be separated
- High readiness to be desorbed after being charged
- High adsorbing capacity even in the face of low concentrations
- Mechanical robustness against changes in temperature
- Gas and steam permeability during adsorption and desorption
- Chemical resistance against gases and water vapour

The following sections explain individual special aspects of thermal separating processes

5.3.1 Layout

The adsorption dryer using heated regeneration (Fig. 5.3.1.1) with built-in heating consists of two (or more) vessels filled with drying medium. Depending on the size of the adsorption dryer and the design, two or more heaters are used per adsorber.

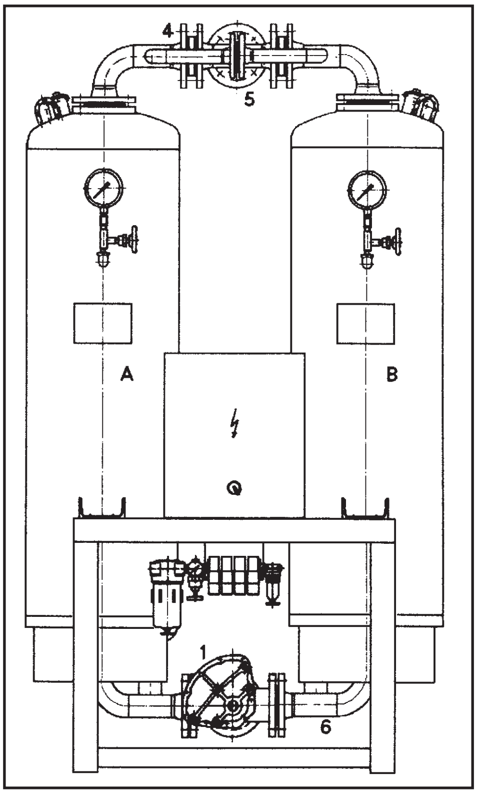

Fig. 5.3.1.1

The most practical solution for arranging the heaters inside the adsorber consists of distributing star shaped heating elements in one or several central part circles. This achieves a relatively even distribution of heat inside the bed of drying medium. Because of thermal expansion, the heating elements must have upward play so that heating element and drying medium do not suffer damage. Fitting the integrated heating system into the bed of adsorbent diminishes the usable cross-section of the adsorber vessel and the volume of drying medium which can be installed. The correct way of compensating for this is by means of a larger diameter but not through a longer adsorber. For construction and design reasons, the flow velocity through internally heat regenerated adsorption dryers with identical adsorber diameters would be slightly higher compared to other systems.

As with heatless adsorption dryers, adsorption dryers with internal heat regeneration (Fig. 5.3.2.1) likewise use flat sieves (item 2) and cylindrical wire meshes (item 3) at the inlet and outlet fitting. This prevents drying medium from being carried over into the downstream compressed air piping during operation, even at high flow velocities. The adsorber vessels are interconnected by piping at the inlet and outlet. The valves for switching over from adsorption to regeneration are integrated into this piping.

A by-pass with purge orifice (item 5) is fitted at the outlet of the adsorption dryer with heat regeneration in parallel to the interconnecting piping. A fraction of the already dried compressed air is branched-off via this by-pass for regeneration. Adsorption takes place at operating pressure, regeneration at atmospheric pressure with simultaneous input of heat through the heating elements. The timing of regeneration and the subsequent building up of pressure is controlled through the exhaust valves (item 6) to the outlet to which silencers (item 7) are fitted.

Adsorption dryers with heat regeneration and internal heating are designed for a pressure dewpoint of -25°C at a dwell time of about 4.5 seconds. Pressure dewpoints deviating from this call for a correction of the dwell time, heating capacity as well as changed regeneration and purge air quantities, depending on the overall heat requirement. Low pressure dewpoints down to -70°C, with powerful heat capacities and correspondingly large quantities of regeneration and purge air, form the economic limit for this system.

The drying media most frequently used in heat regeneration adsorption dryers with heat regeneration are based on a silica gel mixture from water resisting material on the inlet side, and high performance drying material on the outlet side or, alternatively on a complete molecular sieve filling. The silica gel mixture is used for inlet temperatures up to 45°C and pressure dewpoints down to -45°C. Molecular sieve is always utilised for higher inlet temperatures up to 55°C and at low pressure dewpoints down to -70°C.

The electrical control system of heat regenerated adsorption dryers incorporates a time sequence of the individual functions. Thermostats (item 9) limit the heating phase during regeneration, monitoring instruments signal malfunctions. The contactor controls which used to be commonly applied to this dryer system have, in the course of time, been replaced by programmable logic controllers in combination with dewpoint measuring instruments.

5.3.2 Adsorption

The basic principles of adsorption, related to velocity, dwell time and direction of flow inside the adsorber, also apply to adsorption dryers with heat regeneration. The following section, therefore, puts the stress on characteristics particular to systems with heat regeneration thereby, omitting the generally valid properties of adsorption drying.

Adsorption dryers with internally applied heat regeneration, utilise the dynamic receiving capacity of the adsorbents up to maximum 16 - 18 %. Dynamic capacity makes use of the internal and external surface of the drying medium in order to store moisture. In line with the maximum capacity utilisation, the cycles from adsorption to regeneration and back are considerably longer as with a heatless regeneration system.

An adsorption period from 4 - 8 hours has proved its worth. Longer adsorption times call for a larger adsorber with a correspondingly larger quantity of drying medium. Shorter periods present problems, particularly in the case of unfavourable load patterns, because of the regeneration time running in parallel, during which heating and cooling must take place while respecting the overall heat requirement.

From the air or gas mixture, adsorption media preferentially adsorb components with high boiling points. In general, the differences between the boiling temperatures of the adsorbate and of the carrying gas are large, so that the carrying gas has no effect on the course of adsorption. However, adsorbates with closely adjacent boiling temperatures make separation into components difficult or even impossible.

The partial pressure gradient from the dry adsorbent to the moist compressed air causes the deposition of the moisture from the compressed air onto the receptive drying material. In the case of dynamic adsorption in systems with heat regeneration, the compressed air to be dried flows around the drying medium. This causes the drying material to be slowly charged with moisture in the direction of mass flow. A so-called loading or mass transfer zone is formed. Once this zone reaches the adsorber outlet, intensity of drying diminishes and the dewpoint rises steadily.

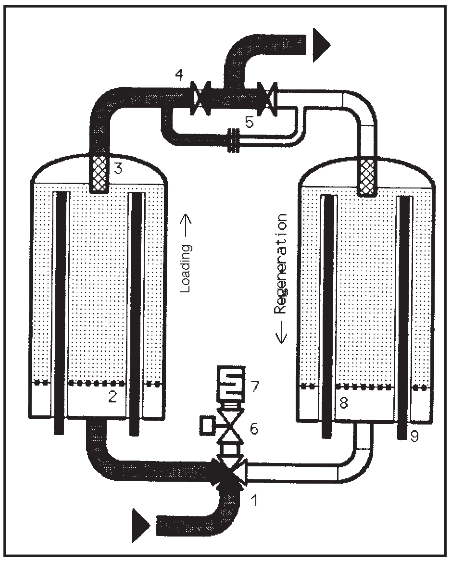

Fig. 5.3.2.1

In contrast to heatless regeneration, heat regeneration also makes use of the internal surfaces of the adsorbents for storing moisture. To have a better understanding of what happens, the storage of moisture from the compressed air by the drying medium is explained in more detail here.

Bonding forces are effective between the individual molecules of the adsorbents. Within the substance, each molecule is orientated in line with the adjacent molecules and thus subjected to the same forces. This state is not achieved at the outside surfaces because the bonding forces are unsaturated here. This free energy exerts an attraction for the water molecules, as soon as the latter reach the tension range of the surface. If this attracting force of the drying medium molecules is sufficiently large in order to overcome the inherent energy of the water molecule, it adheres to the surface. The adsorptive forces in the micropores of the drying medium are particularly strong because of the adjacent surfaces with overlapping of the potential fields. As the pore diameters can be as low as the size range of molecule dimensions, these pores can become filled although the surface itself is covered by a monomolecular layer only.

Capillary condensation is a further action effective in the boundary pores on the strength of monomolecular deposition. The phase capable of adsorption has a high surface energy through its large specific surface. Both materials, moisture and drying medium, aim to achieve the state with the lowest energy level, so that the moisture content of the compressed air condenses, supported by the capillary and adsorption forces, while surface and surface energy diminish at the same time. This process releases a quantity of heat, adsorption heat, in the adsorber bed.

Latent heat of adsorption depends on the amount of moisture already stored in the drying medium under conditions of operating pressure. The higher the percentage of moisture at the point of entry into the adsorber, the higher will be the heat of adsorption. Under unfavourable operating conditions, adsorption may lead to temperatures in the drying medium bed which approach the lower temperature range of regeneration and thus prevent effective drying. At the outlet of the adsorption dryer, the temperature can be 12 - 20°C higher than at the point of entry, given normal operating conditions.

5.3.3 Regeneration

In order to prepare the drying medium bed loaded with moisture for renewed adsorption, the stored humidity must be extracted from the drying material by means of regeneration.

In heat regenerated adsorption dryers, the regeneration of the drying medium is carried out by countercurrent. Through regeneration by countercurrent, the high concentration of moisture at entry is not carried right through the total bed, thus at the same time preventing energy wasting double adsorption.

With countercurrent regeneration, the pressure dewpoint is qualitatively set by the layer of drying medium located at the outlet from the adsorber during the adsorption phase. Only in the course of countercurrent regeneration is this layer exposed to an accurately specified temperature and moisture for a longer period, the pressure dewpoint thus being determined during adsorption.

The total sum of regeneration passes successively through two separate phases:Heating and cooling. At the beginning of regeneration, the integrated electric heating is switched on and the drying medium bed slowly but steadily heated to the final regeneration temperature. The heating elements distributed within the adsorber radiate a ring of even heat (Fig. 5.3.3.1). The geometrical arrangement of the heating elements within the bed is decisive for an even distribution of heat within the adsorber. An ideal arrangement aims at preventing heated zone overlaps as well as cold zones. During the heating phase, the high temperature expels the moisture stored within the adsorption media. At a certain temperature, moisture evaporates and the increasing surface energy overcomes the adsorbtive force.

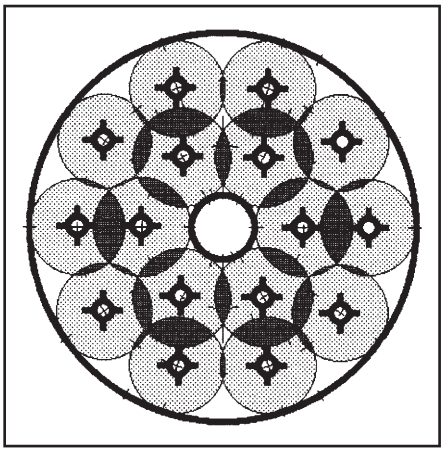

Fig. 5.3.3.1

There is a by-pass duct with fixed orifice (item 5) at the outlet side of the adsorption dryer (Fig. 5.3.2.1). When the exhaust valve (item 6) is open, a fraction of dried compressed air flows towards the atmosphere in the depressurised state in a downward direction through the drying medium bed to be regenerated. Assisted by gravity, this flow drives the moisture out of the system. During the heating phase, the quantity of regeneration air amounts to about 5 % on average. After the final temperature of 140 - 220°C is reached, a signal from the thermostat switches off the heating. Temperatures above 250°C should be avoided in order to prevent thermal damage to the drying medium. Such heating time amounts to 2 - 4 hours, depending on the loading level.

The heat introduced into the drying medium bed in the course of the heating phase must be removed from the adsorber by the end of the regeneration period. Remaining residual heat at the end of a cooling phase, caused by too low a quantity of cooling air, leads to a peak in the pressure dewpoint level difficult to quantify as to time and extent.

The required quantity of cooling air depends on the amount of heat which must be removed from the adsorber by the end of a cooling phase. Under favourable cooling conditions, the quantity of cooling air can amount to 4 - 8 %. The cooling period with this system of dryer lasts 1 - 2 hours on average.

The adsorption dryer using internal heat generation cannot be switched off during the heating phase and should not be switched off during the subsequent cooling phase as, otherwise, it is not possible to achieve an optimum time cycle of the build-up and run down of heat required for regeneration. Failing this, the danger of a large percentage of the moisture remaining in the drying medium bed, and being recondensed during cooling, arises. A safe point in time for switching off occurs only during the holding and pressure build-up period.

5.3.4 Pressure build-up

After regeneration has been accompanied by the removal of moisture as well as of heat from the drying medium bed, the system is brought to an identical pressure level before switching over from vessel A to vessel B. The exhaust valve, through which the regeneration and cooling air is expelled closes, so that the build-up of pressure can begin. Only after successful pressure equalisation via the regeneration duct can the dryer system be switched over from regeneration to adsorption. Pressure build-up takes a few minutes only.

5.3.5 Control system

Control systems for adsorption dryers with heat generation are somewhat more complex, having to fulfil the needs of the overall system. For switching over from adsorption to regeneration and back again, as well as for pressure build-up, individual valves are actuated within a time cycle. Adsorption dryers with heat regeneration are often fitted with a programmable logic controller.

Beyond the basic functions, valve switching and heating, pressure build-up and a fault signal are integrated into the control system. A rigidly fixed time cycle with adsorption dryers using heat regeneration is exceptional and can be justified only if the throughput performance of the compressor is equal to the compressed air consumption, i.e. during continuous operation.

More and more control systems for adsorption dryers using heat regeneration operate as a function of load. The concentration of residual humidity at the outlet is used as a signal for switching over from adsorption to regeneration. The conditions applying to a load dependent cycle are the same for adsorption dryers using heat regeneration as for other adsorption drying systems.

For this reason, this subject will only be briefly described. Control systems operating as a function of load make sense when the moisture load is subject to wide variation.

Modern controllers linked to a humidity measuring device, can register every part load level of an adsorption dryer. Based on this, they make the adsorption period longer while maintaining regeneration time constant. Beyond this, limiting values describing the internal state of the dryer can be utilised or be made visible in signal form. Functions relevant for monitoring are :

- Heating temperature
- Main valve
- Exhaust valve
- Pressure build-up
- Pressure dewpoint

5.3.6 Field of application

Adsorption dryers with internal heat regeneration need only a small share of the compressed air already dried in order to effect regeneration and can achieve pressure dewpoints of down to -70°C in continuous operation.

Photo 5.3.6.1

At high pressure ranges and low entry temperatures, the quantity of regeneration and cooling air required becomes less. At low operating pressure and high inlet temperature, a correspondingly larger quantity of regeneration and cooling air is required in order to effect regeneration.

High inlet temperature accompanied by low operating pressure significantly reduces the capacity of the drying medium. If this is accompanied by a rise in the heat of reaction up to the lower range of regeneration temperature, compressed air drying can under certain circumstances be considerably impaired by such unfavourable operating conditions.

Expansion of the compressed air upon pressure release, once during each cycle, forms the only noise pollution caused by the adsorption dryer at the place of installation. Pressure release can be slowed down, thus further diminishing the emitted noise level.

Adsorption dryers with heat regeneration are, in preference, used

In the performance range of 1000 - 6000 m^3/h
For pressure dewpoints down to -70°C
In the medium pressure range
At medium inlet temperatures
For CO_2 gas drying
If the ambient air contains a high dust level
In an atmosphere rich in toxic substances

5.4 External regeneration by blower

Adsorption dryers with heat regeneration and with externally provided heating and blowing systems, require only small quantities of the already treated compressed air for purging and for building up pressure. The quantity of air required for regeneration is blown in, or drawn in, by means of a vacuum pump from the surrounding atmosphere.

A heat source for regeneration can be provided by electrical energy, steam, hot water, heated oil or other energy carriers to be selected, and the drawn in ambient air heated by means of a heat exchanger.

Blower regeneration is regarded as the classical dryer. An adsorption dryer with vacuum regeneration forms a logical and consistent further development. There is a growing tendency for using such systems also in the lower performance ranges.

Adsorption dryers with heat regeneration with a heating and blowing system external to the adsorber can suffer functional impairment through unfavourable conditions at the point of installation, i.e. be handicapped by the surroundings such as through:

high ambient temperature
high dust or moisture content in the surrounding air
corrosive components in the surrounding atmosphere

However, disadvantages of this type at the point of installation can be effectively eliminated by suitable measures. Operating by blower regeneration offers wide ranging freedom for adaptation to problematic marginal conditions. The regeneration system, consisting of a blower and a heater, is selected from a wide range of choices. Using different materials, specific requirements can be met.

5.4.1 Layout

The adsorption dryer regenerated by heat (Fig. 5.4.1.1) with external heater and blower consists of two adsorbers complete with a sieve bottom and dust sieve. The adsorbers are interconnected by piping at the inlet and outlet, complete with the required valves. Significant additional dryer components can be detected if one makes comparisons with the adsorption dryers so far described:

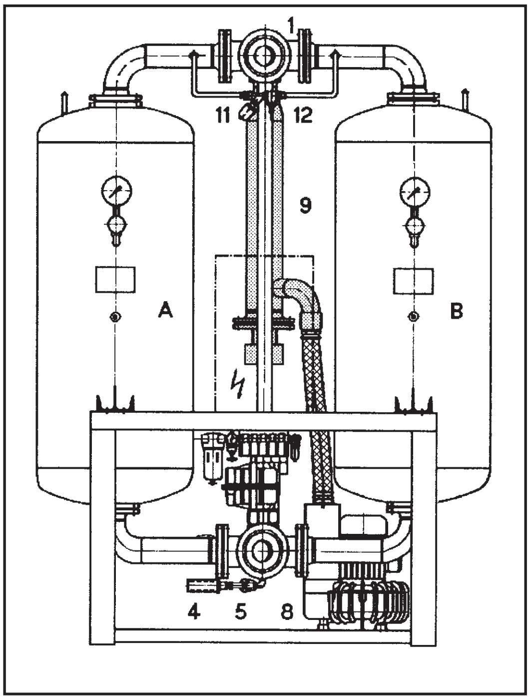

Fig. 5.4.1.1

Two 4/2-way valves (item 1) are fitted in combination, actuated by a pneumatic drive via a common hinged shaft

The external heater (item 9), installed on the outlet side, is linked via a flexible connection to the

External and sound attenuated blower, mounted in line with the heater (item 8)

Adsorption is carried out at operating pressure from bottom to top. Regeneration, on the other hand, by countercurrent and without pressure, with heated blower air. The exhaust valve (item 6) is open during regeneration, closed during pressure build-up after regeneration.

Adsorption dryers with external heat regeneration are designed for pressure dewpoints of -25°C. The rule regarding dwell times of adequate length for the reliable achievement of the pressure dewpoints applies to this design of dryer in equal measure. With the help of blower regeneration, pressure dew points of - 55°C can be reached in continuous operation.

Suitable heating capacity and dwell times for low pressure dewpoints call for a relatively large outlay in device size, adsorption medium and energy use. Depending on the pressure dewpoint, different cooling and purge air quantities are required, in turn depending on the heat requirement.

The drying medium used in heat regenerated adsorption is a silica gel combination of water resisting material on the inlet side, and molecular sieve drying material on the outlet side. The silica gel combination is used for inlet temperatures of up to 40°C and pressure dewpoints down to -40°C. Molecular sieves find their application at higher inlet temperatures up to 45°C and lower pressure dewpoints down to about -55°C.

The electrical control system which processes valve functions and other signals such as regeneration temperature, heating time, cooling and purging phase as well as pressure build-up, has to be compact. For this reason, programmable logic controllers represent modern state of the art for this type of dryer. These types of controller offer the simultaneous advantage of being able to fit additional components and also unlimited possibilities of adaptation to particular operating situations.

As a point of principle, one should consider insulation of the adsorbers by means of mineral or slag wool or other material. This, firstly for reasons of radiated energy saving, secondly as protection against touching. Adsorption dryers of this type are constructed up to performances up to 50 000 m^3/h and even higher. For certain sizes of installation, transport in sub assemblies is necessary. For smaller outputs, the system is mounted on a basic frame as a compact unit.

5.4.2 Adsorption

The principles on which adsorption in heat regenerated adsorption dryers are based were explained in Section 5.3.2. For this reason, the materially important facts are only mentioned briefly and supplemented with important system related peculiarities.

Under normal conditions, the dynamic drying capacity of adsorption dryers regenerated externally by means of blower air, amounts to about 16 - 18%. For this, the internal and external surface of the drying medium is used for the storage of moisture. Taking up water vapour does not alter the form of the adsorbents. Water vapour adsorption by these substances depends on the temperature and on the water vapour concentration of the gas to be dried. Of practical importance for this type of drying is the so-called break-through load. After this is reached, complete drying is no longer possible and the adsorption medium must be regenerated.

The regeneration temperatures usual in practice are around:

120 - 180°C for silica gel
150 - 200°C for activated alumina
180 - 320°C for molecular sieves

In most cases, silica gel is preferred as a drying medium, whereas the molecular sieve is considered when a pressure dewpoint of -40°C is not sufficient for the application in question. Activated alumina is used in special cases only then when the compressed air contains ammonia or hydrogen fluoride, as silica gel would be impaired in its adsorptive properties by the these substances over a period of time. Internal fittings in the adsorber depend on the system, and the entire content of adsorbent can be utilised for drying purposes.

Loading the drying material with humidity from the compressed air flow takes place with the current flowing from bottom to top. The Mass Transfer Zone migrates with increasing saturation from the point of entry to that of outlet of the adsorber. Before the break-through point is reached, the system switches over to comply with the periods of the regeneration cycle. The cycles from adsorption to regeneration and the reverse are set with a view to full capacity utilisation, an economical loading up period of 4 - 6 hours meets most practical requirements.

In practice, adsorption dryers must be able to cope with the most varied states of the ambient air. Fluctuations are caused by the seasonally conditioned meteorological changes. These different changes of state of the air exert a direct influence on the heat of adsorption and, as a secondary effect, may also cause significant changes in :

- the dynamic capacity of the adsorption material
- the running time of the drying installation between cycles
- the temperature of the dried air and thus also of
- the residual moisture in the dried air.

Taking into account these phenomena, up-to-date installations make use of two-layer adsorbers. The lower, waterproof, charge with large pores makes the initial contact with the compressed air entering in the moist or oversaturated state. This layer is endowed with a high loading capacity and offers the additional advantage not to be disintegrated by the impingement of high air moisture, water mist or water droplets, thus avoiding grain fracture, abrasion and increased pressure loss which would diminish the capacity or service life of the drying medium.

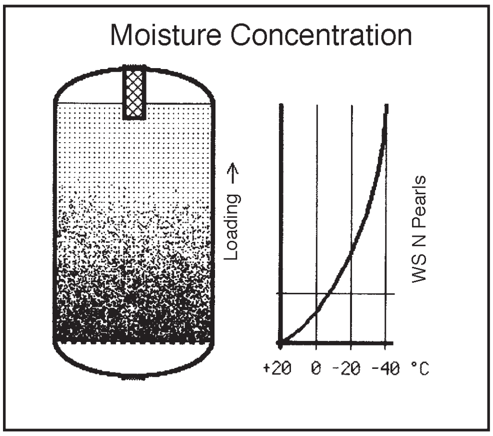

Fig. 5.4.2.1

The first layer is arranged to be of sufficient height that the essential drying operation, accompanied by significant heat of adsorption, is concluded in this zone. Immediately afterwards, the predried air enters the second layer situated above. This layer is filled with hyperactive, small-pored drying medium. Depending on operating conditions, pressure dewpoints down to -55°C can be achieved in this layer under continuous operating conditions.

The rise in temperature caused by loading the drying medium bed of adsorption dryers with heat regeneration always depends on the moisture content at entry and the operating pressure of the air to be dried. The outlet temperature of the compressed air lies between 12 - 20°C above the level of the inlet temperature under normal conditions of utilisation.

5.4.3 Regeneration

Once an adsorber is fully charged with moisture, it must be regenerated. With the regeneration processes discussed previously, the quantity of regeneration air is branched off from the current of dried compressed air as a partial current and thus no longer available for production purposes. In contrast, regeneration by means of external blower air uses only small quantities of compressed air for purging. The schematic representation in Fig. 5.4.3.1 shows the most important elements of blower regeneration and the simple function of adsorption dryer systems using external heat regeneration.

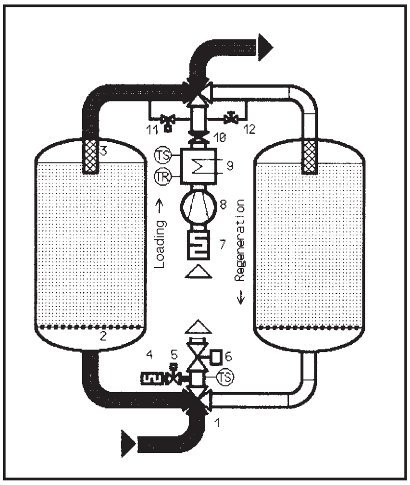

Fig. 5.4.3.1

Taking up the same period of time as adsorption, regeneration takes place in parallel. Via a blower (item 8) with inlet noise attenuator (item 7), ambient air is drawn in and heated (item 9) to the temperature of regeneration. Electrical energy, steam, hot water or also heated oil can be used as sources of heat. The ambient air which has been drawn in by the blower and subsequently heated, is ducted to the vessel to be regenerated via the upper switching valve. In countercurrent to adsorption, the heated regeneration air flows through the adsorber, thus heating the drying medium. Regeneration by countercurrent ensures that the moisture to be extracted is not conveyed through the entire bed of drying medium. The humidity stored in the drying medium evaporates and parts company from the drying medium.

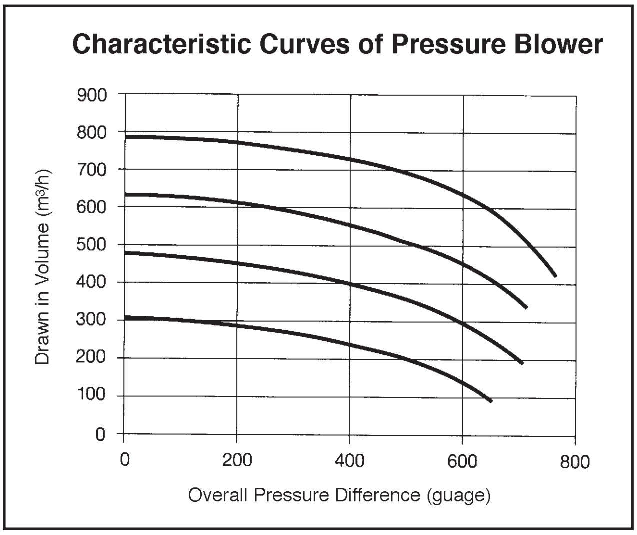

Diagram 5.4.3.1

The heated blower air, humidified by the desorbed moisture, now leaves the adsorber via the lower valve (item 1) and the downstream exhaust valve (item 6).

At the end of the heating phase, monitored by a thermostat (TS), the cooling phase begins. The heating is switched off and unheated cool ambient air is ducted through the system via the same path. Drying medium and adsorber are thus cooled down to a low operating temperature. The cooling phase is terminated after an accurately specified period. This limitation of cooling is necessary in order to avoid a dewpoint peak when switching over from regeneration to adsorption.

As the ambient air, required for regeneration, has a certain water content, it is unavoidable, with this principle of regeneration, that a slight pre-loading with moisture takes place in the upper layer of drying medium when cooling with humid ambient air. This pre-loading causes a dewpoint peak because compressed air dried through adsorption impinges on this very moist zone, re-entraining the moisture and conveying it into the compressed air network.

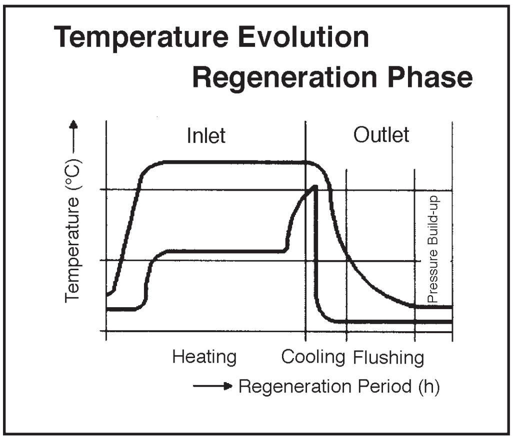

Diagram 5.4.3.2

In order to reduce this dewpoint peak, the vessel is purged with a fraction of already dried compressed air from the system via the purging air line (item 11) during a limited time after the cooling phase. Purge air quantity and purging time result from the heat requirement. As a guidance value, about 5 - 12 % purge air quantity for a period of 1 hour. Seen from the point of view of the overall cycle, this loss is on average smaller than or equal to 2 %.

The exhaust valve (item 6) closes and the pressure build-up phase follows. Blower and heater are protected from pressure bursts through a non-return valve (item 10). The drying installation remains ready for immediate use right up to the switch-over.

After the switch-over, the exhaust valve (item 5) is opened and the regenerated vessel depressurised to atmospheric pressure via a silencer (item 4) fitted at the outlet. Following this, the exhaust valve (item 6) opens and the regeneration process starts again for the adsorber previously loaded.

In the course of regeneration or activation, the adsorbent material is exposed to considerably higher mechanical and physical stress than during adsorption.

Economically optimum operation is achieved with externally regenerated adsorption dryers, when correct setting leads to the following conditions of regeneration :

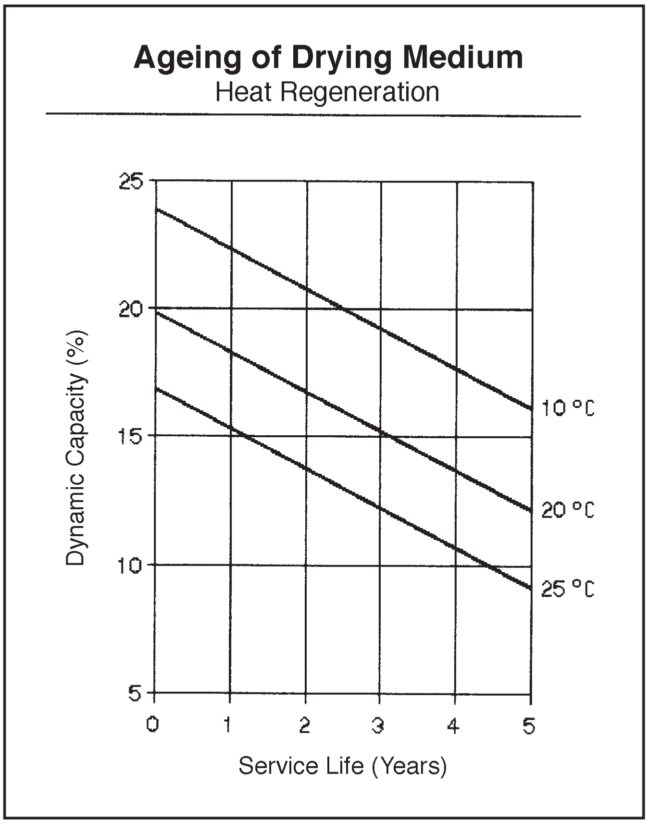

Diagram 5.4.3.3

Maximum exploitation of the loading capacity of the adsorbent material with humidity through dewpoint monitoring. The energy consumption for individual regenerations is lowered as the frequency of regeneration is reduced and pore blockage can be avoided.

Regenerating countercurrent to the direction of adsorption. The water to be desorbed from the charged inlet layer is not carried right through the bed. The water fronts run out, in the opposite direction to the regeneration gas, downward, by gravity. This causes this water front to impinge onto charged silica gel only.

Regeneration velocity of at least 0.08 m/s. With this linear speed, an even distribution of air can be achieved even inside large adsorbent beds, thus largely eliminating undesired recondensation within the adsorbent bed.

Cooling the adsorption material after completed desorption, in order to avoid a temperature shock with correspondingly higher moisture content in the compressed air which is given off at the beginning of adsorption.

5.4.4 Control system

For externally heat regenerated adsorption dryers, load depending controllers consisting of a PLC coupled to a dewpoint measuring instrument, always makes sense. Modern programmable logic controllers, linked to a moisture measuring instrument, are capable of detecting changing operating conditions, to evaluate these and to process these in the form of reliable signals.

Every period of partial loading only of the adsorption dryer is converted into an elongated adsorption period at constant regeneration time. It is the difference between variable adsorption period and constant regeneration period which leads to the saving in regeneration energy. Beyond this, limiting parameters within the dryer are utilised for :

- Heating temperature
- Blower running time
- Main valve functioning
- Exhaust valve functioning
- Pressure build-up
- Pressure dewpoint.

5.4.5 Utilisation benefits and conditions

With their external and autonomous regeneration equipment, these dryers are independent of compressor operation.

Widely differing regeneration energy sources as heat carriers result in a flexible, economical utilisation also in explosion proof areas.

Pressure dew points down to -55°C can reliably be achieved with continuous running.

Expansion during switch-over and the pressure release made necessary by this, occurs only once within the hour cycle and can be made to take place in a delayed manner, thus achieving reduced values of the noise emission level.

The regeneration and cooling air can be polluted by solids, in cases of installation in dust generating branches of industry, and this may influence not only the adsorber but also its adsorbing material.

Increasing differential pressure inside the adsorber impairs the flow of regeneration air, resulting in a proportionally longer heating time.

High inlet temperatures accompanied by low operating pressure reduce the capacity of the drying medium considerably, at the same time increasing the heat of reaction up to the lower range of regeneration temperatures, so that reliable adsorption is no longer assured throughout the entire time.

Externally heat regenerated adsorption dryers are used

- in capacity ranges of up to 15 000 m^3/h
- as special design installations up to 50 000 m^3/h and more
- for pressure dewpoints down to -55°C
- in the medium pressure ranges
- with medium inlet temperatures

5.5 Vacuum regeneration

Vacuum regeneration forms the logical further development from blower regeneration. The material difference arises from the fact that the required quantity of regeneration air is no longer provided by means of a pressurising blower but by using a suction pump. In order to satisfy the demand for higher reliability at constant compressed air and dewpoint quality, while avoiding the waste of compressed air as purge air, the new dryer standard for externally vacuum regenerated adsorption dryers was created.

5.5.1 Layout

Externally heat regenerated adsorption dryers operating according to the vacuum principle are laid out in the opposite manner to those with blower regeneration, from the process technological point of view. Fig. 5.5.1.1 shows the layout principle, with two adsorbers including interconnecting piping at the inlet and outlet, as well as valves for switching over between adsorption and regeneration. Furthermore, there is the regeneration system, consisting of vacuum pump and heater. When comparing this with the external layout of adsorption dryers with pressure generating blowers, two essential differences can be seen :

The external heater (item 9) on the regeneration air suction side in the atmospheric pressure zone, The vacuum pump (item 8) linked to the air outlet side by means of a flexible heat resisting tube.

With these adsorption dryers, drying takes place at operating pressure in the advantageous direction of flow from bottom to top. Regeneration, however, flows in this case in the same direction using drawn-in ambient air heated in the vacuum zone.

The vacuum regenerated adsorption dryer is designed for pressure dewpoints down to -25°C. For this type of dryer, too, the rule concerning dwell times in order to reach the pressure dewpoints reliably, applies. Vacuum regeneration is capable of reaching pressure dewpoints down to about -70°C in continuous operation.

Quantities of purge air from the system are not needed for this process. This is the materially important and ultimately also decisive advantage of vacuum regeneration.

With vacuum regenerated adsorption dryers, the heat resisting drying medium silica gel forms the uniform filling material right through. This water resisting drying material is suitable for inlet temperatures up to maximum 45°C and pressure dew points down to approximately -55°C. Molecular sieves, on the other hand, are utilised when the very lowest pressure dewpoints have to be achieved.

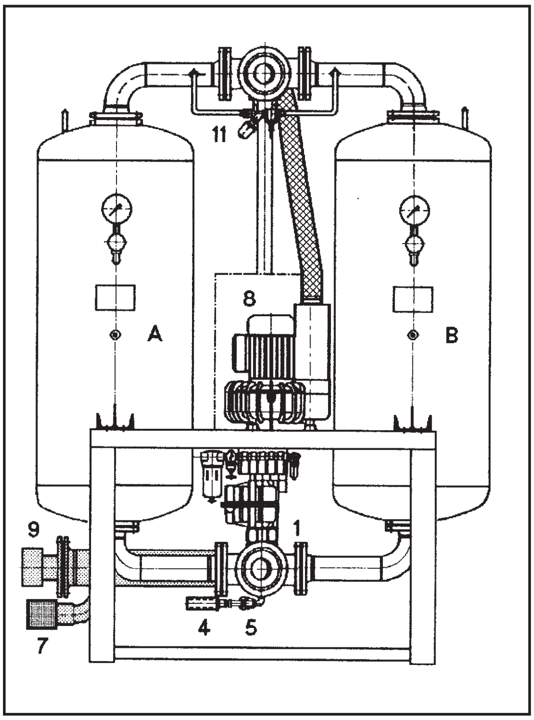

Fig. 5.5.1.1

Programmable logic controllers are used in line with the present-day state of the art. Such a controller, in combination with a dewpoint measuring instrument, brings about optimum adaptation to changing operating conditions.

For reasons of energy saving, it is expedient to insulate the adsorber with mineral or slag wool, also as contact protection. Adsorption dryers of this type are constructed up to capacities of 50 000 m^3/h and more. For smaller capacities, the complete system is manufactured as a compact unit.

5.5.2 Adsorption

The adsorption process with vacuum regenerated adsorption dryers is, in principle, identical to the methods previously explained in conjunction with heat regenerated adsorption, and is thus sketched here only by means of key terms.

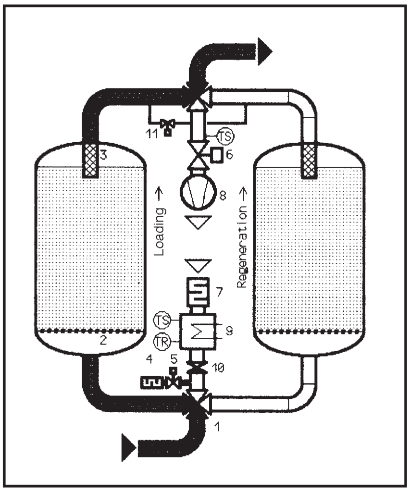

Fig. 5.5.2.1

With vacuum regenerated adsorption dryers, the dynamic capacity of the drying medium is utilised up to 18 - 20 %, making use of the internal and external surface.

Adsorption takes place with the direction of flow from bottom to top. The mass transfer zone migrates with increasing saturation from the inlet to the outlet of the adsorber. When the break-through point is reached, the system switches over to regeneration.

The time cycles are dictated by economic considerations leading to adsorption and regeneration periods of 4 - 6 hours.

With vacuum regenerated adsorption dryers, the temperature increase through heat of adsorption in the drying medium bed brings about an outlet temperature of the compressed air which, under normal operating conditions, is 12 - 20°C higher than approach temperature.

5.5.3 Regeneration

It is with regard to regeneration that the vacuum method pursues an entirely new path. The pump, designed for vacuum operation, sucks ambient air into the adsorber. There, the desorption process takes place. The air, enriched by moisture, is ultimately discharged via the vacuum pump.

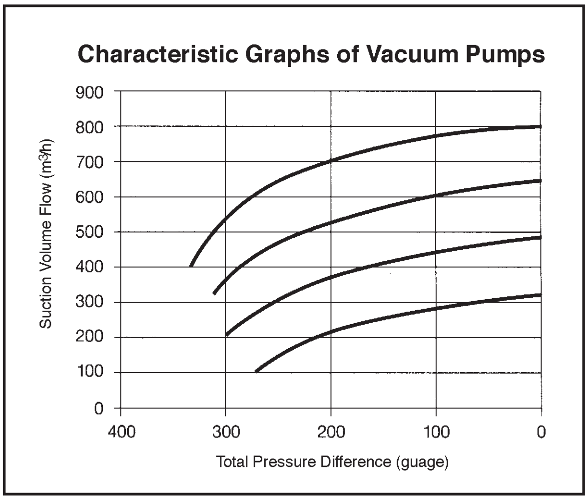

Diagram 5.5.3.1

The suction effect causes lower than atmospheric pressure in the adsorber. The degree of vacuum depends on the pressure gradient, right through the adsorber, of the quantity of air drawn through the adsorber. The level of vacuum is also determined by the adsorber geometry. The vacuum amounts to about 0.08 - 0.1 bar. From this difference, in contrast to the pressurising blower with about 1.1 bar absolute, arise the theoretically effective advantages of vacuum regeneration through

- less humidity entering the adsorber from the surrounding air
- a lower desorption final temperature.

However, in the course of desorption, the vacuum pump is located in the hot air zone. The vacuum pump must be designed to cope with this extreme temperature situation.

After desorption is completed, the heating is switched off via a thermostat. Immediately afterwards, ambient air flowing in the same direction is used to cool the adsorber. Cooling is automatically terminated by the low point contact of the thermostat. There is no need to purge with dry compressed air, as the process conditioned pre-loading of the adsorber with ambient moisture affects the wet zone only.

When desorbing in the same direction of flow as when adsorbing, the drying medium is exposed to the highest temperature levels on the inlet side of the adsorber. A temperature adequate for desorption must be achieved particularly in this zone, as it is this which determines the dryness of the compressed air at the adsorber outlet. This causes the heating period to be theoretically longer than when desorption takes place on the countercurrent principle.

The moisture evaporated by the heated regeneration air current is carried right through the entire bed of drying medium. As the drying medium at the adsorber outlet is not loaded up right to full saturation during the adsorption phase, double adsorption takes place here when the humidity loaded desorption air passes through.

A gain in additional heat through the vacuum pump does not take place when desorbing in the vacuum range. Through the longer heating time and through double adsorption, up to 20 - 25 % additional heating energy is required as compared with desorption by countercurrent. However, this additional expenditure in heat energy is just about compensated by the system conditioned advantages of the vacuum principle, such as:

At a regeneration pressure of below 1 bar absolute and with a constant quantity of regeneration air, working within the vacuum range means that the process calls for a lower regeneration temperature.

Cooling is more advantageous from an energy view point through a lower temperature rise with vacuum operation.

The drawn in quantity of moisture from the surrounding air is lower with vacuum operation and diminishes the amount of humidity per cycle.

The drawn in humid surrounding air loads up the moist entry side of the adsorber during regeneration and not the dry layer at the outlet.

During the entire desorption process, no compressed air whatsoever is required to be taken from the system. The volume flow at the outlet equals the volume flow at the inlet to the dryer.

5.5.4 Optimisation

Consideration of blower and vacuum regeneration, from the process technological and energy requirement point of view, leads to the following result from which conclusions can be drawn :

Vacuum regenerated adsorption dryers in which desorption takes place by countercurrent and associated cooling in the main direction of flow, represent the optimum achievable with present day technology as far as adsorptive drying is concerned. As the flow paths of the regeneration air are reversed for cooling after desorption, a more sophisticated electrical and mechanical control effort is called for. However, the higher investment costs resulting from this are amortised by the more favourable operating costs. In practice, this type of system can achieve pressure dewpoints down to -110°C.

5.5.5 Pressure build-up

After cooling is completed, the exhaust valve (item 6) closes and the holding period follows with subsequent pressure build-up phase. The vacuum pump and the heater are protected by a non-return valve (item 10). Right up to switch over, the drying installation remains in standby mode. After switch over, the exhaust valve (item 5) with the attached silencer (item 4) is opened and the regenerated vessel depressurised down to atmospheric pressure. After this, the blocking flap opens and the regeneration process starts again with changed over adsorbers.

5.5.6 Control

Vacuum regeneration adsorption dryers with a programmable logic controller linked to a dewpoint measuring instrument with a view to load dependent control represent the present day standard version. The possibilities offered by this type of control system have been described in detail in section 5.4.4.

Dryer internal limiting values are utilised for :

- Inlet temperature
- Heating temperature
- Vacuum pump
- Function of main valve
- Function of exhaust valve
- Pressure build-up
- Pressure dewpoint

Signals in addition to the above can be arranged by simple means.

5.5.7 Applications

The external regeneration design makes these dryers independent of compressor operation and in addition, the variable regeneration energy quantities as heat carrier result in flexible economical application possibilities, also in explosion proof areas.

The dewpoint peak after switch over from regeneration to adsorption is so low that it can be neglected.

The same pressure dewpoints using less energy, respectively lower pressure dewpoints for the same expenditure of energy, can be achieved under favourable conditions through the lower residual load on the drying medium. Purge air consisting of already treated compressed air becomes unnecessary, and pressure dewpoints down to -70°C are reached with continuous operation.

There is no heat gain with vacuum regeneration and this has a favourable effect on cooling. However, during desorption, there is also no additional heat.

When the dryer is installed in damp or high temperature conditions, then special care must be taken to ensure that the vacuum pump is working within its design parameters and is not affected by the conditions.

The rise of the pressure gradient in the adsorber reduces the quantity of regeneration air, so that inadequate pump performance extends the heating period in proportion.

Regeneration and cooling air, as well as high inlet temperatures accompanied by low operating pressure, have a considerable negative influence on dryer design.

5.5.8 Utilisation

Vacuum regenerated adsorption dryers are used

- in capacity ranges up to about 15 000 m³/h
- using special designs in installations up to about 50 000 m³/h
- and beyond
- for pressure dewpoints down to -70°C
- using special designs for pressure dew points down to -110°C
- in the medium pressure range
- for medium inlet temperatures.

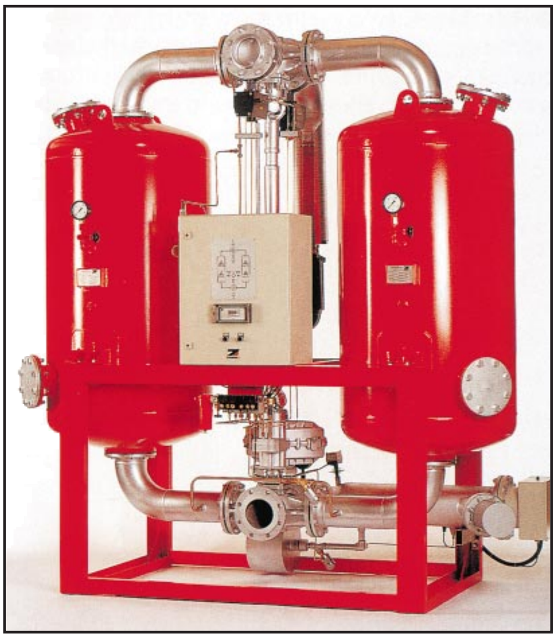

Photo 5.5.8.1

5.6 Heat of compression

Adsorption dryers with heat regeneration in closed loop versions are based on physical processes operating when air is being compressed. The compressed gas is heated, thus utilising the energy fed externally to the compressor in the form of work by converting it into heat for the benefit of the dryer system.

The quantity of energy required for compressing the air is low, if the temperature is kept constant while the pressure is being increased. However, in order to achieve this, compression must be cooled to such an extent that the added energy is immediately conducted away. This would mean achievement of the isothermal state and would represent the ideal compression process. If, however, the change of state of the gas to be compressed in the compression chamber takes place adiabatically, then heat is neither fed into nor withdrawn from the compression process. The entire added energy is utilised for increasing the inner energy.

As it is hardly possible in practice to withdraw at once the entire heat generated or to create a heat insulated compression chamber, compression in reality usually takes place between these two changes of state, i.e. polytropically. The following is valid for establishing the external energy used for polytropic compression :

$$\boxed{L_{pol} = 10000 \frac{n}{n-1} p_a \left[\left(\frac{p_e}{p_a} \right)^{\frac{n-1}{n}} - 1 \right]}$$

Formula 5.6.1

Herewith, analogously, the establishment of the final temperature of compression:

$$\boxed{\frac{T_e}{T_a} = \left(\frac{p_e}{p_a} \right)^{\frac{n-1}{n}}}$$

Formula 5.6.2

In the case of one-stage compression up to about p = 3 bar, temperatures of up to tult = 135°C are reached.

With two-stage compression, however, the compressor outlet temperature would amount to 140 - 180°C. This heat energy is utilised in a targeted manner when adsorption dryers of the closed circuit type are used, as these use the compressor heat for purposes of regeneration.

In conjunction with heat of compression dryer systems, solely oil free compressors are permissible. This decisive aspect must always be observed as a point of principle !

Oil free compressing systems are needed, inter alia, in the food and luxury consumables industry, in paper factories and printing works, in chemical or also pharmaceutical enterprises.

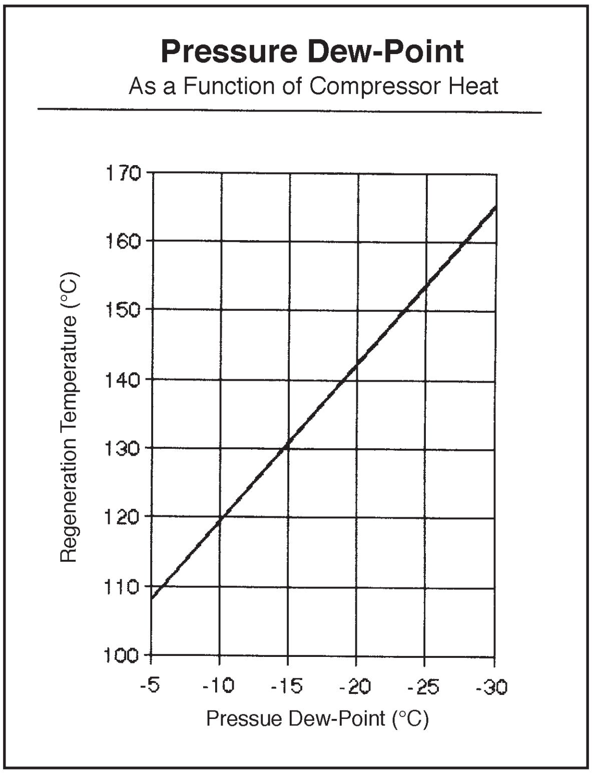

Diagram 5.6.1

The argument in favour of this dryer system states that no energy for desorption has to be provided, as this is available free of cost from the compressor system in the form of the heat generated by compression and available for desorption. The adsorption dryer of the closed loop type always depends on the compressor. Dryer and compressor form one combined unit.

Differing parameters are in an interactive relationship. The pressure dewpoint, normally a parameter independent of the compressor is, with this adsorption dryer system, dependent on the compression temperature of the compressor.

5.6.1 Layout

Adsorption dryers of the closed loop design, Fig. 5.6.1.1, require two adsorbers for continuous operation. The vessels are interconnected by piping with, in each case, independent 4/2-way valves (item 1 and item 4), being the main valves for switch over from adsorption to regeneration.

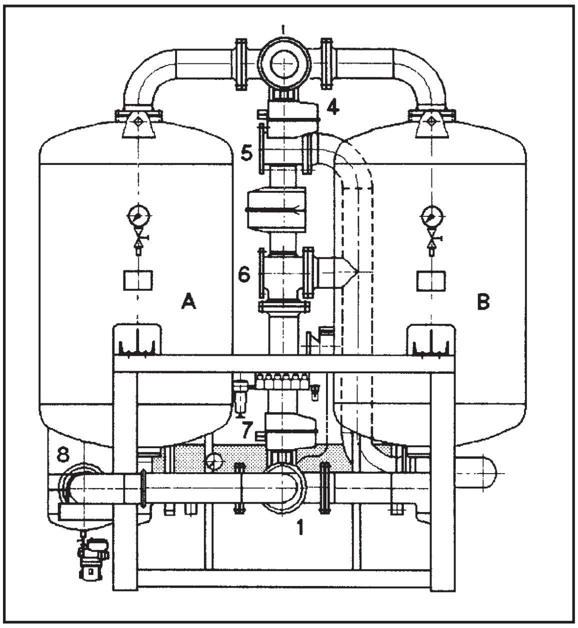

Fig. 5.6.1.1

In addition, two 3/2-way valves (item 5 and item 6) are integrated into the piping system, being linked via a shaft. The additional water cooled heat exchanger (item 7) with attached cyclone separator (item 8) is typical for this system.

The link to the compressor is formed by two alternative connections fulfiling correspondingly different tasks. In order to dry compressed air, low temperatures are needed. In order to regenerate drying media, however, high temperatures are required. For this reason, the dryer possesses one connector each, for hot and cold compressed air.

An entirely new aspect is caused by the technology of the process. Adsorption and regeneration take place under operating pressure. For this reason, components such as exhaust valve, relief valve, regeneration air line and silencer, needed for other drying systems, are not required. This leads to a layout of captivating simplicity and clarity.

A further material difference, as compared with the adsorption dryer systems shown previously, can be seen from Fig. 5.6.1.2. Loading up and regeneration take place in countercurrent as before with the associated cooling operation, however, in the main direction of flow.

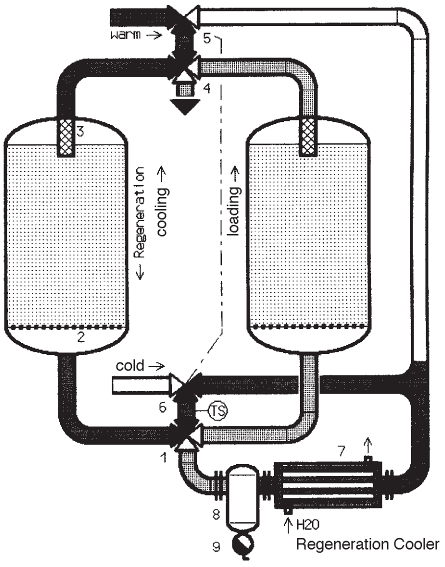

Fig. 5.6.1.2

It is known from process technology that the required regeneration temperature depends on the dewpoint of the regeneration gas. The drier the gas used for regeneration, the lower the regeneration temperature which can expediently be used. With a dryer of closed loop design, the regeneration gas is relatively humid as compared with that in other drying systems. For this reason, closed loop systems always require a higher regeneration temperature in order to reach a specified pressure dewpoint, than is necessary with other designs of dryer.

It is, therefore, barely possible to achieve pressure dewpoints below -30°C, even with continuously running operation. Lower pressure dewpoints call for an additional heater system. The interrelation between pressure dewpoint and compressor temperature is shown in diagram 5.6.1.

5.6.2 Function

The adsorption dryer of closed loop design forms a complex system in conjunction with the compressor. In this, the adsorber vessels are subjected to flow from inlet to outlet of the adsorption dryer, one after the other and also in parallel, while the functions called for by the process are fulfiled in sequence :

Desorption/adsorption
Cooling/adsorption
Adsorption

In order to give a clear explanation of the individual functions of the adsorption dryer of closed loop design, it is necessary to describe dryer and compressor as forming one unit.

The principle of full flow regeneration forms the basis of this description. The principle of full flow regeneration ensures a short desorption period and problems of part-flow regeneration3 under conditions of part load are thus avoided in principle. Working on the basis of full flow regeneration causes :

Adsorption with full flow
Desorption with part-flow
Cooling with part-flow

Adsorption with full flow
Desorption with full flow
Cooling with part-flow

Figs. 5.6.2.1 to 5.6.2.3 illustrate the explanation and also help the understanding for adsorption and desorption as well as cooling in closed loop adsorption dryer systems.

Pipe lines link the oil free compressor and the adsorption dryer to form one unit. After the last compression stage and before the principal cooler of the compressor, it is necessary to fit a 3/2-way valve (item C).

This provides two alternative paths from compressor to dryer. Firstly the hot air connection for desorption and secondly the cold air connection via the principal cooler of the compressor, with the cyclone separator (item A) for adsorption and cooling of the compressor fitted downstream.

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[3] artificial pressure gradient for regeneration gas mixture

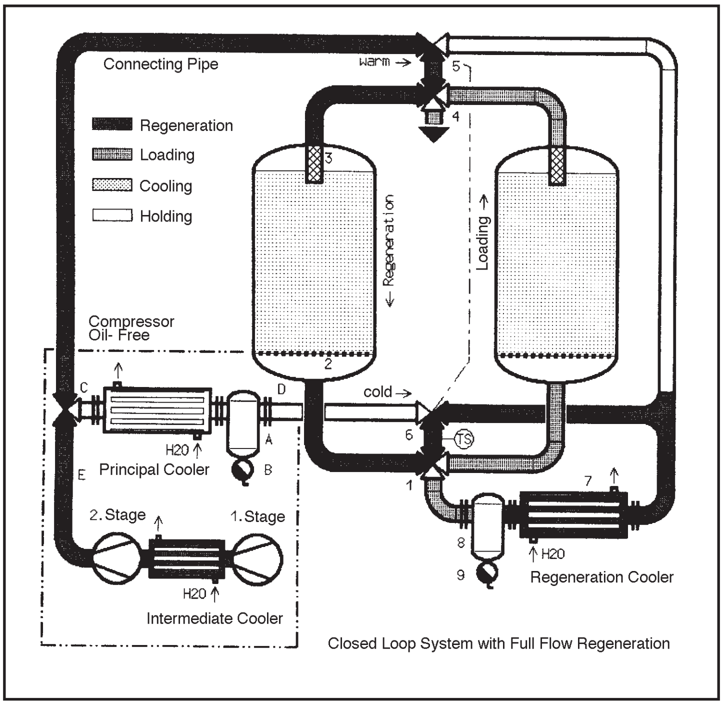

Fig. 5.6.2.1

The hot and cold air connections are each ducted to a 3/2-way valve and linked to each other via a hinged shaft complete with pneumatic rotary drive, so that only one connection is open at any one time. This provides simple and reliable switching of the dryer.

Fig. 5.6.2.1 shows an opened hot air inlet and a cold air inlet, closed, in the opposite direction. Compressed air heated by compression flows via the valves (item 5 and item 4) from top to bottom under operating pressure and uncooled in the direction of gravity through the adsorber already saturated with moisture, thus warming up the latter. If the heat of compression of the air fails to reach the required regeneration temperature, the required level can be achieved by means of an additional heater.

When dimensioning the adsorber, the change of volume through regeneration temperature has to be taken into account. The humidity stored in the adsorber separates from the drying medium and is re-entrained by the quantity of hot unsaturated air.

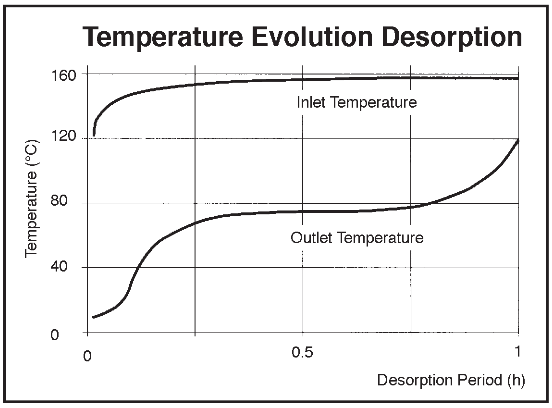

Diagram 5.6.2.1

At the beginning of desorption, when hot regeneration air with a dewpoint of about 60°C impinges upon the still cold drying medium, condensation of the water vapour in the drying medium bed takes place.

It must be possible to regenerate the drying medium adequately by means of regeneration air at temperatures of around 140 - 160°C and with dewpoints around 60 - 70°C. Via valves (item 1 and item 6) of the lower interconnecting piping, the moisture loaded hot compressed air is ducted to the water cooled regeneration cooler (item 7) with the separator (item 8) fitted to its outlet.

The hot compressed air is cooled down to 30 - 35°C within the regeneration cooler and the moisture contained in the compressed air is condensed. The condensed humidity is separated from the compressed air inside the cyclone separator (item 8) and drained off.

At the outlet of the water cooled after cooler, the compressed air is always 100% saturated with respect to a temperature which lies about 10°C above that of the cooling water. Given a cooling water temperature of around 20 - 25°C, the outlet temperature will then amount to around 30 - 35°C.

Cooled but moisture saturated compressed air is now ducted from bottom to top through the valve (item 1) to the second adsorber. Here the compressed air is dried to the dewpoint governed by the regeneration temperature. The dried air reaches the compressed air network via another valve (item 4).

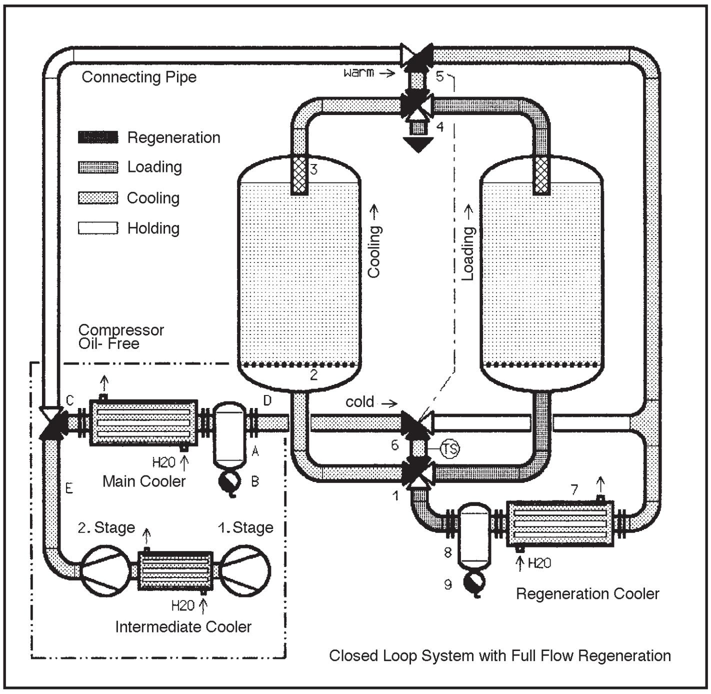

Fig. 5.6.2.2

When the regeneration temperature is reached, the hot air connection (item 5) is closed and the cold air connection (item 6) opened simultaneously. The signal for the switch over is emitted by the temperature switch (TS) and is also directed at the same time to the 3/2-way valve (item C) between compressor and main cooler.

Valve setting is made clear by Fig. 5.6.2.2. The full quantity of compressed air now flows via the main cooler of the compressor and 100% saturated, while at a temperature of about 30 - 35°C, through the lower 3/2-way valve (item 6) and the 4/2-way valve (item 1) into the previously heated adsorber.

The cooled compressed air takes up the heat contained in the heated adsorber and ducts this heat, in the same direction of flow, towards adsorption via the upper 4/2-way valve (item 4) and subsequent 3/2-way valve (item 5) to the installation's regeneration cooler (item 7). In the course of the decrease in temperature within this cooler, the re-entrained humidity is separated from the compressed air and discharged via the drain.

The dehydrated compressed air reaches the adsorber for adsorption via the lower valve combination (item 1 and item 6), in order to pass out of the installation fully dried via the upper 4/2-way valve (item 4), as already described.

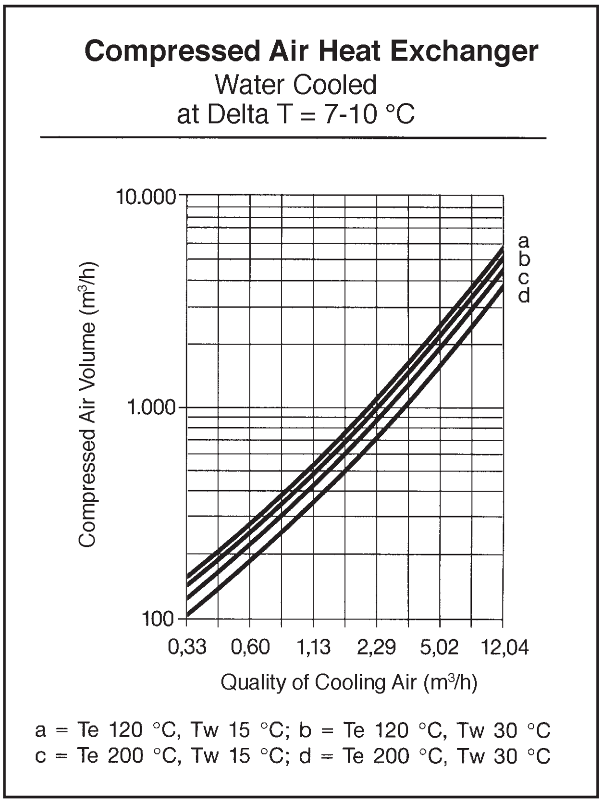

Diagram 5.6.2.2

Contrary to the desorption time period, cooling time is a fixed quantity. The actuation of the lower 4/2-way valve (item 1) is signalled and switched in line with the calculated time period. Valve setting is shown in Fig. 5.6.2.3.

The cold air arriving from the compressor is ducted direct into the adsorber for adsorption via the lower valve combination. This valve position is maintained right up to the end of the drying period.

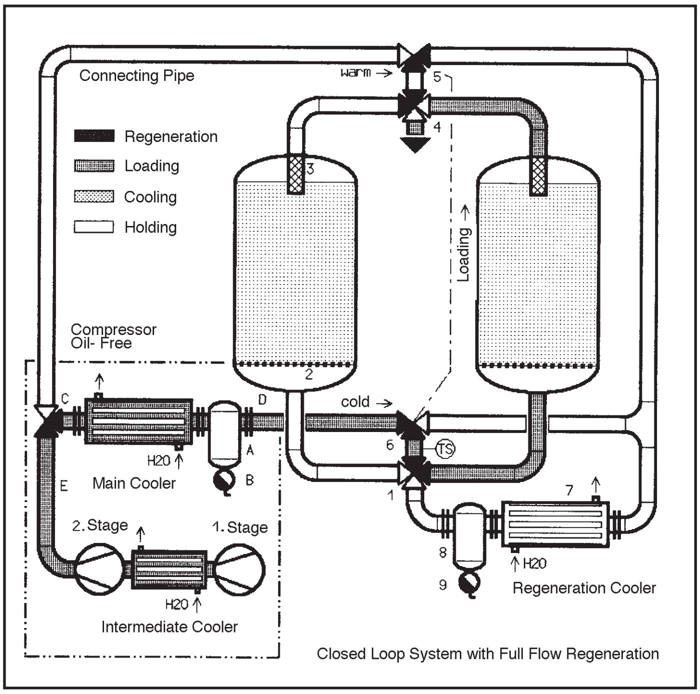

Fig. 5.6.2.3

After adsorption, the other 4/2-way valve (item 4) is rotated by 90° at the same time as the coupled 3/2-way valve (item 5 and item 6) and the entire sequence now starts with the sides reversed taking the process steps previously described.

5.6.3 Special features

With closed loop adsorption dryer systems, operating in accordance with the total output flow principle previously described, the following special features must always be taken into consideration :

Only drying media which is 100% waterproof can be utilised in an adsorber with a loading factor of 12 - 14 %.

Ducting the compressed air through the entire system. Two adsorbers, many valves, coolers, separators and costly piping arrangements result in a pressure drop far exceeding the corresponding values with other dryer systems.

The condensate4, fed into the compressed air system from oil free compression, develops strongly acidic characteristics down to a ph-value of 4.

Assuming an operating pressure of 7 bar absolute at the inlet to the dryer, the following pressure losses are to be expected in practice :

Closed loop	adsorption dryers	up to 0. 6 bar
Other	adsorption dryers	up to 0.15 bar

When comparing the systems, the user of an installation, making his final analysis, attaches importance to which operating pressure is available in the end to the compressed air network after treatment and for productive purposes. Practical experience suggests that the following comparison of pressure losses realistically describes the situation :

With closed loop systems pa = 7 - 0.60 = 6.40 bar abs.
With other systems pa = 7 - 0.15 = 6.85 bar abs.

Expressed differently: If the supply pressure available to the compressed air network immediately after treatment is reduced from p = 6.85 bar abs. to p = 6.4 bar abs, the appropriate laws (Formula 4.5.2.4) establish a loss of performance from 6.852 to 6.42, i.e. by 14.5 %. This loss has to be compensated for by additional compressor performance.

When regenerating by part-current, work energy is lost through reducing the main air flow. Looked at dispassionately, energy costs are, therefore, more or less the same for all processes. On the one hand, the heat for desorption is already available, on the other hand, when compressor heat is used for regeneration in adsorption dryers of closed loop design, this advantage has to be paid for by higher pressure losses as compared with other systems.

With oil free compression, internal losses of the compressor stage are higher than with oil injected compression. The sum total from compressor and dryer performance of the differing systems is, therefore, just about the same. If different results are reported, these are based on marketing considerations without taking into account the fact that compressor plus adsorption dryer form one unit.

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[4] oil/water emulsions ph-value = 7

5.6.4 Control system

Closed loop dryer systems require consoles with one control component only. Output regulators are unnecessary. A programmable logic controller linked to a dewpoint measuring instrument for load dependent control is useful for adaptation to differing states of loading.

The possibilities of such a control system are described in detail in section 5.4.4. Dryer internal limiting values are utilised for :

- Cooling water temperature
- Operating pressure
- Inlet temperature
- Heating temperature
- Functioning of the fittings
- Pressure dewpoint

5.6.5 Applications

Resulting from regeneration by means of compressor heat, these dryers are under the influence of compressor operation. Utilisation in explosion proof zones presents no problem and can be arranged on the basis of simple modifications. Pressure change and release to atmosphere are not necessary, thus avoiding disturbing noise levels.

The closed loop system pollutes the surrounding air neither with cold, wet nor with hot regeneration air. High inlet temperatures accompanied by low operating pressure exert a strong influence on the design of the dryers.

5.6.6 Utilisation

Adsorption dryers of closed loop design are preferentially used

Only in conjunction with oil free compressors
In performance ranges of up to 5 000 m^3/h
In special design installations up to 20 000 m^3/h and above
For pressure dewpoints down to -30°C without additional heating
In the medium pressure ranges
For medium inlet temperatures
For drying a wide variety of gases

Part 6

6.0 Drying media

Present-day technology utilises various processes which contribute towards compressed air purity. One of these processes is the application of adsorption technology using adsorption media. By adsorption media, one understands substances with a widely open pore structure and, a large internal surface. Examples of adsorption media are aluminium oxide (activated alumina), silica gel, molecular sieve and activated charcoal.

This section deals with the adsorption of gases and vapours through solid adsorbents to form adsorbates. It does not deal with adsorption in the liquid phase.

Adsorption makes use of the characteristics of porous solids, endowed with large surfaces, in order to separate low concentrations of vapour selectively from a mixture of gases. The adsorption process with porous adsorbents possessing extended internal surfaces is made up from three kinetic part processes :

- Transfer of matter in the boundary layer
- Diffusion of the substance to be adsorbed in the pore system
- Sorption at the internal surface of the adsorber

Physical adsorption on the surface of solid adsorption media is, to an extent, accompanied by other processes. For this reason, adsorption is regarded as a general sorption process.

Within the micropores of the adsorption medium, capillary condensation of the vapours takes place at higher pressures, or the component to be separated is diffused within the solid material. Chemical adsorption, as a chemical reaction between gaseous components and the solid substance, is also possible. Physical adsorption and chemical adsorption differ in their accompanying heat phenomena.

Adsorption makes possible the total separation of low concentrations of vapours from gaseous mixtures. In cases of high concentration of the matter to be adsorbed, this separation process is often uneconomical, as high concentrations of the substance to be adsorbed call for a high proportion of adsorption medium in relation to the quantity of gas, or frequent regeneration of the loaded up adsorption medium.

Adsorption heat causes an increase in temperature of about 10 - 20°C in adsorbers, however, no cooling is necessary with adsorption, as temperature dependence of the sorptive quantities picked up is relatively small.

Physical and chemical properties of drying media

Characteristics	Aluminium Oxide	Silica Gel	Molecular Sieve	Activated Charcoal
Bead Size mm	2-9	2-8	1-6	1-6
Porosity %	50-60	50-65	45-60	52-75
Specific Surface m^2/g	100-400	300-800	500-900	100-1500
Pore Volume ml/g	0,3-0,5	0,4-1,0	0,5-1,1	0,5-1,6
Pore Size Ä	15-100	21-100	4-15	10-250
Specific Heat kcal/kg°C	0,21-0,25	0,22-0,25	0,19-0,31	0,19
Heaped Volume kg/m^3	600-900	450-800	600-900	200-500
Static Activity kg/kg	0,2-0,3	0,2-0,4	0,3-0,5	0,5-0,9
Adsorption Temperature °C	0-30	5-40	5-50	5-55
Regeneration Temperature °C	170-320	140-250	190-320	110-180
Ignition Temperature °C	**non combustible**			250-400

Table 6.0.1

Table 6.0.1 shows the characteristics of the most important adsorbents in technical use. The high specific surface of adsorption media is of paramount significance. Gas velocity inside adsorbers is in the range of 0.1 - 0.6 m/s. Aluminium oxide, silica gel, molecular sieve and activated charcoal differ in their fields of technical application. Their micropore diameters are in the region of 4 - 250 nm.

Aluminium oxide, silica gel and molecular sieve are particularly suitable for the adsorption of polar compounds, in particular for drying air and gases. The fields of application of activated charcoal encompass purification and the removal or attenuation of odours from air and gases.

In recent years, molecular sieves have found increasing application. These natural or artificial zeolites are crystalline alkali or earth-alkali aluminosilicates. SiO_4 and AlO_4 tetrahydrons form a cubo-octahydron if alternatively arranged as a complex structural component. These cubo-octahydron network three-dimensionally to form a multiplicity of possible zeolite structures. This causes well defined and evenly formed systems of voids (micropores) linked by canals. These can act as physical sieves towards molecules depending on the geometrical dimensions of the latter.

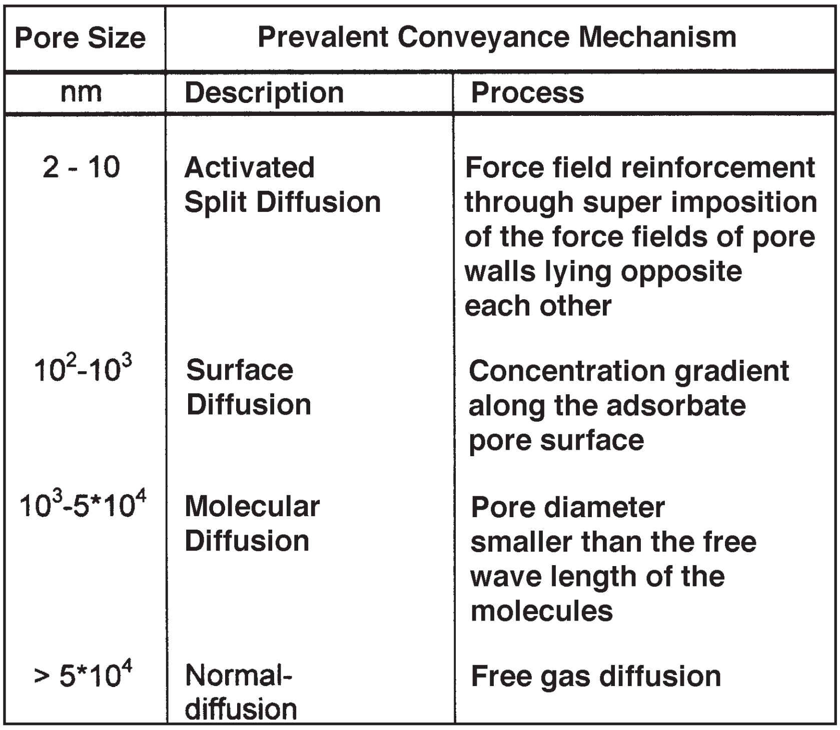
At the same time, there are interaction effects between molecules and heteropolar internal void surfaces, with adsorptive effect. The hollow cross-section of the type dependent highly uniform and constant microchannels lies in the range of 0.3 - 1 nm (kinetic pore diameter). They make possible the separation of mixtures in accordance with the molecular dimensions, e.g. with branched or unbranched hydrocarbons. In addition, zeolites adsorb polar substances such as water, so that they can be used for the intensive drying of gases.

Apart from adsorption at atmospheric pressure, there is the possibility of pressure adsorption under pressurised conditions, as this increases the partial pressure of the adsorbate and thus the equilibrium load of the adsorbent.

If adsorption under pressure is followed by desorption at low pressure, e.g. atmospheric or vacuum, a fractionated (insulating through vapourisation) desorption of the constituents takes place upon depressurisation and this can be used for separating individual components. Within the pore system of the adsorbent particles, the conveyance of matter takes place in accordance with various mechanisms. The large pores act as access pores and the smaller ones as adsorption pores.

Table 6.0.2 gives a survey of the types of diffusion prevalent in adsorptive pores.

Mechanisms which convey matter



Pore Size	Prevalent Conveyance Mechanism	
nm	Description	Process
2 - 10	Activated Split Diffusion	Force field reinforcement through super imposition of the force fields of pore walls lying opposite each other
10^2-10^3	Surface Diffusion	Concentration gradient along the adsorbate pore surface
10^3-$5*10^4$	Molecular Diffusion	Pore diameter smaller than the free wave length of the molecules
> $5*10^4$	Normal-diffusion	Free gas diffusion

Table 6.0.2

Multilayer adsorption in larger pores is accompanied by capillary condensation in the micropores. The latter takes place particularly in adsorbents with a high constituent of mesopores in the pore radius range 1 - 50 µm. Apart from the conveyance of matter through diffusion, liquid is displaced by capillary action.

The conveyance of matter through adsorption takes place as a transition phase of matter, i.e. the substance to be adsorbed is diffused to the solid matter surface (phase boundary) from the flowing gas phase through the boundary layer.

The adsorption speed of matter transition varies within wide limits depending on the nature of the system, and may last from fractions of a second to a duration of hours up to the onset of adsorption equilibrium. Temperature, pressure, molecular mass of the substance to the adsorbed and porosity of the adsorbent, influence the speed of matter transition. The capillary structure of the adsorption medium delays the onset of the equilibrium state.

Speed of adsorption is influenced by :

- Flow conditions within the adsorber
- Matter displacement of the fluid phase to the adsorber surface
- Pore diffusion of the adsorbed substance within the adsorbent
- Speed of adsorbate formation
- Surface migration of the substance to be adsorbed in the adsorbing layer

The activity of the adsorbent and the time of adsorption determine the technical sequence of adsorption and characterise the adsorbing effort in completing the separating task. The activity of the adsorbing medium indicates the adsorbing capacity as quantity of substance adsorbed per unit of mass of the adsorbent, i.e. the activity equals the adsorbent loading. One has to distinguish between the static activity and the dynamic activity.

Static activity presupposes the setting in of a complete equilibrium state between the content in the raw gas of substance to be adsorbed and the loading of the adsorbing medium with this substance and counts as a characteristic of the selective qualities of the adsorbent. Static activity diminishes with rising temperature. The number of adsorption/desorption cycles in service also influences the static activity. Equilibrium loading and adsorption speed are lowered due to ageing of the adsorbent.

Dynamic activity is represented by the adsorption behaviour towards the gases in a state of flow. The displacement of matter inside the adsorbent pores in the form of surface diffusion within the range of the surface tensions of the adsorbent delays the onset of a state of equilibrium. This results in the rising heat of adsorption through the wave of warmth migrating through the adsorbent layer, the equilibrium state evolves in the direction of diminishing adsorbent loading capacity.

To this, one has to add mixed adsorption, leading to the sorption displacement of already adsorbed components through the more easily adsorbable constituents which make their appearance only later in the higher sorbent layers, thus bringing about a duplex and mutually impeding matter displacement at the phase boundary surface.

For example, elements of water vapour replace already adsorbed components from the adsorbent in hydrophile (hygroscopic) means of adsorption such as silica gel. Combined with only part loading, all these phenomena lead to a diminution of dynamic activity in comparison to static activity.

It is at the entry point of the gas that adsorber layers begin to be saturated with the substance to be adsorbed, in this case moisture. It is there that a dynamic adsorption equilibrium between raw gas and adsorbent being loaded up is established. As time goes on, the equilibrium zone penetrates further into the static adsorber layer. The level of the total layer, within which adsorbent loading decreases from the equilibrium value (maximum valve) to zero load, is called adsorption or also mass transition zone. The higher the velocity of adsorption, the narrower.the adsorption zone.

The adsorption zone travels ahead of the equilibrium zone through the overall adsorbent layer at a specific zone migration velocity. Finally, we arrive at break-through, the emerging gas now contains steadily increasing quantities of the substance to be adsorbed.

This adsorption zone model, so far applied to the adsorption of a single component, is in principle valid also for two, or more component mixed adsorption. In such a case, the component being most weakly adsorbed, forms the basis for the design of the apparatus. In each case, the only weakly adsorbed component travels through the adsorber with the highest velocity of zone migration, for this reason it rushes ahead of the other components, initially meets up with unloaded adsorber layers, and is, therefore, adsorbed to a stronger degree than the mixed adsorption equilibrium because of the absence of a more readily adsorbed component. In the end, the succeeding and more strongly adsorbed components replace excess quantities (partial desorption) of adsorbate, thus establishing the mixed adsorption equilibrium characteristic for the particular mixture.

6.1 Aluminium oxide

Aluminium oxide adsorbs water, organic liquids and gases, without undergoing changes of form or characteristics in the process. Activated aluminium oxide is a particularly strong adsorber of molecules with high polarity. Water possesses such high polarity so that aluminium oxide is suitable as a drying medium.

Aluminium oxide, whether found in nature or artificially produced, is a powdery material and has to be granulated by means of a binding substance.

Starting from aluminium hydroxide $Al(OH)_3$, a transition clay is first obtained through partial dehydration. This is formed, provided certain conditions are observed, through calcination in the temperature range 200 - 800°C. These transition clays find particularly frequent use as adsorbents.

Viewed under an electron microscope, highdrargillite crystal $Al(OH)_3$ shows the first surface cracks and fissures at temperatures of.200 - 300°C. Through longer exposure or correspondingly higher temperatures, these become larger, leading to the formation of porous structures and more or less disturbed crystal grids as well as high surface activities. These are all the more considerable, the higher the percentage of X-ray amorphous phases and imperfectly developed crystal phases.

Aluminium oxide as a drying medium displays very good chemical resistance, resists liquid water and displays a high load capacity per grain. However, it has minor catalytical effects which are often undesirable.

The internal surface of activated aluminium oxide lies in the range of 100 - 400 m^2/g. At low degrees of humidity, the drying effect is limited.

The regeneration temperature lies between about 170 - 320°C. When reactivating aluminium oxide, one should ensure that the gas used for regeneration is relatively dry, as high temperatures and an increased water content are particularly inclined to inflict hydrothermal damage upon activated aluminium oxide.

6.2 Silica gel

Silicic acid gels belong to the group of substances with high internal surface, i.e. they possess a large number of small and very small pores. In order to be able to form a picture of the type and appearance of these pores, it is necessary to study the chemical production of silica gel.

Dividing the manufacturing process into two phases, the creation of the brine and the conversion of the latter into gel.

The manufacture of silica brines in most cases starts from basic materials such as silicate solutions in water. Sodium silicate is the one most frequently used. If an acid, e.g. sulphuric acid, is added to such a solution, low molecular silicic acid molecules are formed. Orthosilicic acid forms the basic building block.

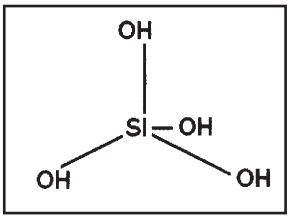


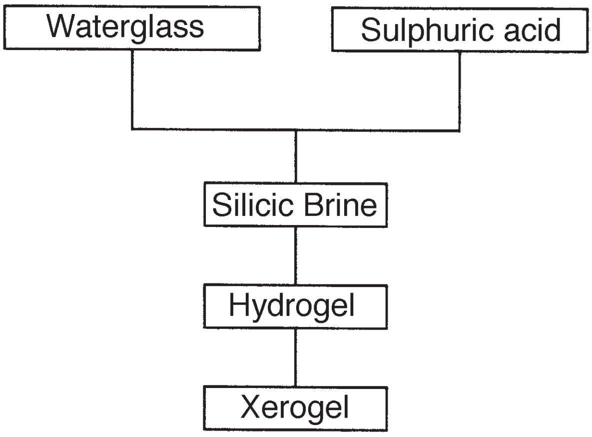
Fig. 6.2.1

OH groups, tetragonally arranged around the silica, are referred to as silanol groups and are highly reactive. If the addition of acid is continued, water is split and chain formation of the silicic acid molecules leads to polycondensation.

The development of.Si-O-Si links to form polysilicic acids leads to the formation of.the smallest particles, possessing about 3 - 50 times the size of the original molecule. In the further course of the reaction, an increasing number of silanol groups are condensed from the polysilicic acids already formed in the brine.

This leads to the creation, accompanied by shedding water and the formation of Si-O-Si links, of molecules which are up to 600 times larger than the particles originally formed in the brine.

This leads to an open but continuous structure, a three dimensional network of randomly orientated chains, ribbons and rings of polysilicic acids. The brine solidifies to become hydrogel, a highly porous solid substance.



After washing out the sodium sulphate formed in the course of the reaction, the syneric (expelled) water is driven out of the pores by subjection to heat. The hydrogel becomes activated silica gel, xerogel.

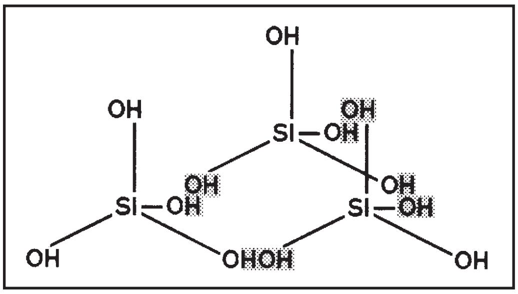


Fig. 6.2.2

This drying operation is controlled in such a way that the silanol groups, which cover the total internal surface, are in principle preserved.

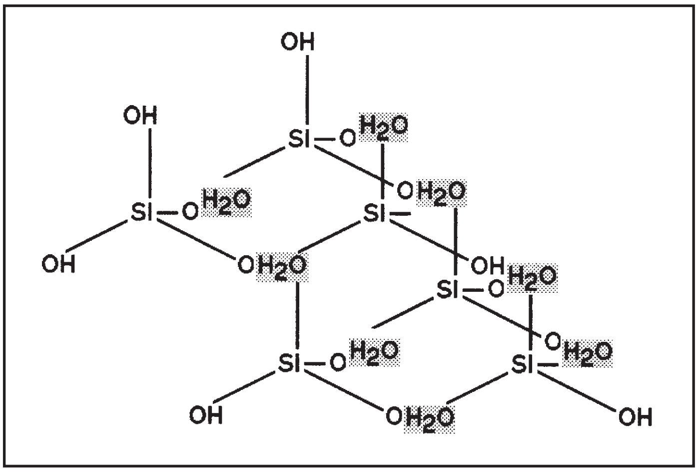


Fig. 6.2.3

They endow the silica gel with its hygroscopic characteristics and also establish the adsorption qualities in conjunction with the capillary system.

6.2.1 Mode of operation

Gas molecules are deposited at the boundary surfaces of a solid body. This process is defined as molecular adsorption on the surfaces of solids.

Depending on the type of link established, one differentiates between chemical and physical adsorption. Chemical adsorption is based on ionic (electrostatic) convalent or co-ordinative links, physical adsorption on Van der Waal's forces.

The adsorption process is represented in the form of an adsorption thermal, similar to a diagram registering the adsorbate as a function of the equilibrium concentration of the substance to be adsorbed. The form or type of the isothermal depends on the interacting forces of the individual reaction partners.

With porous substances, such as silica gel, two types of isothermals apply.

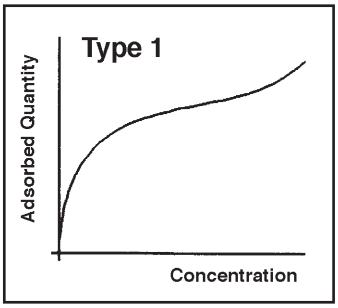


Fig. 6.2.1.1

Type 1 is characterised by a steep rise in the adsorption curve at low concentrations. Type 2 adsorbs mainly at high concentrations.

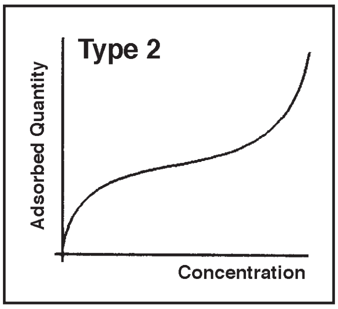


Fig. 6.2.1.2

In order to clarify the adsorption process and the origin of the differing types of isothermals, three different, overlapping phenomena must be considered in the presence of pores:

- Chemical adsorption
- Condensation
- Capillary condensation

These are explained by means of the example with water as adsorbate.

6.2.2 Chemical adsorption

At low concentrations, the entire surface of the silica gel adsorbs. The total surface is composed from pores and the macroscopically visible, very much smaller, surface of the particles. The entire surface is permeated with silanol groups, capable of binding bipolar water molecules via hydrogen bridges.

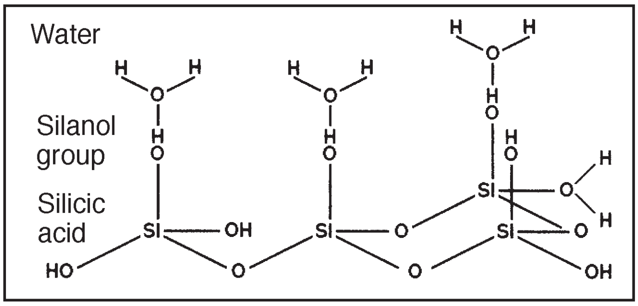


Fig. 6.2.2.1

This process, described as chemical adsorption, leads to a monomolecular layer. The image of the water initially adsorbed at the surface is best presented through the structural diagram. In this way, depending on the size of the specific surface, about 10 - 30 % of the maximum possible loading is bound.

We owe to Langmuir one of the first theories concerning adsorption. Langmuir based his theory on the image of a dynamic equilibrium between gaseous phase and the adsorbed phase, and thus arrived at the following isothermal equation,

$$\boxed{\frac{V}{V_m} = \frac{K \times p}{1 + K \times p}}$$

Formula 6.2.2.1

in which the following quantities are in principle interdependent :

V	the adsorbed quantity at pressure p
V_m	the adsorbed quantity in the monomolecular layer
p	the vapour pressure
K	a constant

The Langmuir isothermal can be directly applied to the formation of a monomolecular layer on the assumption that the heat of adsorption has the same value for each water molecule adsorbed. However, in most cases the heat of adsorption is a function of the degree of coverage.

6.2.3 Condensation

In the course of the adsorption process, condensation causes the formation of further layers of molecules on top of the monomolecular layer created by chemical adsorption. This condensation is a purely physical process. It is the effect of two significant forces which result from the bipolar character of the water molecule : Van-der-Waal forces and the surface energy of the water.

On the strength of this knowledge Brunauer, Emmet and Teller (BET) arrived at an extension and thus a more generally applicable version of Langmuir's theory.

$$\boxed{\frac{V}{V_m} = \frac{C \times p}{(p_o - p)\left[1 + (C-1)\frac{p}{p_o}\right]}}$$

Formula 6.2.3.1

In Formula 6.2.3.1, p_O is the saturation vapour pressure and C a constant.

BET equation takes into account the formation of the monomolecular layer and that of all adsorption layers formed on top of this, using the simplified assumption that the heat of adsorption corresponds to the heat of condensation from the second layer onward.

6.2.4 Capillary condensation

If chemical adsorption plus condensation adsorbs so much water that the tightest passages of small capillaries are filled with liquid and a concave liquid surface has been formed, capillary condensation sets in.

Analogously to the vapour pressure reduction when drops of liquid become larger, a lower vapour pressure then above a level surface becomes effective in tight capillaries with a concave liquid surface.

From this, Lord Kelvin deduced the following interrelation for the change of vapour pressure:

$$\boxed{\ln \frac{p - d_p}{p} = \frac{2 \text{ x } \sigma \quad V \text{ x } \cos\delta}{r \text{ x } R \text{ x } T}}$$

Formula 6.2.4.1

d_p = vapour pressure
s = surface tension
d = edge angle (miniscus)
r = pore radius
V = mol. volume of the vapour
T = temperature
R = general gas constant

Whereas on level surfaces condensation sets in only when saturation vapour pressure has been reached, water condenses inside the pores already at low vapour pressures. The capillaries become filled with the substance (in this case water) to be adsorbed.

It follows from the Kelvin equation according to Formula 6.4.2.1, that the vapour pressure reduction inside the capillaries will be the stronger, the narrower the pores. This means that the tightest pores within the silica gel will be filled with water in the first instance and only after this, the pores with larger diameter.

The process of condensation continues until vapour pressure equilibrium is reached, i.e. up to the point at which the vapour pressure of the water in the surrounding gaseous phase is equal to the vapour pressure inside the pores. The larger the internal surface of a particular silica gel, the greater will be the number of silanol groups, and the tighter the pores, the stronger will be the effect of capillary condensation, thus making the gel a particularly effective drying medium. This process corresponds to the sequence of the isothermal of type 1 (Fig 6.2.1.1).

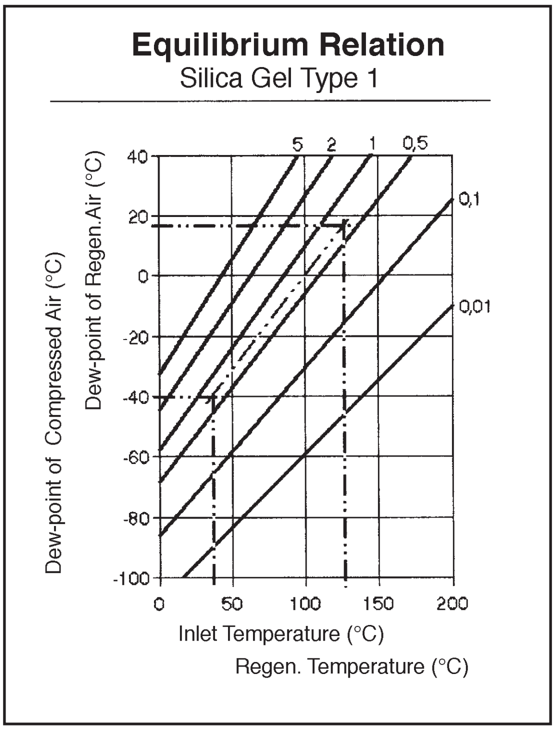


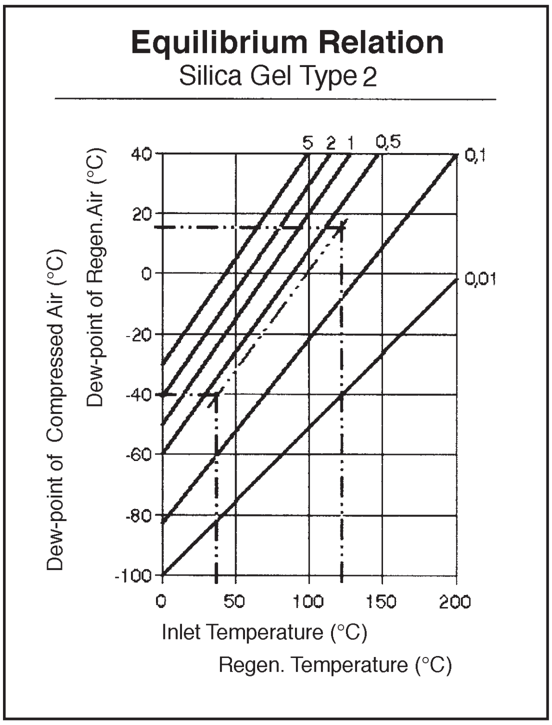
Diagram 6.2.4.1

The dotted line entered into Diagram 6.4.2.1 shows the equilibrium relationship between water loading, regeneration temperature of the drying medium and the dewpoint.

At an ambient temperature of tamb = 25°C and relative humidity of RH = 60%, the real dewpoint temperature of the regenerating gas and Td_p = 15°C, entered above on the Y axis. Likewise on the Y axis, one finds the horizontal line of the dewpoint of the compressed air with T_p = -40°C. On the X axis, the inlet temperature of the compressed air is assumed to be Ti = 35°C.

Parallel to the line of constant residual water loading expressed in weight percentages, the equilibrium relation to the regeneration temperature TReg = 140°C can be established.

The larger the pores, and therefore the total pore volume, the larger the quantity of water which the silica gel can take up, i.e. the capacity is correspondingly higher. This is demonstrated by isothermal type 2 (Fig. 6.2.1.2).



Equilibrium Relation
Silica Gel Type 2

Diagram 6.2.4.2

Diagram 6.2.4.2 shows the equilibrium relationship of a drying medium typical for isothermal type 2.

6.3 Molecular sieve

Molecular sieves are crystalline metal aluminosilicates with a three-dimensional net shaped structure of silicic acid and clay tetrahedrons.

6.3.1 Description

Molecular sieve tetrahedrons consist of four oxygen atoms which surround a silicon or aluminium atom. Each oxygen atom has two negative charges, whereas every silicon atom possesses four positive charges. Owing to the trivalency of the aluminium, the tetrahedron of the aluminium oxide carries a negative charge. A positively charged ion (cation) is needed to compensate. This compensation can take place via potassium, sodium or other cations.

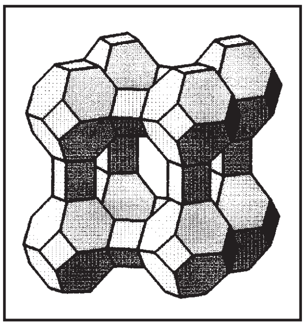


Fig. 6.3.1.1

Molecular sieves or zeolites consist of blunt octahedrons, made up from tetrahedrons. These structural components are known as sodalite cages. If sodalite cages are built up in layers to form simple cubic shapes, a dice like network of hollow spaces is created, possessing a diameter of up to 15 Angström (1.5 nm).

These voids are always of equal size and accessible through pores from six sides. In the case of sodium compounds, this crystalline structure is expressed by the following chemical formula :

$$\mathbf{Na_{12}(AlO_2)_{12}(SiO_2)_{12}]}$$

The water content fills the voids during crystallisation and is loosely linked. Heating causes the water content to be removed and the spaces previously filled with water have now become available as pore volumes for the adsorption of various gases.

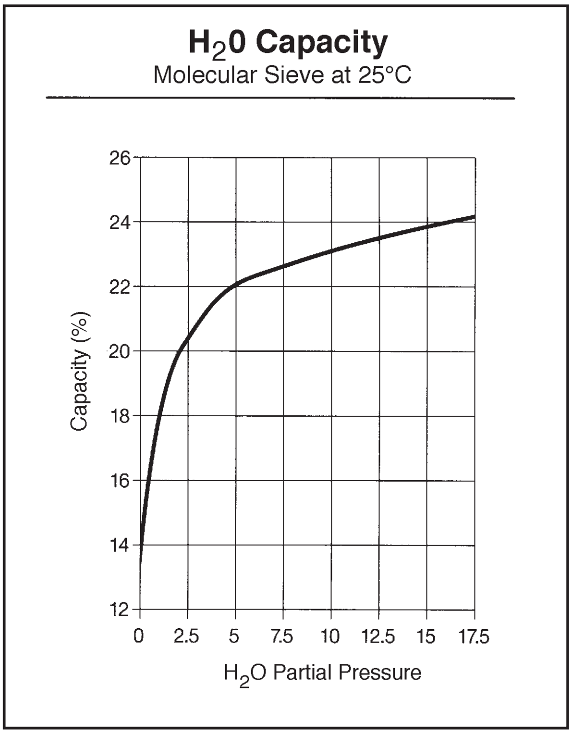


Diagram 6.3.1.1

The number of water molecules in the structure for value x may amount statically to 27, water will then amount to 28.5 % of the total weight of the zeolite in saturated form. However, a molecular sieve with a pore diameter of 10 Angström (1nm) is capable of taking up as much as 35 % of its total weight in saturated form.

A typical dynamic adsorption thermal for water with a molecular sieve is shown in Diagram 6.3.1.1. With this adsorption system, the adsorption capacity of drying medium molecular sieve rises quickly with increasing concentration to reach a high value followed by the saturation value.

The relatively fast achievement of the saturation value at low concentrations, distinguishes molecular sieves from other drying media in common use.

Diagram 6.3.1.2 shows the dependence of the H_2O equilibrium capacity from relative humidity, in the case of the molecular sieve (MS), silica gel (SG).and aluminium gel (Al).

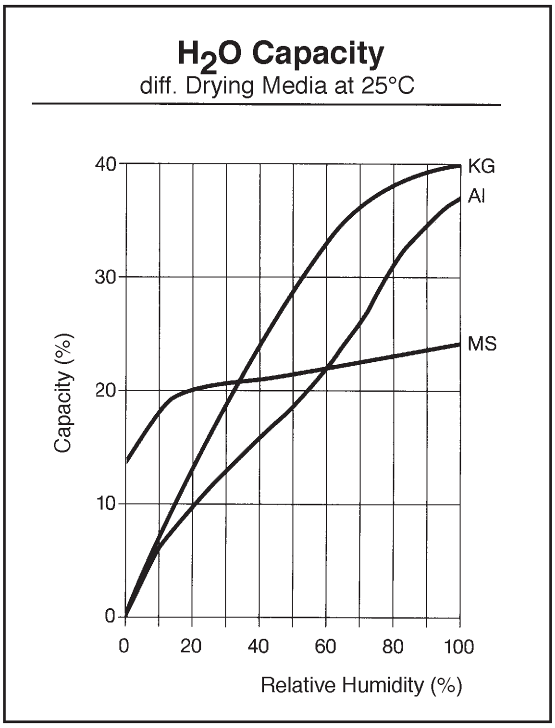


Diagram 6.3.1.2

The separation of differing molecules from a flow of air is influenced by factors of molecule diameter and pore diameter of the drying medium.

The separation of water from a flow of air is dependent on whether the water molecule can pass through the pore opening of the drying medium and is stored within the internal structure of the zeolite. A water molecule has a critical diameter of 2.8 Angström (0.28 nm). Such a water molecule becomes stored in a drying medium with a pore size larger than 2.8 Angström.

Occasionally, an unusual effect is observed at specific temperatures, i.e. the adsorption of molecules with a critical diameter larger than the effective diameter of the pore opening. This apparent contradiction can be explained by the elasticity of the adsorbed molecule and the vibrations within the crystal system of molecular sieves.

Molecular sieves are manufactured in spherical form.Their active internal surface is of the order of size of 500 - 900 m^2/g. Molecular sieves possess a macropore structure of high capacity, making possible rapid diffusion of the molecules to be adsorbed towards the internal surface of the drying medium sphere.

6.3.2 Dynamic adsorption

The process technological sequence of an adsorption dryer installation is influenced by differing factors which are decisive for its trouble free, optimum operation.

These factors are subject to complex interaction effects but, for clearer understanding, they will be described separately and independently of each other.

6.3.3 Mass transfer zone

In an adsorber vessel, the transfer of water from the flow of air to the molecular sieves takes place in the mass transfer zone (MTZ).

The mass transfer zone is that section of the adsorber bed in which the water load from the air current is deposited on the drying medium, thereby reducing the level of humidity from the inlet concentration to that at the outlet.

The width of the mass transfer zone is primarily a function of flow velocity, inlet and outlet concentration of the drying medium and the type of drying medium.

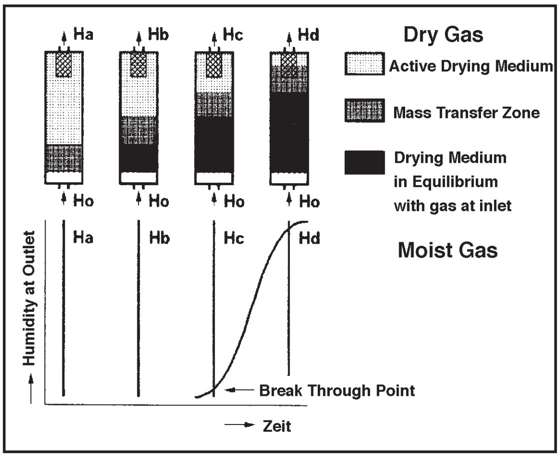


Fig. 6.3.3.1

The mass transfer zone migrates with increasing saturation from the inlet side to the outlet side of the adsorber vessel. Once the upper limit of the mass transfer zone reaches the end of the adsorber bed, the break-through of moisture commences.

6.3.4 Flow velocity

A low mass transfer performance during adsorption can be caused by too high a flow velocity of the air current through the drying material bed. When dimensioning the adsorber, care must be taken that the flow velocity stays within the turbulence range, as laminar flow could cause inadequate dispersion through the formation of channels. Favourable flow velocities for compressed air and gases are between 5-15 m/min referred to the open cross-section.

6.3.5 Capacity

The usable capacity of molecular sieves is largely unimpaired by a rise in temperature. Other drying media, on the other hand, show considerably higher capacity losses with rising operating temperature, as shown in diagram 6.3.5.1.

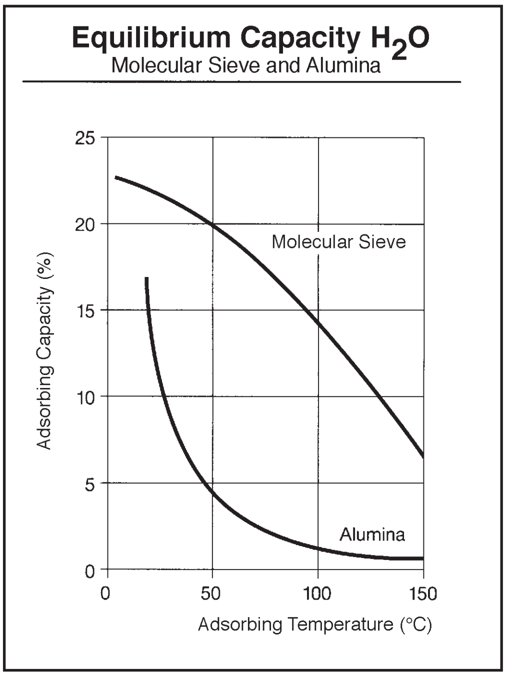


Diagram 6.3.5.1

Within the normal pressure range of the usual industrial compressed air systems, the operating pressure has little significance for the performance of molecular sieves.

6.3.6 Contamination

Given the most varied fields of application, the danger arises that pollutants collect in the pores of the adsorption material. During regeneration with higher temperatures, such contamination can lead to cracking or polymerisation of organic molecules. The remaining detritus has a significant influence on the service life of molecular sieves.

6.3.7 Regeneration

The original adsorption capacity of molecular sieves is restored by regeneration or reactivation.

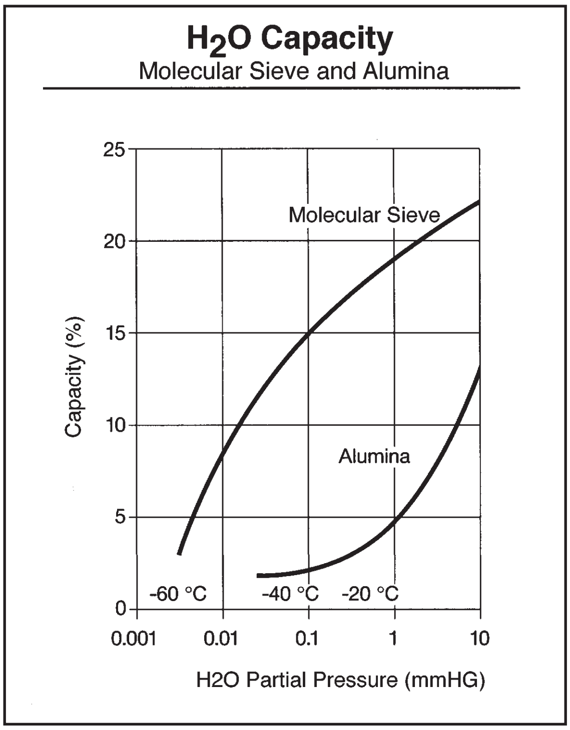


Diagram 6.3.7.1

In order to maintain continuity of adsorption during regeneration of the bed, adsorption takes place in a second adsorber bed. There are various regeneration processes, but these are all based on the same principle. Conditions within the adsorber bed should, in practice, be arranged to result in a moderate loading on the adsorbent.

6.3.8 Thermal Regeneration

Through the input of heat,the molecular sieve is heated to such an extent that the adsorbed material leaves the pores. This type of regeneration can simply and reliably be adapted to the most varied operating situations

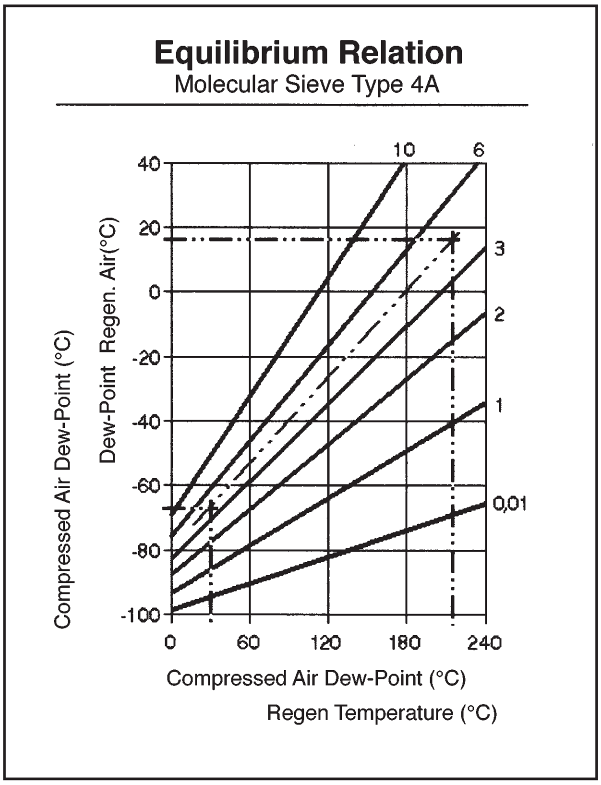


Diagram 6.3.8.1

As molecular sieves possess a relatively low thermal conductivity, heating the adsorber bed is best effected indirectly by means of a current of hot gas. This, at the same time, serves as flushing medium, removing the adsorbed material from the molecular sieve bed. The nature of the adsorbates and the product purity aimed at, are among the factors determining the temperature to which the molecular sieve bed has to be heated in order to effect regeneration. The product purity achieved by an adsorption installation based on a molecular sieve depends on the regeneration temperature and the adsorbate content of the flushing gas. In practice, temperatures between 180°C and 250°C are required. The heat allowance (see section 7.2) for adequate reactivation includes the following heat quantities :

- Heat requirement when heating and evaporating the adsorbate
- Heat capacity of the equipment, piping and of the adsorbent

- Desorption heat of the adsorbate
- Heat loss of the adsorption installation

In addition, the adsorber bed should be heated slowly only, so that maximum temperature of the regeneration gas is achieved only in the course of a period of one hour or more. Such slow heating favours the removal of reactive molecules at low temperatures, thus strongly diminishing the possibility of carbonisation or polymerisation.

The heating phase during reactivation normally includes a cooling phase, in the course of which the bed is brought back to adsorption temperature. For this, the same gas current as for reactivation is usually employed, however, avoiding an input of heat.

6.3.9 Pressure change regeneration

Pressure change regeneration is based on reducing adsorption capacity through lowering system pressure at constant temperature. For this purpose, the adsorber is depressurised, causing the partial pressure of the contaminants to diminish materially. Such low partial pressure corresponds to a very small equilibrium capacity, at which the adsorbate is desorbed and can be removed by means of a purge gas.

6.4 Activated charcoal

Activated charcoal is an auxiliary material which has been used by industry for decades. Activated charcoal is available in powder, granular or shaped block form, in addition, different types with different characteristics are manufactured.

Unlike graphite or diamond, activated charcoal does not constitute an accurately defined form of the element carbon, but is a generic term for a group of porous charcoals. All activated charcoals share this structure consisting of a spongiform secondary grid of small graphite crystallites, three dimensionally cross-linked by amorphous carbon.

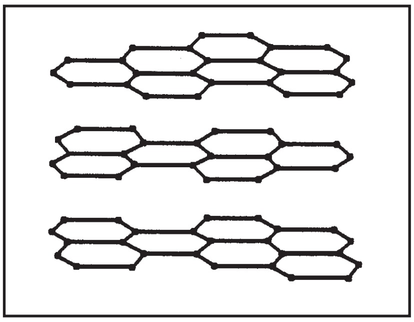


Fig. 6.4.1

Whereas graphite forms relatively large crystals, containing carbon layers in strict orientation, there are only very small crystallites with approx. 7 - 11 Ä height in activated charcoal, with an idealised diameter of 20 - 25 Ä. These layers are linked through random shifts and displacements.

The specific structure of activated charcoal leads to the formation of a multiplicity of cracks and crevices, which are called pores, an idealised description being that of cylinders. Depending on the open width of these pores, one distinguishes:

- Micro pores with radii smaller than 10 Ä
- Meso pores with radii from 10 to 250 Ä
- Macro pores with radii larger than 250 Ä

The distribution of differing pore radii is often represented in graphical form, in which the prevalent pore volume is allocated to that of the pore radii and entered appropriately.

The wall surface of the pores is described as the internal surface and, with commercially activated charcoals, is of a value of 500 - 1500 m^2/g. The micropores, particularly, make a very large contribution to the total surface, whereas activated charcoal with large pore sizes often possesses only a relatively small total surface in spite of high porosity.

The manufacture of activated charcoal from non-porous carbon-containing starting materials, is known as activation. In the course of this activation, microcrystalline carbon is generated, and this should ideally be permeated as evenly as possible by a large number of statically distributed pores of varying size.

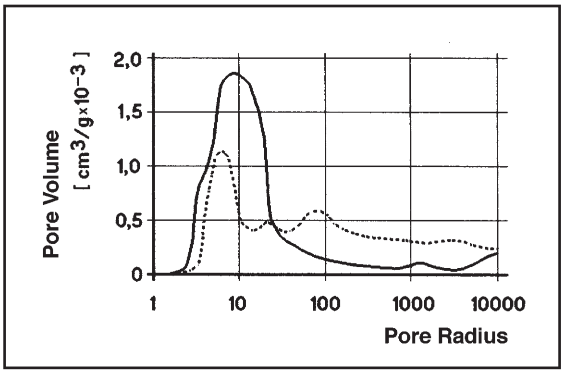


Diagram 6.4.1

Two processes for manufacturing activated charcoal have become the most prevalent ones :

- Gaseous activation using steam and carbon dioxide
- Chemical activation using phosphoric acid or zinc chloride

Following activation, particular types of activated charcoal are selectively separated, through grinding as well as crushing and sieving processes, in order to achieve the required grain size range.

For many tasks, such as the chemical adsorption of toxic gases, impregnation with inorganic salts or organic compounds is necessary. This often calls for an additional heat or gas treatment, in order to activate impregnation and achieve suitable chemical transformation.

Adsorption is the accumulation of substances on the surface of a solid. Such accumulation is effected mainly through physical forces, the so-called van der Waal forces. Adsorption processes are reversible and the opposite process is called desorption.

Adsorption forces can act only across very small distances; thus pore size assumes a considerable significance in addition to the size of the internal surface. It is necessary to adapt pore distribution to the particular task in hand.

For adsorbing relatively small gas or vapour molecules, fine pored activates are preferred.

In order to achieve adsorption equilibrium, the charge materials are conveyed through the pore network by means of diffusion.

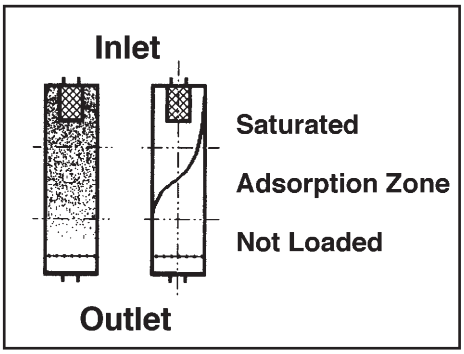


Fig. 6.4.2

The phenomenon of diffusion has the effect that the matter to be adsorbed is not spontaneously adsorbed when flowing through activated charcoal beds. Adsorption takes place in the direction of flow and within a specified layer of activated charcoal, the so-called mass transfer zone. This applies to gaseous media at the usual linear flow velocities of 6 - 30 m/s.

The length of the mass transfer zone forms an important parameter for dimensioning and economically operating an activated charcoal adsorber.

The mass transfer zone is influenced by the following parameters :

Linear approach flow velocity, exercising strong influence on the length of the adsorption zone. High velocities lead to long mass transfer zones and to rather elevated filter resistances.

Particle size of the activated charcoal used as significant factor for the length of the mass transfer zone. Small grain sizes lead to a compact adsorption zone but also to high pressure loss.

Suitable pore distribution favours the diffusion process, however, drawbacks as far as the mechanical hardness of the activated charcoal is concerned, may well arise.

Higher temperature with more rapidly proceeding diffusion processes, as the viscosity of the gaseous medium is materially diminished. At the same time, higher temperature causes a clear reduction of the pressure loss in the charcoal bed.

The mass transfer zone is constant throughout the total adsorption period only if one sole substance is targeted. In the case of mixtures of substances of varying affinities to be adsorbed, the weakly adsorbable compounds are displaced from the inlet side in favour of more readily adsorbable components and thus moved along in the direction of the outlet side. This leads to an elongation of the adsorption zone in the course of operating time.

6.4.1 Forms of activated charcoal

Depending on its external appearance, activated charcoal is divided into three groups :

- Powdered charcoal
- Granular charcoal
- Shaped charcoal

Powdered charcoal is ground to a degree of fineness which leads to 50 - 80% of particles being smaller than 40 micron, thus leaving 20 - 50% above 40 micron. Powdered charcoal is used principally for water treatment.

For this reason, this is not the place to deal with such activated charcoal in greater detail.

Granular charcoal usually consists of fractured granules, either already activated, or fractured and graded to reach the state in which it is offered. Grades are characterised by indication of.grain sizes. Granular charcoal is used for purifying air and gas. Grain size distribution of granular charcoal exerts a significant influence on the kinetics of adsorption.

Shaped coal is traded in the form of small cylinders. Various grades are manufactured, with particle diameters varying between 1 - 4 mm. The proportion between grain length and grain diameter is about 3 : 1, with downward tolerances. Shaped coal is utilised like granular coal. In the gaseous phase, shaped coal offers benefits because of the low flow resistance, good mechanical hardness and because shaped coal makes it possible to fill the adsorber in an even and stable manner.

6.4.2 Carbon structure

Although ash and water free, the structure of activated charcoal does not consist of pure carbon. Depending on the mode of manufacture and starting material, not only carbon but also oxygen and hydrogen, and sometimes nitrogen, are present in bound form. The carbon content mostly amounts to 85 - 98 %. Oxygen forms so-called surface oxides, which can endow the charcoal surface with alkaline or acid characteristics. A reaction of the surface compounds can be observed through pH-value changes of a charcoal suspension (slurry). In many cases, surface oxides are the cause of catalytic properties of activated charcoal, particularly in the case of reactive processes. As with graphite, pure carbon surfaces are water repellent. However, through the presence of surface oxides, hygroscopic areas are formed, so that carbon with a high content of surface oxides is easily wetted by water. Activated charcoal, a carbonaceous substance, is naturally combustible. However, carefully prepared activates, particularly water vapour activates, are not auto-igniting. By the point of ignition, one means the temperature at which the first exothermal reaction takes place in the course of being heated. The ignition temperature of activated charcoal lies in the range of 250 - 400°C.

6.4.3 Application

Shaped charcoals are activated only after having been formed. This makes the particles very hard and endows them with a high level of activity in contrast to granulates from powdered coal.

Shaped charcoal is predominantly used in the gaseous phase. The adsorption processes then occurring, function on the basis of 4 - 5 seconds of contact time, the linear flow velocity of the gaseous phase lies within 0.1 - 0.5 m/s. To achieve the optimum effect of activated charcoal used for compressed air purification, turbulent flow has to be maintained.

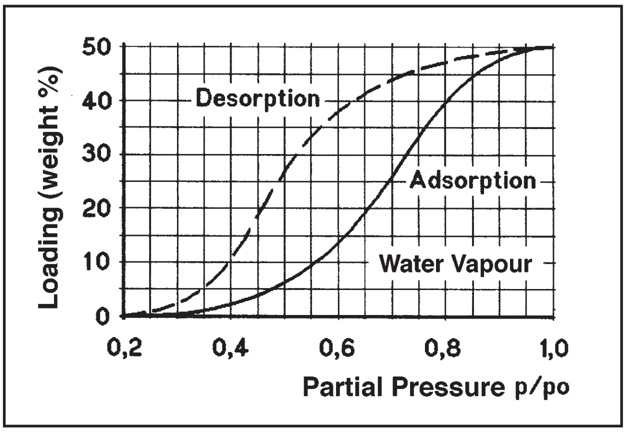


Diagram 6.4.3.1

The favourable kinetics of activated charcoal are based on the fact that most substances to be adsorbed from the gaseous phase are present as relatively small molecules, the diffusion of which (within the network of pores) meets with few obstacles.

Activates with fine pores are mainly utilised in the gaseous phase. The pore radius distribution and the level of activity of shaped charcoal up to 4 mm diameter is varied, thus offering optimum adsorption and desorption characteristics for solving any particular task.

According to the course of the water vapour isothermal (Diagram 6.4.3.1), activated charcoal is hydrophobic (water repellent). Only from relative humidity above about 30 %, water vapour is adsorbed to a significant extent. At even higher water contents in the air, the load capacity even for well adsorbable vapours is impaired through co-adsorption of water.

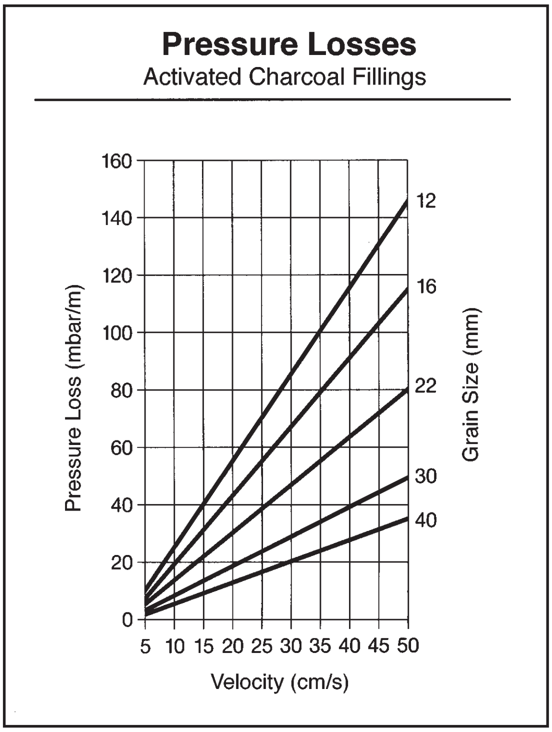


Diagram 6.4.3.2

When designing activated charcoal fillings for gaseous phase utilisation,.flow resistance must be taken into account. Diagram 6.4.3.2 shows pressure loss as a function of gas velocity and grain size.

Part 7

7.0 Adsorber layout design

Adsorption dryers are used to dry compressed air or gases. Although many conditions influence the design of an adsorption dryer, dryer size has to be specified. The size of a dryer, depending on the particular application, is determined by critical factors such as gaseous medium, volume flow, operating pressure, inlet temperature and pressure dewpoint.

Apart from the nature of the gaseous medium, the size of an adsorption dryer is primarily determined by the maximum moisture loading of the gas to be dried. The maximum moisture loading is determined at the highest throughput performance, the highest inlet temperature and the lowest operating gauge pressure.

Alternatively, the minimum moisture loading of the gas to be dried is fixed by the lowest throughput performance, the lowest inlet temperature and the highest operating gauge pressure.

Between these limit values of the loading situation (Fig. 7.0.1), minimum and maximum moisture loading, the loading factor varies with the pressure dewpoint.

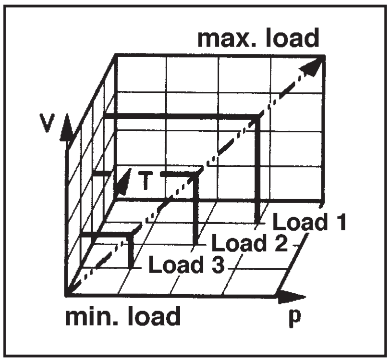


Fig. 7.0.1

Minimum moisture loading has little influence on the size of the adsorption dryer but does, however, determine the limiting value of the maximum possible adsorption time.

The necessary calculation schemes are based on logic and outline important criteria when designing an adsorption dryer. The following demonstrates the calculation scheme for heatless and heat regenerated adsorption dryers.

Adsorption dryers with heatless regeneration require the calculation of dryer size on the basis of the optimum quantity of desiccant, supplemented by the specification of the regeneration volume flow.

Calculations for adsorption dryers with heat regeneration are considerably more complex, because the load factor has to be established first and then the regeneration energy as a function of the overall heat allowance

The calculation examples of heat regenerated adsorption dryers are based on normal data and is meant solely to stimulate understanding of the complicated interrelationships. It is, therefore, presented in a generally valid manner, on the basis of external blower regeneration.

Values indicated take into account the recommendations of desiccant manufacturers. All limiting values are input parameters and, in all likelihood, judged differently by various manufacturers of adsorption dryers. To ignore physical laws or process technological limitations involves risks which will not be dealt with in detail here.

Layout design is divided into three steps :

Determination of the moisture loading per cycle
Dimensioning the adsorber vessel
Establishing the regeneration energy

The examples can be used as a framework for estimating or checking calculations and modified for specific applications.

7.1 Heatless regeneration

The following calculation scheme for adsorption dryers with heatless regeneration is based on commercially available desiccant. This section deals with the layout design for compressed air. The diagrams presented are not valid for extreme values. The following data, valid at the adsorber inlet point have, in principle, to be indicated for minimum and maximum loading range as a basis for the design :

Volume flow referred to 1 bar	V	(m^3/hr)	t = time (mins)
operating pressure	p_o	(bar abs)	
Inlet temperature	T_i	(°C)	
Pressure dewpoint	P_{dp}	(°C)	

This data will be required for the individual steps in the calculation and are usually based on

- estimated experience values
- data measured at the installation

In practice, many people operate almost exclusively with experience values. However, only measured values form an accurate basis for dryer design. The calculation is worked out for a specified adsorption time t_a. Adsorber layout design takes place in individual steps on the basis of physical laws.

7.1.1 Adsorption

a) Effective volume flow

Volume flow at the inlet of the adsorber has to be converted on the basis of reference values to obtain the effective volume flow V_e.

$$\boxed{V_e = \frac{V \mathbf{x} \left(T_n + T_i\right)}{T_n + t}}$$

Formula 7.1.1.1

b) Operating volume flow

Based on effective volume flow V_e and minimum operating pressure p_o, maximum operating flow V_o is calculated.

$$\boxed{V_o = \frac{V_e}{p_o}}$$

Formula 7.1.1.2

c) Operating volume per cycle

Adsorber design is also significantly influenced through the operating volume per unit of time. Operating volume Voc per cycle is established in accordance with

$$\boxed{V_{oc} = V_{o} \times \frac{t_{a}}{60}}$$

Formula 7.1.1.3

For adsorption dryers with heatless regeneration, adsorption time ta amounts to a few minutes only.

d) Moisture load per cycle

An important parameter for establishing dryer size arises from the moisture load per cycle. Humidity content h, referred to inlet temperature T_i, can be read from Diagram 7.1.1.1 ($h/1000 = kg/m^3$) and inserted into Formula 7.1.1.4. Multiplied by the operating volume per cycle V_{OC}, the moisture load per cycle hc is determined.

$$\boxed{h_{c} = V_{oc} \times \frac{f}{1000}}$$

Formula 7.1.1.4

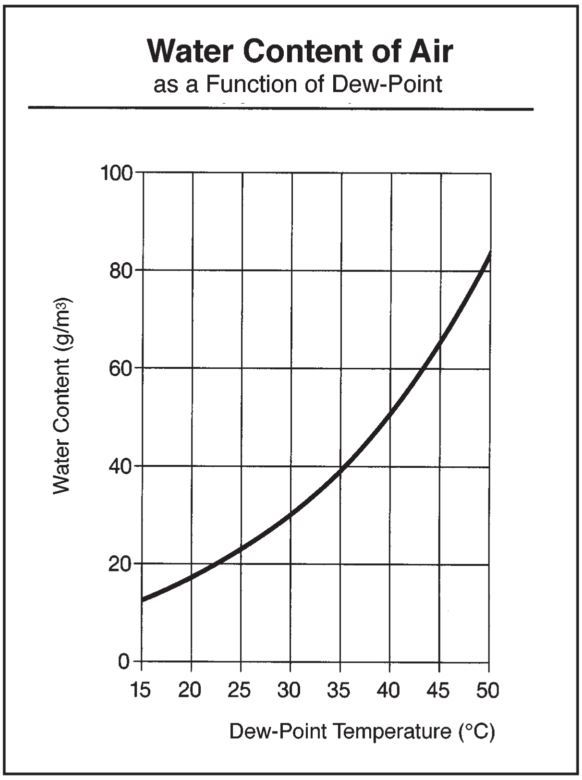


Diagram 7.1.1.1

e) Load factor

The load factor K_l for the design calculation of adsorption dryers with heatless regeneration should be smaller than 0.5 kgH_2O/kg_{dr}, depending on the type of desiccant utilised, as the danger of oversaturation when loading otherwise arises. For a reliable and safe design specification, for adsorption drying of compressed air, the loading factor referred to the cycle is :

$$Kl < 0.5\ kgH2O/kg_{dr}$$

f) Quantity of drying material (desiccant)

The quantity of mdr per adsorber depends on the maximum moisture loading and the reliable determination of the load factor K_l

The quantity of desiccant per adsorber should always be established when comparing adsorption dryers.

$$\boxed{m_{dr} = h_c \times \frac{100}{K_l}}$$

Formula 7.1.1.5

g) Adsorber volume

After establishing the quantity of desiccant m_{dr}, the adsorber volume V_{dr} is determined.

The packed density (d_r of commercially available drying media (see Section 6.0) varies in its effect on the adsorber volume with the type of desiccant utilised.

For adsorption dryers with heatless regeneration, molecular sieves are frequently used and these have a packed density in line with table 6.0.1.

$$\boxed{V_{dr} = \frac{m_{dr}}{ddr}}$$

Formula 7.1.1.6

h) Flow velocity

The effective flow velocity we for air can be obtained from diagram 7.1.1.2 in relation to operating pressure p_O. The value of flow velocity read from the diagram should not be exceeded by more than 25 % in the unfilled adsorber.

At high flow velocity (see Section 5.1), the danger arises that the drying medium in the adsorber bed is agitated and thus subjected to strong mechanical strain or even damage.

Alternatively, at low flow velocity, an undesirable laminar flow can lead to channelling and thus preperential flow through the adsorber.

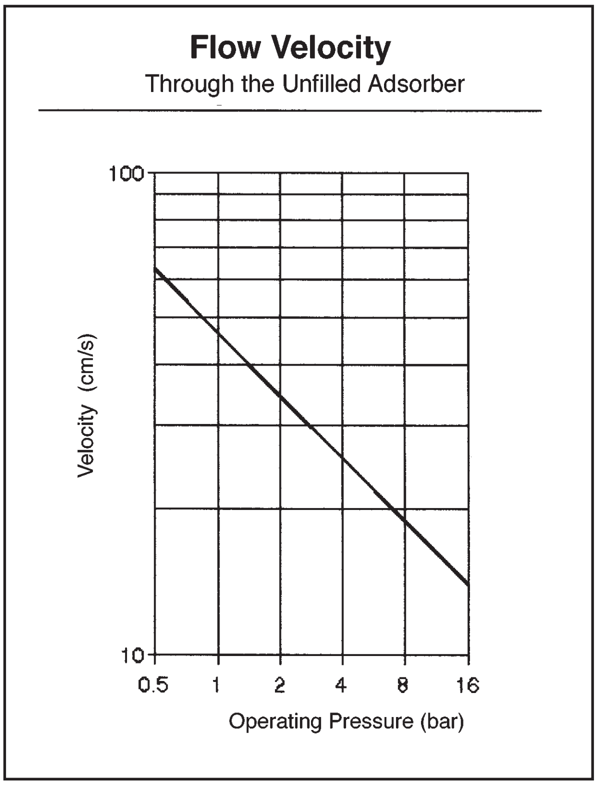


Diagram 7.1.1.2

i) Adsorber cross sectioned surface area

Using the operating volume flow V_O and the effective flow velocity we from Diagram 7.1.1.2, the adsorber cross sectioned surface area A_{dr} is calculated, taking units into account and using the following formula :

$$\boxed{A_{dr} = \frac{V_o}{w_e \times 3600} \text{(m}^2\text{)}}$$

Formula 7.1.1.7

With the adsorber surface, the adsorber diameter ddr (m) is also established. It is rarely necessary to correct these values.

j) Filling height

The geometric filling height F_h of adsorbers is determined from the already calculated values of the adsorber volume V_{dr} and the adsorber surface A_{dr}, in accordance with Formula 7.1.1.8.

$$\boxed{F_{h\,(m)} = \frac{V_{dr}}{A_{dr}}}$$

Formula 7.1.1.8

k) Dwell time

The quality of the compressed air to be dried depends on a theoretically sufficient dwell time t_d. Provided that the minimum dwell time is adhered to, the required pressure dewpoint P_{dp} is achieved easily in the course of operation. Dwell time td is obtained from Formula 7.1.1.9 and Diagram 7.1.1.3. If the dwell time is insufficient, the adsorber surface Adr and filling height Fh have to be re-determined. If the required minimum dwell time is not adhered to, the reliable achievement of the pressure dewpoint throughout operating life becomes suspect.

$$\boxed{t_d = \frac{F_h}{w_e}}$$

Formula 7.1.1.9

For a certain pressure dewpoint of P_{dp} -40°C, the dwell time should on no account fall below t of td = 4.5 s. Deviating pressure dewpoints with the corresponding dwell times can be obtained from Diagram 7.1.1.3 and should be taken as guide line values. Because of the dwell time in the adsorber, the adsorption dryer must be given larger dimensions for lower pressure dew points, compared to a dryer design from which a pressure dewpoint of lower quality would be considered sufficient.

The effect of pressure dewpoint on dryer size is frequently underestimated in practice.

Targeting a specific pressure dewpoint P_{dp} must, therefore, be based on the realistic requirement and not on the possible maximum performance limit of the adsorption dryer. The overriding aim is always the determination of the most economical adsorber size.

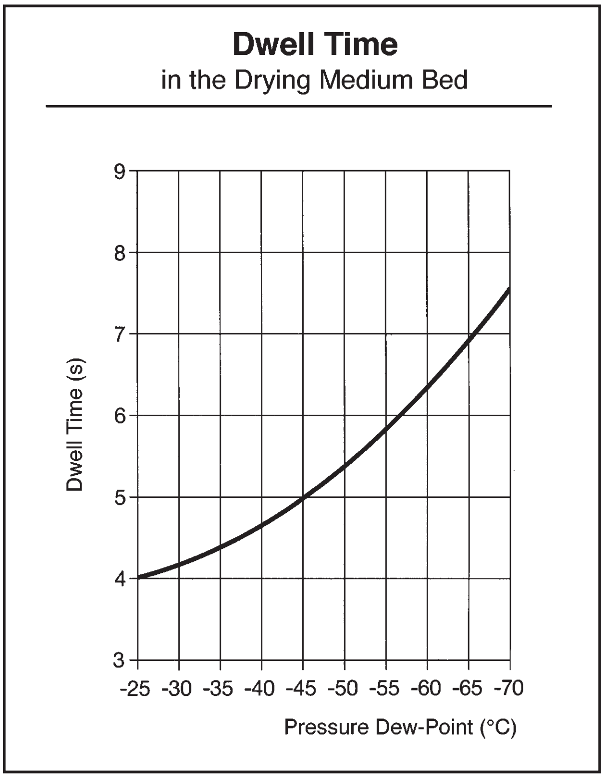


Diagram 7.1.1.3

l) Pressure loss

In order to obtain the theoretical pressure loss of the adsorption dryer between the inlet and outlet the basis of theory, far reaching and complicated calculations are necessary (see Formula 7.2.1.13), as the air flow through the adsorption dryer is complex, the pressure loss has to be established separately for each part. The sum of the individual pressure losses results in the overall pressure loss.

Diagram 7.1.1.4 helps to obtain the pressure loss in the adsorber bed. The relevant flow velocity we from Diagram 7.1.1.2 has to be utilised in order to determine the differential pressure.

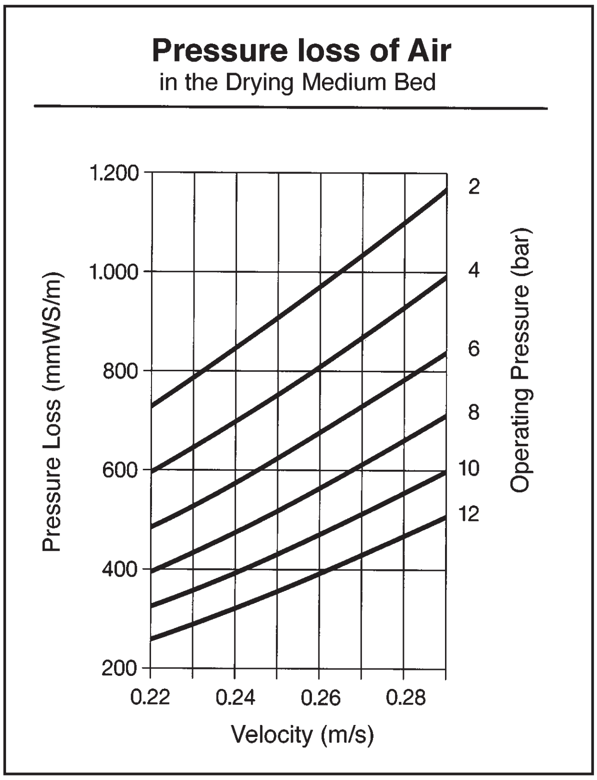


Diagram 7.1.1.4

Diagram 7.1.1.4 presents pressure losses as a function of operating pressure and at differing flow velocities through the adsorber, referred to 1 m of filling height. To determine the pressure loss, the value established from the diagram has to be multiplied by the filling height F_h obtained.

$$\boxed{\Delta p_g = \Delta p * S_h}$$

Formula 7.1.1.10

7.1.2 Correction factor

Correction factors, as aids to the layout design of adsorption dryers, are to be used in only as a rough estimate of dryer size. If the determination of dryer size is based solely on correction factors as far as its basic parameters are concerned, a reliable evaluation close to limiting values is not possible. The correction factors refer to pressure dewpoints of P_{dp} -40°C. Factors from Diagram 7.1.2.1 are not obtained from a specific product but based on physical and generally valid laws.

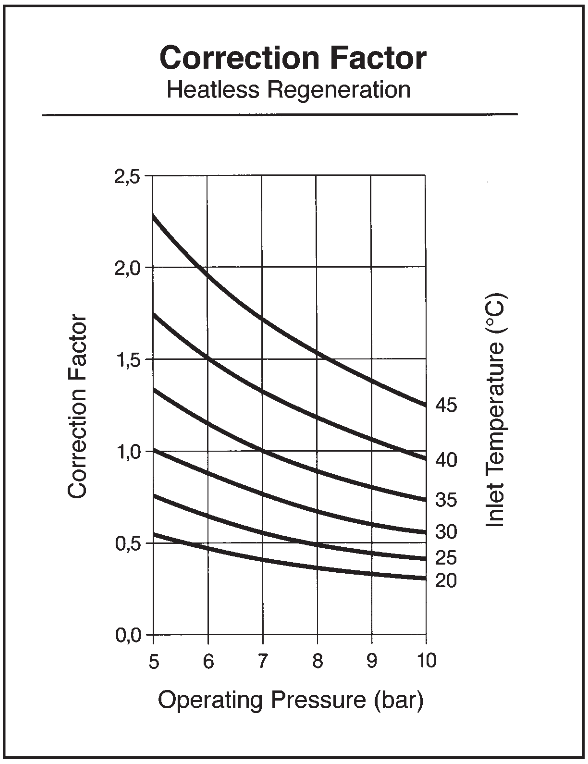


Diagram 7.1.2.1

These factors clearly show how different parameters at the dryer inlet cause differences in dryer performance. Thus dryer capacity with an inlet temperature of t_i = 40°C and operating pressure p_o = 7 bar absolute, is reduced to about 77 %, corresponding to the factor 1.29 obtained from the diagram. Looked at another way, i.e. assuming unaltered capacity, the dryer has to be larger by a factor of at least 1.29.

7.1.3 Regeneration air

Regeneration air can be specified as volume flow per unit of time. To specify it as a percentage of overall flow is not acceptable for practical purposes.

a) Regeneration volume flow

Regeneration volume flow Vrf is determined by means of Formula 7.1.3.1 which, in practice, is sufficiently accurate given a pressure dewpoint P_{dp} = -40°C.

The calculation is carried out, using the effective (gauge) operating pressure $p_i = p_o - 1$. For rough estimates, it is only necessary to use the first part of the equation, provided that the cycle value c is sufficiently large.

$$\boxed{V_{rf} = \left(\frac{V \, x \, 1.033}{p_i} + \frac{p_o}{20 \, x \, c} \right)}$$

Formula 7.1.3.1

b) Regeneration air requirement expressed in %

Alternatively, the regeneration air requirement expressed as a percentage is determined using formula 7.1.3.2. In order to avoid misunderstandings, reference points for deviating parameters must be specified and always stated.

$$\boxed{V_{rf} = \left(\frac{V \, x \, 1.033}{p_i} + \frac{p_o}{20 \, x \, c} \right) \frac{100}{V}}$$

Formula 7.1.3.2

In practice, the regeneration air requirement expressed as a percentage is often misleading and should, in principle, be avoided.

c) Deviating regeneration air requirement

The regeneration air requirement obtained using Formula 7.1.3.2, is based on a pressure dewpoint of P_{dp} -40°C. For other pressure dewpoints, the values in Diagram 7.1.2.1 apply and should be used. Adsorption dryer layout is designed in such a way that compressed air volume flow at the inlet of the adsorption dryer is considered to be the basic value. Regeneration air, on the other hand, is no longer available at the outlet of the dryer and must be considered a loss.

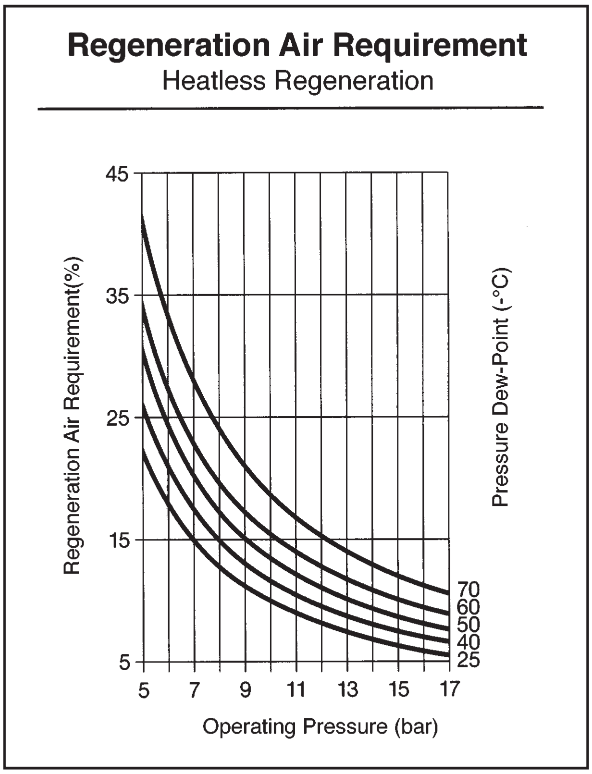


Diagram 7.1.3.1

For low pressure dewpoints accompanied by low operating pressures, a correspondingly high regeneration air requirement arises. This interdependence is shown by Diagram 7.1.3.1. Inlet temperatures above ti = 35°C were intentionally not covered by this diagram.

7.1.4 Regeneration orifice

The theoretical determination of regeneration volume flow can be carried out with accuracy, the design and, the construction of the regeneration orifice, can cause a multiplicity of practical problems. The air velocity inside the regeneration orifice, and the volume of regeneration air flowing out, depends on the construction and surface characteristics of the orifice. For an orifice with straight cylindrical form with apered form, the volume of funnelled and emerging regeneration air depends on the smallest cross-section.

If the pressure behind the orifice is lower than the critical pressure, the pressure within the orifice cannot drop below the critical pressure but will only expand to atmospheric pressure downstream from the orifice and without increase in velocity.

The regeneration volume flowing through an orifice at above critical pressure conditions, is calculated in accordance with Formula 7.1.4.1.

$$\boxed{V_{rf} = \frac{p_1}{p_2} \; x \; A_B \; x \left(\frac{2}{n+1}\right)^{\frac{1}{n-1}} x \sqrt{2 \; x \; g \; x \; R \; x \; T \; x \; \frac{n}{n+1}}}$$

Formula 7.1.4.1

The effectiveness of the orifice is below 1, causing the volume of the outlet regeneration flow V_{rfo} to be smaller than the theoretically calculated regeneration volume flow $V_{rf.}$ In practice, a degree of effectiveness is additionally obtained from the ratio between adsorption period length t_A to desorption time t_D, which is taken into account when calculating the orifice by :

$$\boxed{n_{tot} = \frac{t_D}{t_A} \; x \; \frac{V_{rfo}}{V_{rf}}}$$

Formula 7.1.4.2

After simplification and conversion of Formula 7.1.4.1, the orifice diameter do is calculated, depending on regeneration volume flow V_{rf} at the inlet pressure p_i and outlet pressure p_o, establishing first the orifice cross-sectional area A_O, taking into account the overall degree of effectiveness from Formula 7.1.4.2. Thus the following applies to air :

$$\boxed{d_o = \sqrt{1{,}735 \frac{V_{rf}}{n} \quad \frac{p_o}{p_i}}}$$

Formula 7.1.4.3

The theoretically determined orifice diameter is rounded up to appropriate practical manufacturing possibilities. An alternative solution consists of using diagrams or tables in order to determine the orifice diameter and to adapt it to changed operating conditions.

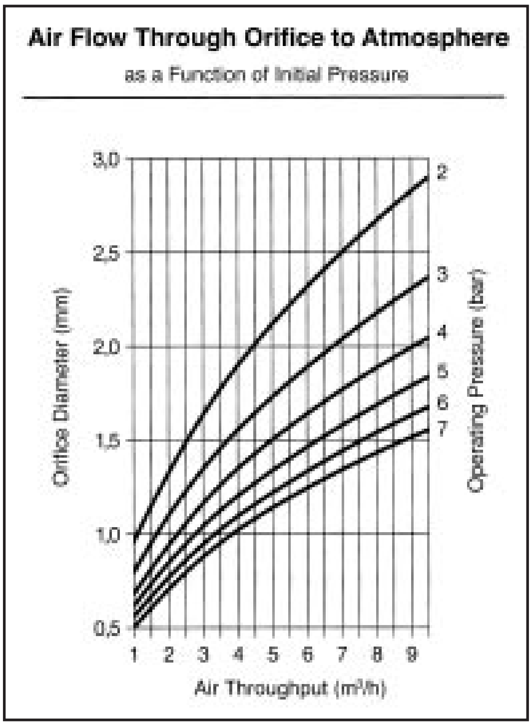


Diagram 7.1.4.1

Further diagrams of regeneration air orifices for different performances are listed in the Appendix Part 12.

7.2 Heat regeneration

The layout of externally regenerated adsorption dryers, filled with silica gel, serves as an example also for other adsorbers using heat regeneration. The simplified layout for compressed air is explained and the logical structure of the calculation, including heat allowance, are shown. All numerical values and diagrams apply, as long as extreme limiting values are not exceeded.

To form a basis for the design, the following data must be pre-determined :

Volume flow referred to 1 bar absolute	V
operating pressure	p_o
inlet temperature	T_i
pressure dewpoint	P_{dp}
loading or charging time	t_L

Further values or materials data for the adsorber layout can be obtained from the applicable diagrams or tables in each case. Indications are provided in places where this applies.

7.2.1 Adsorption

a) Volume flow

The initial calculation steps for heat regenerated adsorption dryers are identical to those for adsorption dryers with heatless regeneration and are listed solely for the sake of completeness.

$$\boxed{V_e = \frac{V \text{ x } (T_n + T_i)}{T_n + t}}$$

Formula 7.2.1.1

b) Operating volume flow

The volume of air per unit time is generally stated at atmospheric pressure and a temperature of 20°C. For design calculations of a drying installation, determination of the operational state V_O is required.

$$\boxed{V_o = \frac{V_e}{\text{po}}}$$

Formula 7.2.1.2

c) Operating volume per cycle

Adsorption dryers with heat regeneration make use of dynamic capacity (Diagram 7.2.1.2) up to the maximum possible value. This leads to the achievement of a loading cycle t_l of several hours. With an adsorption period of 6 - 8 hours, the optimum can be obtained.

$$\boxed{V_{oc} = V_o \text{ x } t_l}$$

Formula 7.2.1.3

d) Moisture load per cycle

The size of the adsorber is determined by the humidity load hc per cycle. Moisture content h at inlet temperature T_i can be obtained from curve a) of Diagram 7.2.1.1. This moisture content refers to air volume Voc at operating pressure po and inlet temperature T_i (f/1000 = kg/m^3 / g/m^3).

$$\boxed{h_c = V_{oc} \times \frac{h}{1000}}$$

Formula 7.2.1.4

In order to avoid the desiccant bed being subjected to elevated moisture loads, the operating temperature should not exceed T_i = 40° C when drying compressed air. If the operating pressure is low, the moisture loading will also be high.

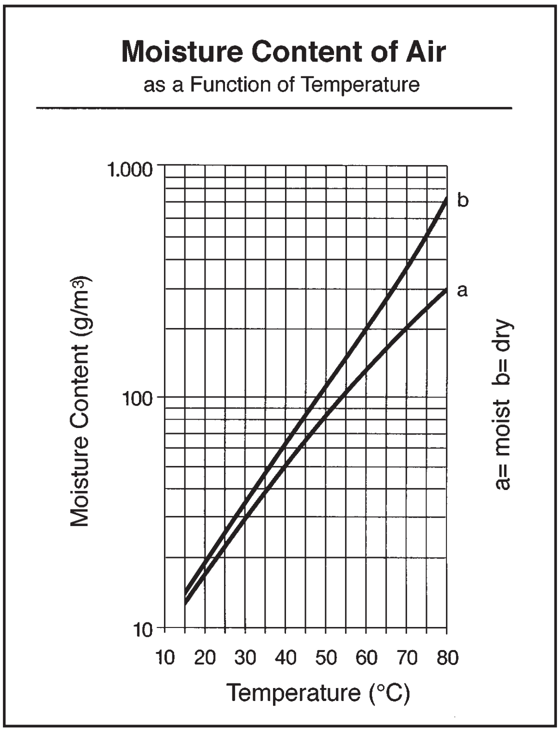


Diagram 7.2.1.1

e) Theoretical temperature rise

When moisture is adsorbed by the desiccant, adsorption heat of up to 2.2°C/gH_2O/m^3 is released. This causes the desiccant and the compressed air passing through it to be heated up. Heating causes the relative humidity of the compressed air to be reduced.

$$\boxed{DT = \frac{h_o \times 2.2}{po}}$$

Formula 7.2.1.5

This is based on a specific heat for air of 0.31 kcal/m^3°C. The moisture content h_O for air T_i can be obtained from Diagram 7.2.1.1, curve b, and then inserted into the equation. The moisture content of the humid air h_O, to be inserted into Formula 7.2.1.5, is referred to the dry air volume and the operating pressure.

f) Theoretical outlet temperature

The theoretical outlet temperature, is derived from the addition of inlet temperature plus temperature rise, and should not exceed 60° C. From this temperature value onward, the capacity of the drying medium is reduced as the transition to regeneration temperatures is flexible.

$$\boxed{T_o = T_i + Dt}$$

Formula 7.2.1.6

g) Secondary relative humidity

Particularly in the adsorption zone, the rise in temperature causes a reduction in the relative humidity of the air to be dried. However, calculations are intentionally based on the assumption that the entire heat of adsorption leads exclusively to the heating of the air. Losses are not taken into account. Moisture content ho refers to inlet temperature Ti, and moisture content ho1 refers to outlet temperature To ex Diagram 7.2.1.1, curve b).

$$S_{rh} = \frac{h_o \times 100}{h_{o1}}$$

Formula 7.2.1.7

h) Load factor

Load factor K_l is the proportion of the adsorbed quantity of water in kg, per kg of drying material utilised, referred to the operating conditions. The load factor (breakthrough capacity) results from the secondary relative humidity Srh and the assumed dwell time. According to Diagram 7.2.1.2, the mean value K_l = 8 - 20 %.

Diagram 7.2.1.2 applies to the achievement of a stable dewpoint of Pdp -40° C at the end of the drying period, measured at 1 bar absolute.

During the greater part of the drying period, the dewpoints are significantly better. If a one layer filling of water proof silica gel is used exclusively, the capacity read from the diagram should be multiplied by factor 0.7.

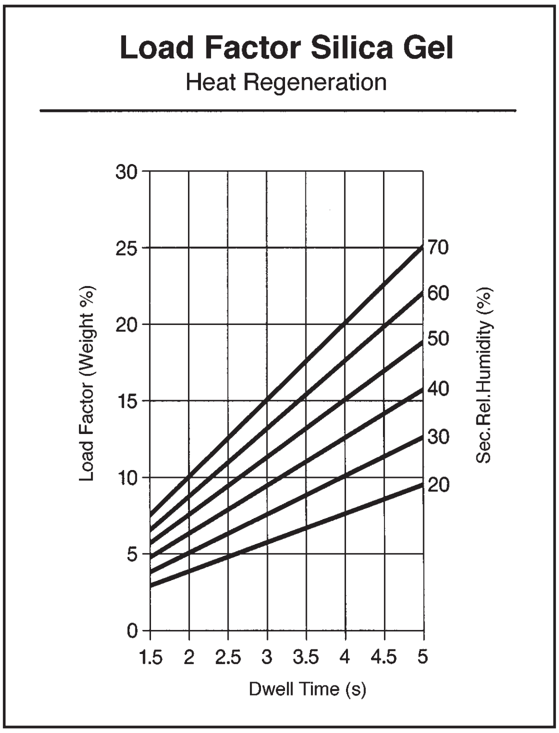


Diagram 7.2.1.2

The influence of load factor K_l on the size of the dryer is frequently underestimated in practice, as this value

depends on the secondary relative humidity

can become extremely small at low operating pressure and high inlet temperature

I) Quantity of desiccant

An adequate quantity of desiccant mdr, a reserve margin for the particular application, is important. The desiccant quantity is determined from the moisture load per cycle and the load factor.

$$\boxed{mdr = hc \times \frac{100}{Kl}}$$

Formula 7.2.1.8

j) Adsorber volume

In order to protect the adsorption material from liquid water, a protective layer of 20 - 25% of the drying medium is formed at the inlet side of the drying bed, using waterproof material. The adsorption dryer with heat regeneration used for normal compressed air drying is filled with a drying medium of silica gel :

20 - 25% waterproof material at the inlet
75 - 80% non waterproof material at the outlet

The total packed density of this combination of waterproof and non-waterproof material is to be inserted into the formula, using the values from Table 6.0.1.

$$\boxed{V_{dr} = \frac{m_{dr}}{d_{dr}}}$$

Formula 7.2.1.9

k.) Flow velocity

The permitted flow velocity for the gas/air relative to be the operating pressure can be obtained from Diagram 7.2.1.3 and should not be exceeded by more than 20 %. If the velocity in the adsorber is exceeded, the vessel diameter must be increased.

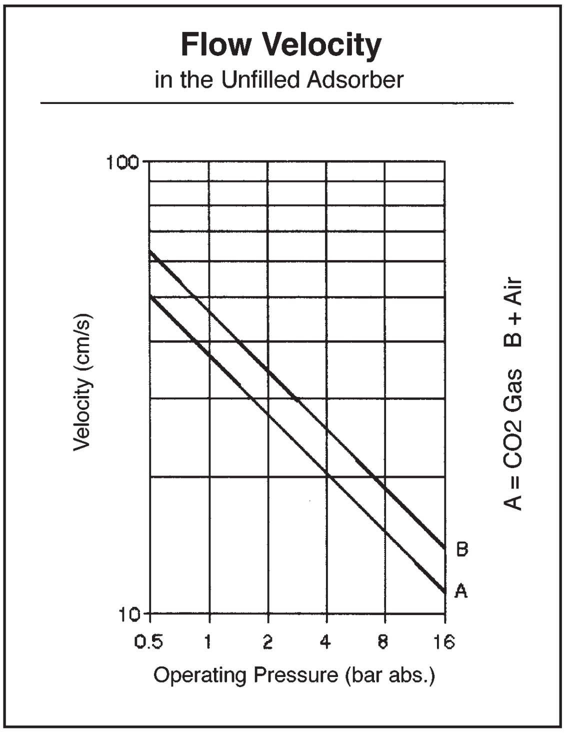


Diagram 7.2.1.3

l) Adsorber surface

With the operating volume flow V_O from Formula 7.2.1.2 and the flow velocity we from Diagram 7.2.1.3, the adsorber cross sectional surface area A_{dr} is determined, using Formula 7.2.1.10 while taking into account the units which apply, i.e. m³/h or m/s.

$$\boxed{A_{dr} = \frac{Vo}{w_e \times 3600}}$$

Formula 7.2.1.10

m) Filling height

Adsorbers are dimensioned in such a way that the filling height amounts to at least 500 - 600 mm. At the same time, the relation ship of diameter to filling height, as well as the air inlet, must be arranged in such a way that even flow through the drying material is ensured.

$$\boxed{F_h = \frac{V_{dr}}{A_{dr}}}$$

Formula 7.2.1.11

n) Dwell time

Given normal applications in the air drying field, the dwell time should be of the order of about 5 seconds. As can be seen from Diagram 7.2.1.2, the capacity of the desiccant diminishes if the dwell time is shortened. The dwell time also influences the degree of compressed air drying. The values from Diagram 7.1.1.3 serve as a guide.

$$\boxed{t_d = \frac{F_h}{w_e}}$$

Formula 7.2.1.12

o) Pressure loss

At the specified flow velocity we and operating pressure p_O, the pressure loss l1,2 of the air when flowing through a layer of silica gel, which has been compacted by vibration, can be determined in line with Diagram 7.2.1.4 per metre of filling height F_{hm}.

The pressure losses specified in the diagram apply if the desiccant bed is packed as tight as possible without destroying the beds of desiccant. In practice, these values are reached only after a lengthy time of operation.

When determining the pressure loss in order to specify the pressure capacity of the regenerating blower, there should be a sufficiently large safety margin. However, what is read from Diagram 7.2.1.4 is solely the pressure loss caused in the desiccant bed per metre of filling height.

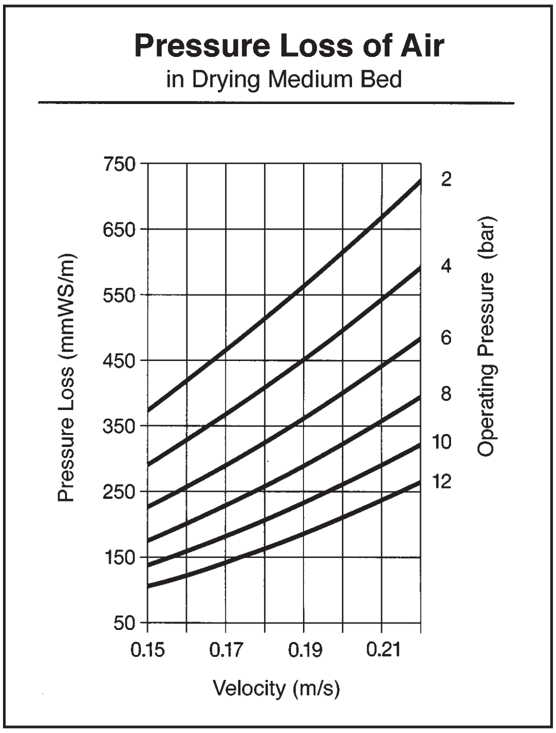


Diagram 7.2.1.4

In order to determine the total pressure loss in the adsorption dryer, all individual pressure losses arising from the dryer components, such as inlet valve, piping at inlet and outlet, outlet valve and the fittings within the adsorber vessel have to be added up.

$$\boxed{\Delta p = 1{,}6 \times 10^{8} \times \frac{V^{1{,}85} \times L}{d^{5} \times p_1}}$$

Formula 7.2.1.13

Calculating the total pressure loss using Formula 7.2.1.13 is relatively difficult. For this reason, this is generally obtained in practice with relative accuracy by using nomograms and tables.

7.2.2 Correction factor

When designing an adsorption dryer using heat regeneration, the determination of the loading capacity is quite complex, and has to undergo critical evaluation in order to arrive at reliable results. Deduced from the calculation example, Diagram 7.2.2.1 shows correction factors as a function of inlet temperature T_i and operating pressure p_o.

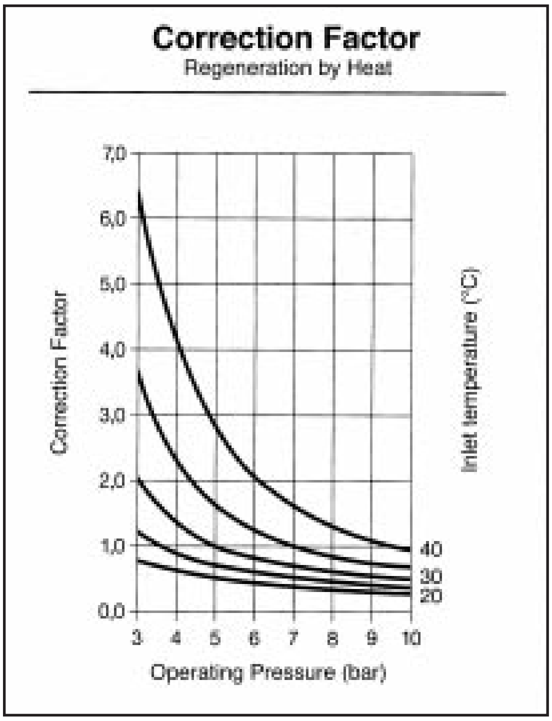


Diagram 7.2.2.1

The higher the temperature and the lower the operating pressure at the inlet to the equipment, the larger the adsorber must be, in order to be sure of achieving the desired drying capacity.

The outlet temperature must not exceed the lower regeneration temperature range, otherwise the quality of compressed air drying through the entire period of adsorption becomes questionable.

7.2.3 Regeneration

a.) Desorption temperature

Desorption takes place, using heated blower air. As a source of heat, electrical energy, steam, hot water or even heated oil could be used. The available energy must be sufficient to heat the adsorber to the appropriate desorption temperature T_{RE}.

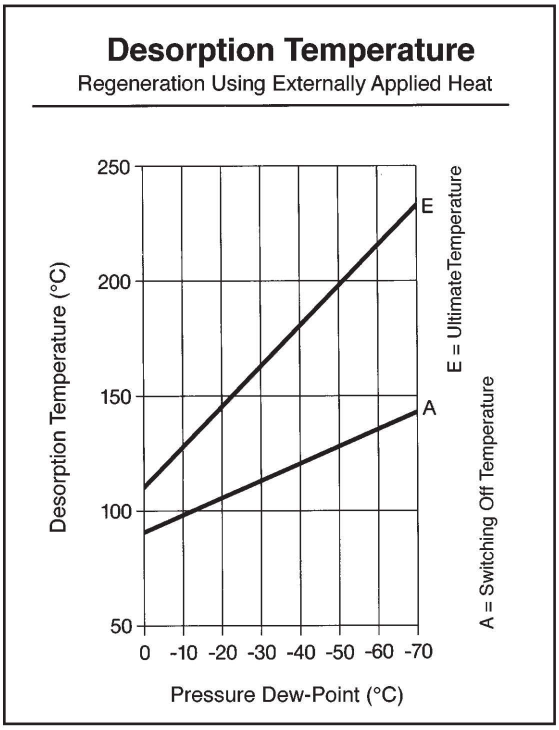


Diagram 7.2.3.1

Desorption temperature and pressure dewpoint Pdp vary indirectly in accordance with Diagram 7.2.3.1, curve E). In order to be certain of a pressure dewpoint P_{dp} -40°C, a desorption temperature of T_{RE} = 180°C is necessary.

b) Switch off temperature

In the course of desorption, the temperature level within the adsorber is continuously moved along the latter's length towards its outlet. A temperature change at the adsorber outlet signals completion of temperature migration and is used to trigger the switching off of the heating phase.

Switch off temperature T_{RO} can, correspond to the pressure dewpoint, use curve A) of Diagram 7.2.3.1 as a guideline value. Changing the switch off temperature exerts considerable influence on the pressure dewpoint.

c) Temperature difference

Given a high level of moisture loading on the desiccant ($QH_2O/QS > 0.7$), it suffices to determine the regeneration air quantity via the desorption temperature.

In practice, a situation is rarely met, and is not described in further detail in this section. Given low loading of the desiccant ($Q_{H_2O}/Q_S < 0.7$), a significant portion of the heat is used (see Section 7.2.4) for heating the drying medium and the equipment.

The quantity of regeneration air required is calculated, using the logarithmic temperature difference. The method for determining the temperature difference is explained later.

d) Logarithmic temperature difference, desorption

The logarithmic temperature difference, desorption, is obtained from the desorption temperature T_{RE}, the switch off temperature T_{RO} and the temperature of the desiccant bed T_{BC}.

$$\boxed{\Delta T_{r\,\log} = \frac{T_{RO} - T_{BC}}{\ln \dfrac{T_{RE} - T_{BC}}{T_{RE} - T_{RO}}}}$$

Formula 7.2.3.1

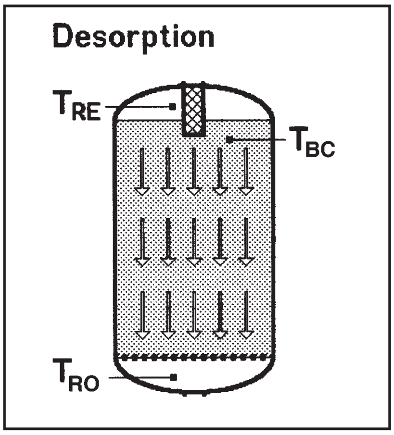


Fig. 7.2.3.1

e) Logarithmic temperature difference, cooling

The logarithmic temperature difference during the cooling stage is obtained from the desorption temperature T_{RE}, the inlet temperature T_i and outlet temperature T_{CO} of the cooling gas.

The inlet temperature of cooling gas equals the ambient temperature plus the temperature rise caused by the blower (about 5 - 15 °C on top of the ambient temperature).

The outlet temperature T_{CO} of the cooling gas should not exceed 70 - 80°C, in order that the humidity within the blower air on the dry side of the adsorber bed is kept as low as possible. The lower the outlet temperature obtained, the greater the probability of an elevated pressure dewpoint peak remaining constant (see Section 7.2.7) over a long period of time.

$$\boxed{\Delta T_{K\,\log} = \frac{T_{RE} - T_{CO}}{\ln \dfrac{T_{RE} - T_{o}}{T_{CO} - T_{o}}}}$$

Formula 7.2.3.2

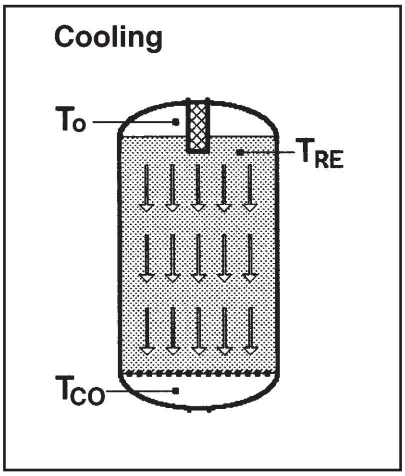


Fig. 7.2.3.2

Figs. 7.2.3.1 and 7.2.3.2 show the previously mentioned temperature zones for the desorption and cooling phase for determining the logarithmic temperature difference. An accurate and, realistic determination of the logarithmic temperature difference is essential for the overall heat allowance.

The desiccant medium and the adsorber are cooled to a low operating temperature during the cooling phase. The cooling phase (see Section 5.4.3) is terminated after a specified time period.

It is important to limit cooling in order to avoid a harmful pressure dewpoint peak when cycling from regeneration to adsorption.

As the ambient air used for regeneration has a certain moisture component, it is when cooling with moist ambient air, the upper layer of the desiccant material will always be slightly preloaded.

This preloading causes a pressure dewpoint peak so that, during adsorption, the dried compressed air contacts this humid zone, and re-entrains some of this moisture again and carries it into the compressed air piping.

Using Diagram 7.2.3.2 and assuming an inlet temperature T_i = 30°C and an operating pressure p_O = 7 bar, the logarithmic temperature difference can be roughly determined for different pressure dewpoints.

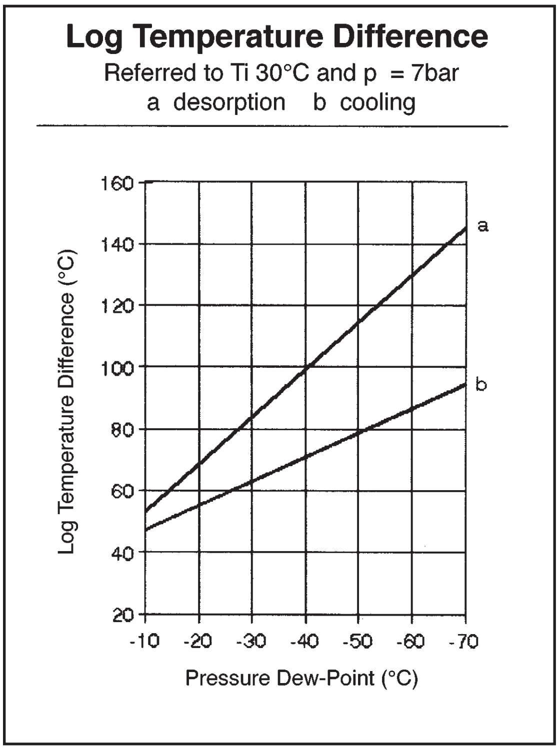


Diagram 7.2.3.2

For different values, Formulae 7.2.3.1 and 7.2.3.2 are used to obtain the logarithmical temperature difference.

7.2.4 Energy requirement

a) Drying medium

The energy requirement for the quantity of drying material (silica gel), or other desiccant, is calculated with the specific heat value cdr from Table 6.0.1, using Formula :

$$\boxed{Q_{dr} = m_{dr} \times c_{dr} \times (T_{RE} - T_o)}$$

Formula 7.2.4.1

b) Moisture load

The adsorption heat QH depends on the load factor K_l from Diagram 7.2.1.1. Adsorption heat Q_H from the diagram is multiplied by the moisture load h_c from Formula 7.2.1.4.

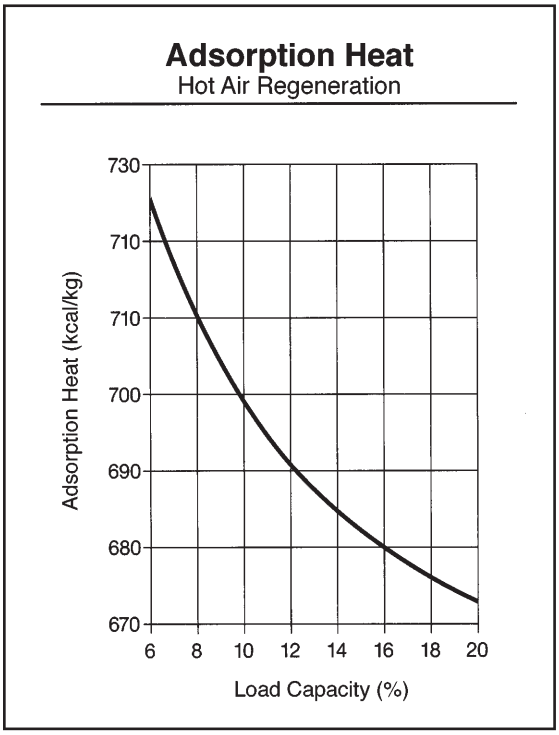


Diagram 7.2.4.1

Depending on the load variations at the adsorber inlet, the heat of adsorption for a given moisture content may differ considerably from the design assumptions.

Adsorption dryers are, in principle, designed for the theoretical maximum moisture load. However, under practical operating conditions, they are very frequently charged with a lower moisture load. Utilisation of the reserve resulting from this takes place as a function of loading.

$$\boxed{Q_{H2O} = h_c \times Q_H}$$

Formula 7.2.4.2

c) Vessel

In order to obtain the percentage of the energy taken up by the vessel, a rough estimate of the vessel weight has to be made in the first instance. For this, specified data is necessary, based on loading receiver technical regulations :

wall thickness	s	= x mm
thickness of bottom	s_1	= y mm
length	S_{h1}	= z mm
fitting	m_Z	= in%
spec.grav.	Stδb	= 7.85 kg/dm^3

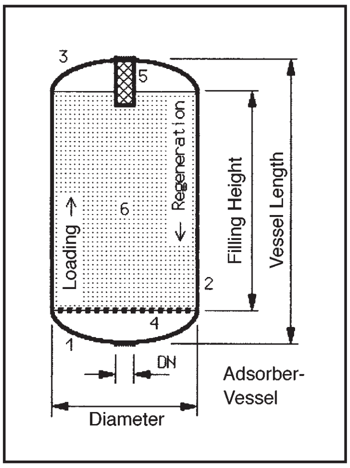


Fig. 7.2.4.1

The vessel weight m_V is determined.

For the energy requirement Q_{St} of the adsorber, a supplement m_Z has to be added to the vessel weight m_V, as fittings within the vessel increase the weight and not only the adsorber but also further components such as connecting piping and valves are partly heated up during desorption.

Whereas the energy requirements arising from the desiccant and the moisture loading are determined with a high degree of certainty, the energy requirement of the total mass of steel mst including components must be within a range of tolerances.

The determination of the mass of steel to be heated depends on a significant variety of factors, e.g. differing surrounding conditions and different locations.

The specific heat value for standard steel cst = 0.11 kcal/kg°C has been taken into account in Formula 7.2.4.3. A correction for the cst value is required depending on the material selection.

$$\boxed{Q_{st} = m_{st} \times c_{st} \times \Delta T_{r\,\log}}$$

Formula 7.2.4.3

d) Energy requirement

The energy for desiccant Q_{dr}, moisture loading QH_2O and vessel Qst are combined to obtain the sum of the energy requirement Q_S.

$$\boxed{Q_S = Q_{dr} + Q_{H_2O} + Q_{st}}$$

Formula 7.2.4.4

e) Additional energy requirement, radiation

The radiation energy requirement Q_{ra} of an adsorber depends on its' location. The following may serve as a general indicator: The higher the logarithmic temperature difference for desorption, the higher the heat loss through radiation. In the absence of all required parameters, it is hardly possible to predetermine radiation in practice. For this reason, and depending on the type of application and the location, qra is assumed to be 4 - 8 % of the total energy requirement Q_S.

$$\boxed{Q_{ra} = Q_s \text{ x } \frac{q_{ra}}{100}}$$

Formula 7.2.4.5

f) Grand total energy requirement

Putting forward a grand total of energy requirements for heat regenerated adsorbers can only be theoretical. A general tolerance of 2 - 5% is to be expected. As the parameters, to some extent, mutually affect each other, an appropriate and low as possible safety factor, based on experience and visual observation, s required.

$$\boxed{Q_{tot} = Q_s + Q_{ra}}$$

Formula 7.2.4.6

g) Energy requirement, cooling

The energy requirement for cooling is considerably lower than that for desorption. For one thing, only the drying materials and the adsorber are cooled, for another, we have the favourable temperature gradient of cooling. Under normal conditions, the relationship between desorption and cooling is about 4:1.

$$\boxed{Q_C = [(m_{st} \text{ x } c_{st}) + (m_{dr} \text{ x } c_{dr})] \text{ x } DTc_{log}}$$

Formula 7.2.4.7

7.2.5 Air requirement

a) Regeneration air quantity

In order to determine the quantity V_{rh}, by means of the heat allowance, the heat content cdr and also the heat quantity qdr of the desiccant has to be inserted into Formula 7.2.5.1.

The equation firstly determines the regeneration air quantity for the moisture load first part, and secondly without moisture load. The valid values for heat quantity qdr = 31.0 kcal/m^3 and heat capacity
c_{dr} = 0.31 kcal/m^{3}°C.

$$\boxed{V_{rh} = \frac{Q_{H2O}}{q_{dr}} + \frac{Q_{ges} - Q_{H2O}}{c_{dr} \times \Delta T_{R\log}}}$$

Formula 7.2.5.1

b) Cooling air quantity

$$\boxed{V_{rc} = \frac{Q_k}{c_{dr} \times \Delta T_{K\log}}}$$

Formula 7.2.5.2

For the cooling air quantity V_{rc}, the energy requirement Q_c, the difference in temperature and the heat content cdr are taken into account.

c) Total air volume

Given a regeneration period tr, regeneration air quantity V_{rh} and cooling air quantity V_{rc}, the total air volume V_t for the unit of time is determined.

$$\boxed{V_t = \frac{V_{rh}}{t_r}}$$

Formula 7.2.5.3

7.2.6 Regeneration period

a) Desorption time

Desorption time th is obtained by dividing regeneration air quantity V_{rh} by the total air volume V_t.

$$\boxed{t_h = \frac{V_{rc}}{V_t}}$$

Formula 7.2.6.1

b) Cooling time

Cooling time t_c is obtained by dividing cooling air quantity V_{rc} by the total air volume V_t.

$$\boxed{t_c = \frac{V_{rc}}{V_t}}$$

Formula 7.2.6.2

7.2.7 Power requirement

a) Total energy heater

The total energy requirement Q_{tot} is calculated with Formula 7.2.4.6 and used for obtaining the heating power P_e, taking into account the efficiency of the heating system.

$$\boxed{P_e = \frac{Q_{tot}}{860 \times nH}}$$

Formula 7.2.7.1

b) Heater power

The heater power arises from the total energy of the heater P_h and the heating time th. The theoretically obtained figure is rounded off to form a standard value.

If required, an addition to be on the safe side can be included. The difference between the theoretically obtained value and that after rounding up to a standard figure incorporates a heating capacity reserve.

There must, however, be some harmony between the safety factor and the reserve, so that costly over dimensioning of the heating capacity is avoided.

$$\boxed{P_h = \frac{P_e}{t_h}}$$

Formula 7.2.7.2

c) Blower power

The most commonly used method for determining the blower power P_b consists of extracting the appropriate data from the performance curves of the blower (Diagram 7.2.7.1). As an alternative, there is the following Formula for calculating blower power, which takes into account the efficiency with a mean value of about 0.3 - 0.4:

$$\boxed{P_b = \frac{V_b \text{ x } Dp}{102 \text{ x } n}}$$

Formula 7.2.7.3

For adsorption dryers with external heat regeneration, the blower draws ambient air and heats this by means of the heater to reach regeneration temperature, so that it can subsequently be passed through the dryer system.

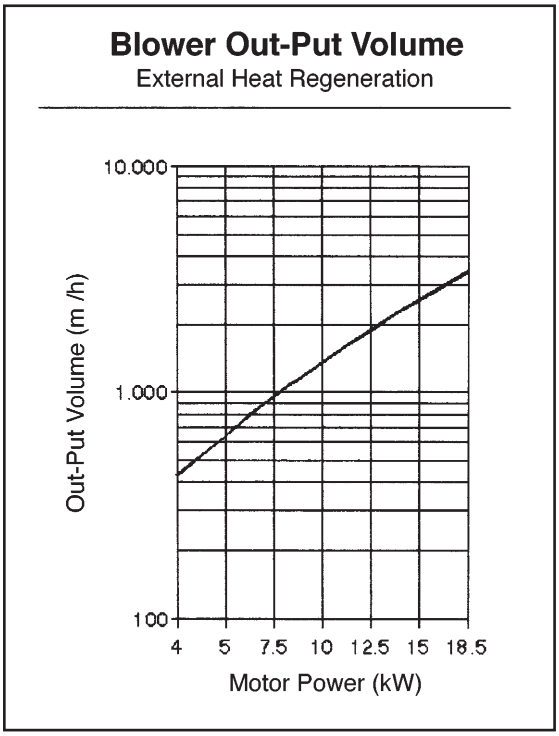


Diagram 7.2.7.1

If a high differential pressure (see Section 7.2.1) rise or the blower is designed on the low power side, there is a danger of insufficient regeneration. This can be compensated for only by a longer heating period. The situation then becomes critical if a long heating period prevents sufficient cooling.

d) Mean power requirement, heating

The mean power requirement for the heating device P_{hm} is of importance to the operating costs as these determine the economic viability of an adsorption dryer.

$$\boxed{P_{hm} = P_e \times \frac{t_h}{t_B}}$$

Formula 7.2.7.4

e) Mean power requirement, blower

Whereas for the mean power requirement of the heating arrangements, only the desorption period is of significance, assessment of the mean power requirement of the blower P_{bm} must, in addition, consider the cooling period.

$$\boxed{P_{bm} = P_g \times \left(\frac{t_h + t_C}{t_B}\right)}$$

Formula 7.2.7.5

f) Mean total power requirement

The mean total power requirement P_m provides a specific value which can, pro-rata, be used for calculating the operating costs of adsorption dryers.

$$\boxed{P_m = P_{hm} + P_{bm}}$$

Formula 7.2.7.6

g) Flushing air quantity

In order to prevent a pressure dewpoint peak (see Section 5.4.3) it may, under certain circumstances, be necessary to flush the adsorber with a fraction of already dried compressed air after the cooling phase. As a guideline quantity, one calculates a requirement of 3 - 6% for the duration of about 1 hour

$$\boxed{V_{fl} = V_b - V_{beff}}$$

Formula 7.2.7.7

determines the difference between the theoretical and the effective blower volume flow.

h) Remark

When considering the design layout of adsorption dryers with heat regeneration, it becomes clear in the heat allowance that an under sized dryer does not have favourable overall power requirement.

Savings in the initial investment can easily be confused with the apparent saving of energy used in its operation.

Additionally, if the ageing of the desiccant due to the higher thermal loading is taken into account, any reduction in capital costs are lost through higher service costs over a relatively short period.

Part 8

8.0 Dewpoint measurement

Humidity measurement of air is carried out in order to record specific values of moisture content. The importance of moisture in the fields of industry, biology and medicine has increased with time. In many manufacturing processes, the humidity of air can exert a decisive influence on the quality of its' products. Continuous monitoring of humidity is therefore an important factor in industrial production.

Compressed air drying and dewpoint measurement may be differing areas of technology but many aspects of process and measurement technology are frequently closely interlinked. Adsorption drying and dewpoint measurement complement each other ideally. In the increasingly widespread use of adsorption dryers, dewpoint measurement technology will improve monitoring, economy, operating safety and reliability.

Dealing with compressed or dried air is subject to conflicting points of view. On one hand, high humidity must be avoided in all cases, yet the air must be dried only so far that its absolute humidity affects neither systems nor product quality. A low moisture content in air is acquired at the price of high operating costs. Endeavouring to adapt the dewpoint to the manufacturing process is an optimum compromise.

Manufacturers of the pure gases or plastics granules as well as intermediate products must offer guarantees for the product quality linked to moisture content against the background of ever more stringent quality and product liability requirements. Many plastics, such as polyester or modified polycarbonate, must not be processed if the moisture content is more than 0.01 %. Most dryers, therefore, operate with a safety margin in order to keep within guaranteed residual moisture contents.

Improved dryer performances, more precisely specified product characteristics and ecological points of view are determining factors when controlling moisture. Next to avoiding too high an air humidity, the avoidance of too low air humidity has also become important. If, for instance, the previously mentioned polycarbonates show too high a level of desiccation, they lose qualities such as insulation or surface lustre. Too high a level of drying also leads to colour changes or material brittleness.

8.1 Development

The dewpoint temperature signifies the temperature at which water condensation occurs when air cools to the dewpoint temperature. The dewpoint temperature in degree Centigrade is, related to the absolute humidity of the air, usually lower than the air temperature. Only at a relative air humidity of 100 % are both temperature values identical.

For this reason, the gap between dewpoint temperature and air temperature, also known as dewpoint temperature gap, is of the highest significance as an early warning of the formation of condensate water.

The absolute air humidity or true water vapour content of air is independent of temperature. For all production sequences where water precipitation from air has to be kept under observation, it is only this dewpoint temperature which is decisive.

Before, dewpoint measurement could be effectively used for dryer control systems, a long and arduous path had to be trodden before reaching the present state of the art.

There have been sensors for measuring air humidity for about 400 years. The value of relative humidity (RH), which they measured, was considered unproblematic for a long time, as measurements of highest accuracy were, required to a limited extent only. The mere concept of relative humidity already implies the dependence of this parameter on a second basic value subject to strong fluctuations, the air temperature.

Dewpoint was previously established by means of a simple air humidity measuring instrument such as the air hygrometer. However, this instrument required continuous servicing and regeneration as, otherwise, reading errors of up to 20 % became possible. Because of its strong dependence on temperature, the value indicated was valid only for the current temperature at the location of measurement.

An air hygrometer, for instance, gives different readings depending on whether it is situated close to a source of heat or mounted on a cool wall, although the absolute air humidity in the room concerned is the same. It makes no physical sense in many cases to measure the relative air humidity as, from the point of view of process technology, the true water vapour content of the air, independent of the temperature at the time, has to be monitored.

With mounting quality requirements of industry, the RH measurements were increasingly seen as an inaccurate measurement method, associated with cumbersome installation and maintenance efforts. On top of this, there was the difficult re-calibration of the sensors which had to be carried out frequently.

The development of the Lithium Chlorite (LiCL) measuring element paved the way for a more accurate determination of the true water vapour content of air and other gases.

The measurement principle consists of warming a hygroscopic lithium solution on the measurement element for as long as, and until the heat exchange between the LiCl solution and the air surrounding the measuring element is balanced, so that the partial water pressure above the LiCl solution is also identical with that of the surrounding air. The temperature of the LiCl solution, which is reached upon achievement of this state of equilibrium, represents a direct measure of the absolute air humidity.

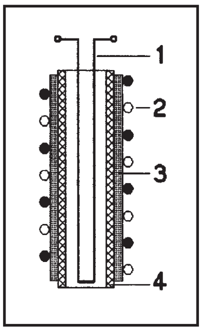


Fig. 8.1.1

The LiCl measuring element (Fig. 8.1.1) consists of a thin glass tube (item 4) over which a specially prepared glass wool hose (item 3) has been slipped after being soaked in a special LiCl solution. Two precious metal wires (item 2), electrically insulated from each other, are wound around the glass wool hose.

An alternating current of 24 Volt is applied to the terminals at the free ends, and this makes a current flow through the LiCl solution. The heat generated by the current evaporates the moisture and crystals are formed, so that conductivity and thus also the current, are reduced. The LiCl solution resumes picking up moisture from the air, renewed warming up takes place until a state of equilibrium is reached at a specific temperature.

The temperature measured by means of a thermometer (item 1) determines the value of the absolute humidity.

Neither the air hygrometer nor the LiCl measuring element provided a technically practicable solution which could have found utilisation for controlling adsorption dryers. Further endeavours were made to find a universal and accurately functioning humidity measuring system valid under harsh operating conditions. Engineers were looking for a suitable dewpoint sensor.

The decisive step forward occurred in 1968, when David Chleck an American Engineer applied for a world wide patent covering an aluminium oxide moisture sensor, gold coated by vapour deposition. For the first time, this measurement sensor, provided absolute measurement characteristics and eliminated the interfering temperature and hysteresis effects.

Seen in general terms, humidity measurement is more difficult to carry out than the measurement of temperature, pressure, length or weight. Many interference factors are capable of influencing the exchange mechanism between the substances to be dried (compressed air) and the surface of a solid (sensor surface). The sensor technology known today has been tested and improved in the course of development.

The characteristics of the aluminium oxide moisture sensors satisfy the extreme demands of industrial application. They resist harmful materials or pollution through dust, are insensitive towards flow, condensation, vibration or temperature shocks, and are stable for a long time.

All this has contributed to the fact that process parameter humidity can now be measured accurately and without too much trouble as a universal quality indicator. For compressed air drying, humidity measuring technology will assume an ever more important role.

8.2 Humidity measuring technology

The physical fundamentals of humidity have been dealt with elsewhere. Here, only the explanations necessary for understanding the measured values will be explained. Definition and units in the field of humidity measurement technology are not uniform. The moisture content of a gas, for instance, is given in g/m^3 or g/kg, in volume proportions or dewpoint temperatures.

Depending on the field of application, certain definitions are, however, preferred, arising from favourable measurement possibilities. For humidity measurements in gases, these are :

- moisture content of dewpoint temperature
- moisture content of volume proportions

If one establishes the proportion between water weight and weight of gas, or also between water volume and the volume of the gas under consideration, pure proportion figures are obtained. The abbreviated term ppm (parts per million) has proved its usefulness. For reasons of measurement technology, one uses volume shares in the case of gases, ppm_V.

The determination of water vapour volume presents considerable difficulties. Basing itself on the gas laws, the volume share ppmv is determined by establishing the proportional share of the water vapour pressure in relation to the total pressure.

The general gas law applies to water vapour :

$$\boxed{p \times V_w = n_w \times R \times T}$$

Formula 8.2.1

For the overall volume, also called total volume, the following equation is valid :

$$\boxed{p \times V_T = n_T \times R \times T}$$

Formula 8.2.2

Dividing equations 8.2.1 and 8.2.2 leads to the following relation :

$$\boxed{\frac{V_w}{V_T} = \frac{n_w}{n_T}}$$

Formula 8.2.3

The volumes behave like quantities of material. On the basis of the fact that a certain volume is filled with water vapour, the equations defining the state arise:

$$\boxed{p_w \, x \, V = n_w \, x \, R \, x \, T}$$

Formula 8.2.4

$$\boxed{p_T \, x \, V = n_T \, x \, R \, x \, T}$$

Formula 8.2.5

Equation 8.2.4 divided by equation 8.2.5 results in :

$$\boxed{\frac{p_w}{p_T} = \frac{n_w}{n_T}}$$

Formula 8.2.6

The pressures behave like quantities of material or volumes.

$$\boxed{f\left[ppm_v\right] = \frac{p_w}{p_T} x \, 10^6}$$

Formula 8.2.7

Often, however, only an indication of relative humidity obtained by the relationship of water vapour partial pressure to water vapour saturation pressure, are all that is of interest.

$$\boxed{r_H \, [\%] = \frac{p_w}{p_T} x \, 10^6}$$

Formula 8.2.8

The concept of relative humidity is known from meteorology. The relative humidity is.the proportion of the absolute humidity h of the air to the saturation maximum h_S. The latter indicates the water vapour quantity in g, which 1 m^3 of moist air can take up without water condensation occurring.

8.3 Description of equipment

Monitoring the level of moisture in a compressed air system is carried out with the type of application in mind and recorded with the help of a dewpoint measuring instrument.

The dewpoint measuring instrument for monitoring moisture is, in its usual form, composed of the humidity value encoder (humidity sensor) with integrated electronics and the moisture measuring sensor. Both units are linked by means of a sensor lead. Depending on what is required from the installation being monitored, a plotter or signal emitter is connected to the terminals of the moisture measuring instrument.

Dewpoint measuring gauges are used for continuous measurement of absolute humidity of compressed air within the measurement range of -80°C to +20°C. The digital reading indication refers to a pressure of p_{abs} = 1 bar. For other operating pressures, a re-calibration (verification) for the targeted correction value is necessary. The possibility of selecting the measurement range makes it possible to adapt the measurements accurately to the application in question.

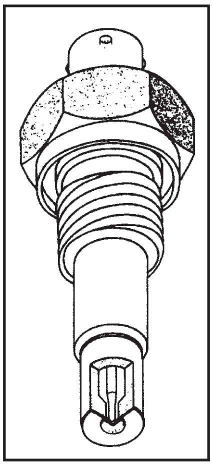


Fig. 8.3.1

The humidity measurement encoder (Fig. 8.3.1) consists of a humidity sensor and integrated electronics. The actual measuring element is an aluminium cylinder, the and face of which is covered by a thin layer of porous aluminium oxide. As an opposing electrode, a very thin layer of gold is vapour deposited onto this.

Depending on the level of the water vapour partial pressure, more or less water molecules penetrate the porous oxide layer of the sensor. The change in humidity resulting from this, causes a change of energy consumption capacity within the humidity measuring encoder.

Sensor capacity forms part of an oscillator (vibration generator) integrated into the sensor and determines the former’s frequency. The current pulses emitted by the measuring value encoder are converted into voltage pulses and, then transmuted into a D.C. voltage at the input of the measuring instrument. The linearised voltage becomes a digital reading via a transducer and a digital counting circuit.

The entire measurement encoder possesses a characteristic graph which is linearised. This ensures a high level of accuracy and simple adaptation for changing operating parameters. A limit switch which has been pre-set for an expedient value of dewpoint temperature or of moisture content, signals the limit value as an alarm or switching flag. These signals emit with 4 - 20 mA as analogue outputs.

8.4 Humidity measurement

There are, essentially, two phenomena which can make it difficult to measure traces of moisture :

Normal ambient air has a high moisture content up to about 10 000 ppm. Minute leaks in the piping system or tubing can thus lead to incorrect value measurements.

Arising from its molecular structure, water is highly polarised, causing a strong inclination or affinity to be adsorbed.

In general principle, every measurement is associated with some inaccuracies. In order to reduce these inaccuracies to a minimum, special precautions have to be observed when aiming at accurate humidity measurement.

8.4.1 Sensor installation

If possible, the sensor is fitted inside a measuring chamber and allocated to a measuring point in the compressed air network at which the humidity content is to be determined. One should avoid fitting the measurement sensor directly into the piping, in order to avoid reading distortions caused by pollution. Contamination in the piping such as carbon or oil should, in the first instance, be regarded as additional carriers of stored moisture and lead to a slowing down of the indicating response time.

This makes it practically impossible to obtain readings of very low dewpoints. In such cases, the piping would have to be purged. In individual cases, it should be checked which solvent is most suitable for dissolving polluting elements.

A sample extraction system (Fig. 8.4.1.1) should always be designed when measuring humidity. Sample extraction is, as far as possible, branched from the centre of the pipe, as moisture is distributed unevenly within the volume flow of compressed air.

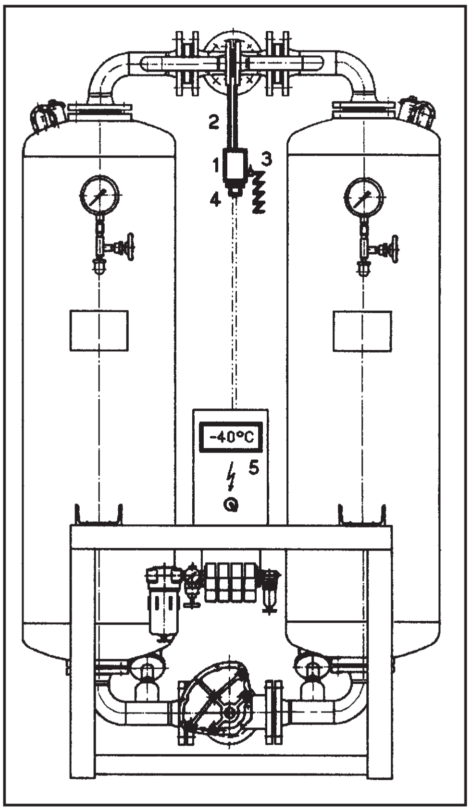


Fig. 8.4.1.1

Fitting the measurement sensor (item 4) in a measurement sensor chamber of small total volume (item 1) is therefore an essential precondition. The measurement ducting (item 2) should be built without connectors, fittings and dead corners, in order to avoid interference by stored moisture and condensate. The path between pipe network and sample extraction system should be kept as short as possible, as otherwise

- The response time of measurement is affected by the conveyance delay of the compressed air
- The walls of the measurement duct tubing act as an additional storage, influencing the indicating response time
- Temperature fluctuations in the measurement duct system exert an influence on the level of adsorption and desorption
- Long thin measurement lines with high flow velocity and resulting pressure drop falsify the value recorded.

8.4.2 Measurement tubing

The level of the adsorption inclination of the moisture depends on the raw material of the measurement tubing. The lower the dewpoint temperature, the more significant is the effect of this influence.

Unsuitable materials for the measurement tubing are, particularly, rubber or plastics with the exception of PTFE. Above the dewpoint temperature of -25°C, copper, aluminium or brass are suitable. For dewpoints below -50°C, nickel or stainless steel form the best choice as an ideal material.

In order to keep the storage or delaying effect of the sample extraction system as low as possible, relatively high flow velocities are necessary. The higher the flow velocity of the gas being monitored, the more rapidly a change in moisture is detected. The maximum flow velocities for the flow of gas at the measurement value recorder must, however, be within the tolerance range.

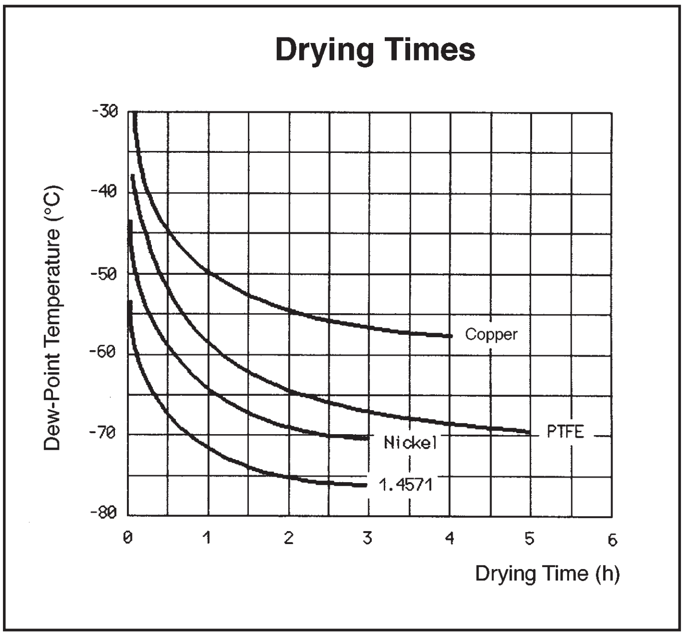


Diagram 8.4.2.1

In principle, flow does not affect the accuracy of the reading, only the` response time.

8.4.3 Influence of pressure

The partial water vapour pressure of compressed air changes in proportion to the absolute pressure of the gas being monitored. As each value of a particular water vapour partial pressure is associated with a specific dewpoint, the dewpoint also changes if the pressure changes.

Measurement, however, is not pressure dependent and the dewpoint sensor always indicates the currently prevailing dewpoint at the measurement point, without a correction value being required. Adsorption and desorption effect, on the other hand, cause the more harmful distortions, the lower the dewpoint temperature. That is why one measures within the range at which the highest dewpoint is to be expected.

With every pressure release of the measured air following the measurement chamber, heat is conducted from the surroundings, so that the release is accompanied by cooling. The lower temperature of the air being monitored resulting from this, leads to an increase in the adsorption inclination of the moisture in the air concerned. For this reason, the pressure release point in the piping should be followed by a calming stretch of about 2 m length and of spiral shape.

8.4.4 Influence of temperature

The temperature of the sample extracting system must be kept constant, as every change in temperature leads to a change in adsorption condition and therefore to a temporary change in the value likely to be measured.

Given small moisture contents, low flow velocity, dirty piping, incorrect sample extraction or unsuitable tubing materials, the measured value changes will, in extreme cases, become subject to time constants of several days and form the reason for the so-called “24 hour effect”.

As soon as the difference between dewpoint temperature and ambient temperature becomes too small and therefore the relative humidity too high, condensation collects within the pores of the aluminium oxide sensor. This has the effect of making the measured values increasingly unreproducible.

For this reason, the temperature difference between that of the dewpoint and that of the gas must be maintained to at least 15°C. However, the measurement sensor’s characteristics are not changed by condensed moisture.

8.4.5 Leaks

Ambient humidity usually surpasses the moisture content of the dry gas to be monitored many times over. For this reason, the slightest leaks into the system always cause incorrect measurements. The large difference between the water vapour partial pressures inside and outside the piping cause the moisture to penetrate into gas carrying piping, even though the latter is under pressure. Even now, piping systems for compressed air still display leakages of up to 20%. Flanged and threaded connections, as well as push-in couplings all contribute to leakage of compressed air lines. At such connecting points, ambient moisture diffuses into the system against the operating pressure. Less so with short lines with few joints than with correspondingly longer piping or plug-in lines.

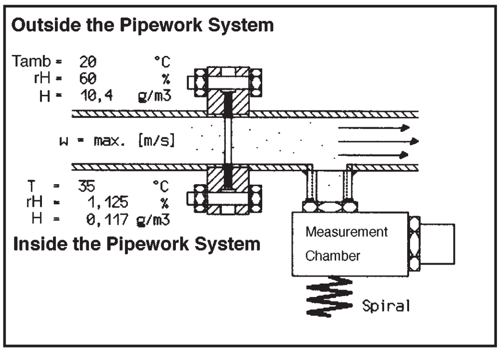


Fig. 8.4.5.1

Leakages in a gas line are normally regarded as approximately constant. Changes in the moisture content indicate a leakage. With a high throughput, this influence regarding the moisture content diminishes, and at slower flow velocity the moisture share increases.

If no compressed air is consumed and the flow velocity within the system thus equals nought, the diffusion of moisture at the connecting point has a stronger effect. The influence of leakages at maximum flow velocity of compressed air diminishes through dilution of the intruded humidity over a larger quantity of compressed air.

Ambient moisture can also penetrate into the sample extraction system from the measurement outlet and against the direction of flow. There should, therefore be a length of pipe of at least 2 m length and of spiral shape to be fitted to the measurement chamber outlet, so that the compressed air has to flow through this before entering the atmosphere.

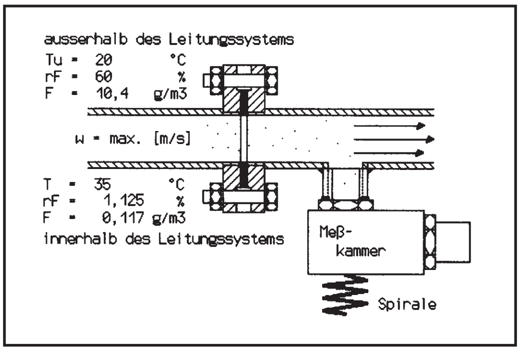


Fig. 8.4.5.2

The measurement sensors are suitable for measurements where extreme demands of leak/tightness are important. The specified rate of leakage is in the range of $<10^{-7}$ bar L/s.

8.5 Response time of indication

With humidity measurements, it follows therefore, that the speed of indication of the measurement depends not only on the sensor itself, but is to a large extent also affected by the system into which the sensor is fitted.

Parameters decisively influencing the measurement response time are, in this case :

- Material characteristics of the measuring system
- flow velocity of the gas being monitored
- temperature of the sample extraction tube
- influence of pollution
- influence of changes in humidity at any time

The last mentioned point has to be understood in the following manner: Adsorption and desorption have the more significant effect, the lower the dewpoint temperature. For this reason, a jump in humidity from 0°C to -20°C is indicated much more rapidly than a jump in humidity from -50°C to -70°C (see Section 5.2.2).

The indicating response time is therefore affected by the variations in the marginal conditions accompanying the measurement.

8.6 Dewpoint control

In an ideal case, dewpoint measurement instruments and adsorption dryers form a complex unit based on mutually complementary systems. The aim is to not only monitor the dewpoint, but the primary discussion objective is how to achieve effective control of the dewpoint, given all the required possibilities.

If humidity is accurately controlled, reduced desorption surpluses in the region of two digit percentages can be achieved, thus reaching more economical operating situations and clear savings in energy when adsorption drying. Compressed air, which is too dry, however can also lead to unnecessary equipment wear and therefore.shorter service life.

Adsorption dryers in combination with a humidity measuring system make possible an improvement in the quality of compressed air right up to the boundaries of present-day technical possibilities. Conceived as load dependent control system instead of time cycle control, dewpoint control systems are practically immune from maintenance problems and can be integrated into process control consoles at any time. By means of modern electronics and microprocessor technology, values obtained can be directly exploited via computer.

When drying by adsorption, not only the compressed air but also the saturation limit of the adsorbents have to be monitored. Regenerating adsorbers too early means unnecessary waste of energy, whereas on the other hand, regenerating adsorbers too late can cause ‘troughs’ in the quality level when drying compressed air.

Contrary to a time dependent control system of traditional design, continuously working humidity measurement systems are capable of permanently reacting to changing operating conditions, such as

- moisture saturation of the gaseous medium
- differences in volume flow
- fluctuations in temperature or
- pressure fluctuations

With a time dependent control system, regeneration always commences after firmly programmed time intervals, whatever the state of loading of the drying material. In conjunction with a dewpoint measuring system, is it possible to achieve continuous and stepless adjustment of the regeneration of adsorption dryers, finely tuned to the desired dewpoint.

A load dependent control system always brings about a variable cycle if there are fluctuations in the flow of compressed air, or if the inlet temperature with its associated moisture load varies strongly from summer to winter operation, or if there is the possibility of pressure fluctuations over a wide range arising from fluctuations in consumption.

Differences in moisture load at the inlet of the adsorption dryer through changes in volume, pressure or temperature cause changes of dewpoint at the outlet of the dryer. Depending on the requirement for residual humidity, the pressure dewpoint of the compressed air.is specified as a limiting value and used as control parameter in relation to a varying load situation.

Electronic programmable systems, coupled to a humidity measuring instrument, are capable of detecting the changing operating conditions, to evaluate them and to transmit them as secured signals. Every partial loading of the adsorption dryer is therefore directly converted into an extension of the adsorption period, while the desorption time remains constant. The saving in desorption energy results from the difference between variable adsorption time and constant desorption time.

A special characteristic has to be observed when using load dependent control systems with adsorption dryers regenerated by a percentage of the dried purge air. If one assumes the utilised load on the dryer with time dependent control to be 70 % of capacity, given a constant compressor output flow, the quantity of air for desorption is set for just this 70 % of the compressor performance.

When using load dependent control systems, on the other hand, this setting is always for 100 %, because the load dependent control utilises the dryer to 100 % through an appropriately lengthened cycle. Within the range of partial loading, the adsorption period is extended in proportion to the moisture load and calculated to correspond to a full load situation.

In doing so, the desorption period is not variably adapted with a correspondingly reduced desorption air quantity, as a partial load can, at any time, be followed by a full load and the necessary desorption period must have been fully concluded at such a point in time. Desorption time remains set at a constant level, corresponding to the shortest cycle time.

Overloading the adsorption dryer can, in principle, not be compensated for by a load dependent control system. Dewpoint control arrangements are suitable for all adsorption dryers, whatever mode of regeneration is used.

Part 9

9.0 System evaluation

The essential characteristics of the different types of adsorption dryer have now been described. The question is asked as to which adsorption dryer system is the best. Numerous publications have been issued on this subject, furnishing very interesting results. It is understandable that every manufacturer of adsorption dryers tends to allocate a premier position to his own system. It is the aim of a system comparison, not to evaluate a system as such but the peculiarities of a particular method of drying. Using fundamental parameters, it is possible to arrive at an objective evaluation.

It is assumed that the principal calculation schemes of adsorption dryers with heatless or heat regeneration are known. Such calculations form the basis of a logical comparison between systems The mathematically based relationships, form the basis for an objective study of the systems which are available. Thus, a system comparison with reproducible dryer data for the varying performance ranges can be developed and utilised for practical purposes.

Every system comparison is based on specific dryer data. This data is supplemented by the effective operating costs using different types of energy, e.g. steam, hot water, hot oil or electricity, which are available to the user. Estimated compressed air cost data, are out of place here. System comparisons based on assumed compressed air costs are not logical, for:

- It is the purpose of the system comparison to find out the cost of compressed air. The aim of the investigation cannot be used as its starting point.

- The installation is being supplemented by a new item so that only units which have already been installed can be taken into account.

- The unit present in the system is being exchanged for a new system with totally different performance data.

- Because of a demand for additional purified compressed air, the units already installed in the system are being extended and supplemented.

Other operating costs arising from the application case in question, such as power, water and steam costs, are input and are based on reliable experience.

Adsorption dryers with heatless regeneration are regenerated using a fraction (purge) of already dried compressed air, whereas adsorption dryers with heat regeneration have the energy for this supplied mainly from an external source.

A considerable error could be included into a system comparison, unless the real and differing energy costs have been specified correctly.

Only by the use of true compressed air parameters can an objective evaluation of various systems be achieved. This is based on allocating a uniform energy cost to the energy requirements for all types of regeneration. An unbiased comparison between all types of regeneration methods then becomes possible.

For example, the specific energy requirement of oil injected screw compressors amounts to about 6 kW/m^3/min (see Table 9.7.1). Given an output flow volume of 1000 m^3/h, adsorption dryers with heatless regeneration working at 7 bar require a quantity of regeneration air of 143 m^3/h. The compressor power requirement is then:

- The output flow of 6 kW/m^3/min x 1000 m^3/h x 1h/60 min = 100.0 kW.
- The regeneration air quantity 100 kW x 143 m^3/h/ 1000 m^3/h = 14.3 kW.

Pressure losses must also be taken into account if there is to be an objective system comparison. The proportion of pressure losses is obtained from the difference between p1[1] and p2[1] and is expressed in %. As a result, there is less energy available at the outlet of the adsorption dryer and therefore fed into the compressed air system. The difference in pressure is also taken into account when evaluating performance, all energies and losses are allocated to a comparable unit.

On this basis, a comparison of adsorption dryer data from the most varied designs can be objectively carried out without bias.

In addition, various factors have to be considered, all of which influence the selection of an adsorption dryer, objectively and subjectively, with reference to:

a) Investment

- cost effective investment
- pressure dewpoint required
- specific energy requirement
- low-cost energy source
- economical service life
- effective operating load

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[1] pressure/volume

b) Operation

- ecological evaluation
- low waste material disposal
- appropriate noise protection
- good access
- reliable servicing

c) Installation

- uniform spares storage
- dust loaded ambient air
- explosion prone location
- computer assisted monitoring
- location subject to frost
- off-shore operation

To mention only the most important decision characteristics. Every system manufacturer and operator of adsorption drying installations is called upon to list all aspects relevant to the particular application, thus facilitating a purchase decision.

It would be irresponsible to arrive at a universally valid statement advocating or rejecting a particular system without an adequately based evaluation. The wide range of applications, from the small receiver mounted compressor to the sophisticated compressed air plant, have to be considered in a different manner.

9.1 Ecological assessment

One has to take into account the most varied criteria when carrying out a qualified judgment of adsorption dryers. This means that adsorption dryers have, in principle, also be viewed critically from the ecological point of view.

Every system comparison, must include not only the energy consumption of the equipment but also the cost of responsible disposal or removal of accumulating auxiliary substances. Only then can an all embracing and economic decision be determined.

Responsible behaviour, when selecting a system, calls for new thinking so far as manufacturers and users of adsorption dryers are concerned. For this reason, the following additional points have to be considered when drying compressed air:

Waste product reduction by selecting the optimum system for the application.
Analyse energy costs and evaluate these objectively, using comparable energy data.
Decide on the basis of a reliable layout and long service life.

Ecological awareness with regard to all these aspects has to be considered. Of course, the economic performance of the adsorption dryer must still be borne in mind.

Low energy consumption products form part of this philosophy, as well as the consideration that a product can be claimed to be of the highest quality only if it is produced ecologically and economically, and can be utilised without causing unnecessary waste.

9.2 The environment as a factor

Comparison of adsorption dryer systems and their relevant operating data usually takes place without giving the environmental aspect much thought.

Environmental protection, when treating compressed air, is a subject of debate. The discussion concerning refrigeration dryers with refrigerants containing CFC's (chloro fluoro carbons) has been treated in great detail by the specialist press. The environmental acceptability of adsorption dryers is, in principle, regulated by the new waste product disposal legislation. This obliges every manufacturer and producer to declare environmentally relevant data regarding these products.

Ecological behaviour calls for a social conscience. Products used for compressed air treatment should place as little additional load on to the environment as possible. Clean and pure are terms always closely associated with adsorption dryers. Clean and pure characterises quality air which is achieved through such installations i.e. for parameters such as dewpoint, residual oil content, drainage rate and particle size. In these terms, evaluation of adsorption dryer systems has taken place for many years.

When these systems are assessed from the point of view of environmental technology, it becomes apparent that there are differences between the individual drying systems, as far as their by-products are concerned. Even small environmental drawbacks such as sources of harmful materials generated in the course of normal operation, while acceptable and within the limit values prescribed by law, are often ignored, and underestimated. In order to obtain an overall perception of a product, the criteria:-

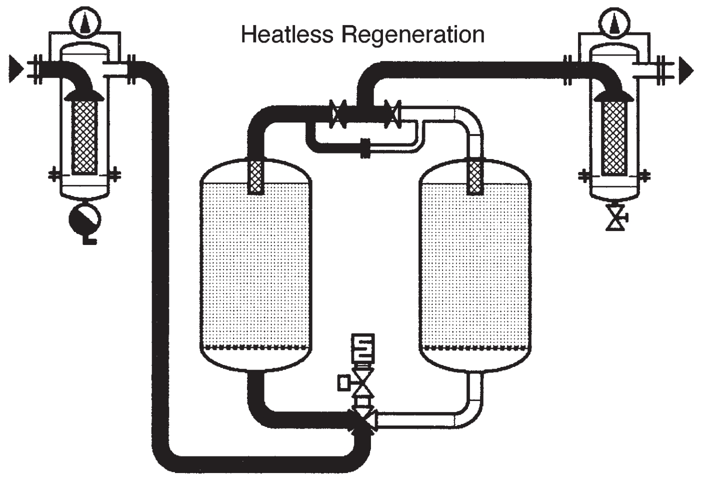
- Waste products
- Noise protection
- Service life

will be explained in more detail in the following paragraphs.

9.3 Waste products

Various substances used in the adsorption dryer have to be replaced in the course of its operating life. In addition to this, the operation of an adsorption dryer leads, to further by-products in addition to the substances consumed.

The concept of consumable material shows clearly that, in the first place, economical i.e. operating and works economy aspects, are reviewed. The enforcement of new waste product laws means that essential aspects of compressed air purification also have to be considered.



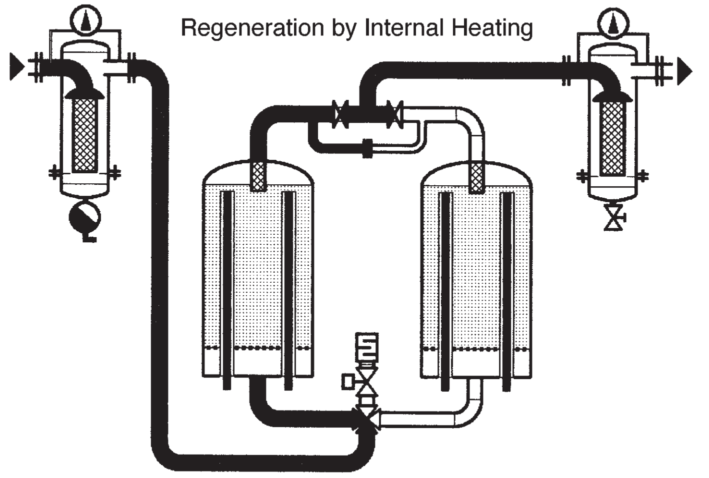
Prefilter	Adsorption Dryer	After Filter
Element	Drying Material	Element
Condensate pH-value 7	Moisture from Regeneration	
	Expansion Noise	

Fig. 9.3.1

Apart from the priority attached to the avoidance of waste products, there is also the responsibility of the manufacturer concerning the responsible disposal of the product manufactured by him. At the same time, there must be information made available about any by-products concerned and applicable safety data must be stated. Every operator is obliged to avoid pollution or, at least, to reduce it to an absolute minimum.

Compressed air dryers generate clean, dry compressed air but also by-products which cannot be avoided.

By-products and residual substances arising from the operation of compressed air dryers are those groups of waste materials arising mainly at service intervals from the replacement of operating aids such as filter elements and drying material.



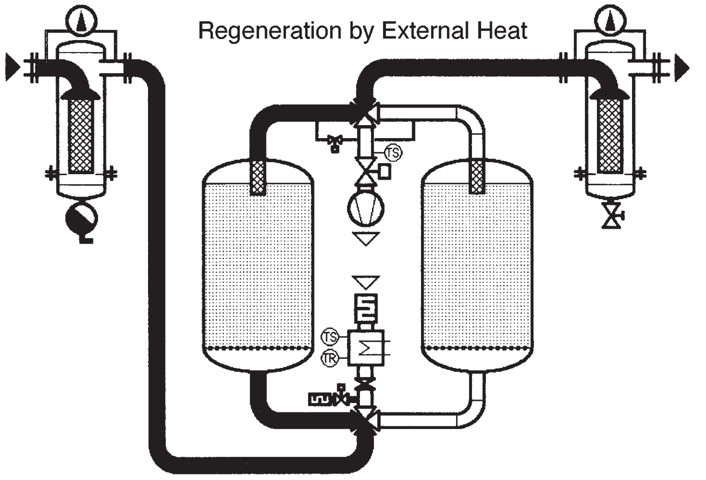
Prefilter	Adsorption Dryer	After Filter
Element	Drying Material	Element
Condensate pH-value 7	Moisture from Regeneration	
	Expansion Noise	
	Heat from Regeneration	

Fig. 9.3.2

Oil free compression promotes acid formation within the condensate and oil lubricated compression also becomes a polluting factor. Oil saturated prefilter elements may have to be disposed of as special waste products in accordance with legislation concerning used oil.

Contamination of the drying material with oil residues has to be looked at.
Oil lubricated systems are always protected by coalescing oil removal filters.

Assuming an inlet temperature of 30°C, the drying material is polluted by 0.015 mg/m^3 of oil (see Diagram 4.7.4.1) and at the same time charged with 30 g/m^3 of water (see Diagram 2.4.3.1). The proportion between oil loading and water loading thus amounts to 1:2000.000. The pollution of the drying medium (see section 4.7) with oil vapour is considerably less than often assumed. In its new state, drying material can be classified in accordance with the DIN safety data sheet. After some years of service life, the operator must carry out a new assessment.

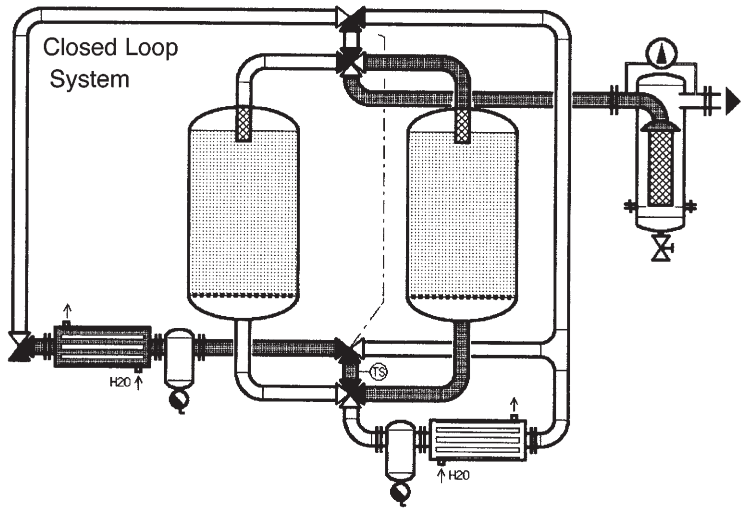


Prefilter	Adsorption Dryer	After Filter
Element	Drying Material	Element
Condensate pH-value 7	Moisture from Regeneration	
	Expansion Noise	
	Heat from Regeneration	

Fig. 9.3.3

As drying materials have a catalytic effect, the disposal of harmful substances must be considered. The best precaution is a conventional layout of the installation which usually leads to a prolonged service life of the filling where service lives (see Diagram 5.4.3.3) of 3-5 years are typical.

In accordance with European waste products legislation, every manufacturer is obliged to take back all material such as filter elements and drying materials, as pollution of the operating materials during service life in part drastically changes these materials so that they no longer correspond to the original product. Only officially licensed waste disposers are permitted to receive materials contaminated by the system.



Prefilter	Adsorption Dryer	After Filter
Element	Drying Material	Element
Condensate pH-value 4	Moisture from Regeneration	

Fig. 9.3.4

If in doubt, the disposal recommendations mentioned in the waste product catalogue should be applied. According to the latest European regulations, waste product removers or disposers are no longer allowed to accept waste products without disposal documentation approved by a waste product authority office.

Adsorption dryers are, in most cases, regenerated by means of their own or by outside air. We are thus dealing with regeneration air as well as with air which re-enters the atmosphere upon depressurisation. The fraction of the airflow which is released by heatless as well as internally heat regenerated dryers, as well as the regeneration and blower air of externally heated dryers are all exhaust air. Such exhaust air is released to the environment as a by-product or ducted via a suitable pipe. The regeneration air of both processes can include not only moisture but also dust, caused by the catalytic effect of the adsorption mass. With heat regenerated installations, one also has to consider the residual heat of the regeneration air.

Various locations and industrial areas presuppose that the exhaust air meets the requirements of TA-air. For pressure releases and depressurisation processes it is important that the exhaust filters retain dust particles which could otherwise enter the atmosphere. With closed loop installations, which regenerate at operating pressure, such exhaust air does not arise.

As compressed air is being dried, another by-product arises naturally, i.e. the condensate (see Part 11). Depending on the type of application and the design of the compressor, one has to deal with acidic condensate or oil/water emulsions. Responsible disposal or regeneration of condensate by means of Oil/Water Separators, filter installations or effluent water treatment forms part of the installation requirement.

Figs. 9.3.1 to 9.3.4 shown in this section represent the most important adsorption dryer processes complete with their characteristic by-products and residual substances. This data is based on operating experience with the systems shown.

9.4 Noise protection

The operation of an adsorption dryer is often associated with a high sound level. This sound level represents not only a disturbing or nuisance element; noise can damage hearing and is best reduced at its source.

The adsorption dryer with heatless regeneration, involving a continuous pressure release at a cycle of a few minutes with a relatively high sound pressure level of about 90 - 100 dB(A), is fitted with an effective silencer in order to cut down the noise. Free “blow-off” of the dryer during regeneration must be assured for technical process reasons. Silencing hoods in addition to the silencers reduce the sound level by about 5 - 7 dB(A). Microfilter silencers further lower the sound level by about 7 - 11 dB(A). (It has to be borne in mind that the elements of microfilter silencers have to be changed regularly.

Dryers with internal and external heat regeneration involve noise sources arising through the release valves, blower motor as well as suction and flow noises. Using a suction inlet silencer, these noises can be reduced to about 75 dB(A) without significant technical effort. Further reductions are possible through additional measures such as automatic silencing hoods. In adsorption dryers with heat regeneration, release is carried out in a throttled condition. This considerably reduces exhaust noises.

Closed loop adsorption dryer systems, which regenerate at operating pressure and thus without depressurisations during operation, complete their cycles with little noise. At the site of installation, the compressor and dryer sound sources add up.

When adding sources of equal sound level, the overall level
$L_t = 10 \log n_p = L + 10 \log n$.

2 noise sources of equal level increase the value by 3 dB(A)
10 noise sources of equal level increase the value by 10 dB(A)
100 noise sources of equal level increase the value by 20 dB(A)

When adding unequal noise sources, the overall level
$L_t = 10 \log [10^{0.1p1} + 10^{0.1p2} + 10^{0.1p3} + ...]$

9.5 Service life

An important aspect of the conventionally designed adsorption dryer is a long service life which offers the user many advantages. Longer life means fewer waste products, less material consumption, lower energy costs and longer availability, all of which have to be considered as benefits from the operation from the dryer.

Optimum service life is achieved through selection of components of high quality as well as effective protection against corrosion. One should always consider the option of stainless steel materials of construction in the wet sections of the installation.

Simple maintenance of the equipment and easy repair of the components used contribute to a long service life. This calls for high quality design and imaginative product development.

However, long service life for such equipment is not only a matter for the manufacturers of adsorption dryers and filters. The operators, have to contribute. Suction inlet conditions of the compressors at the place of installation have a far reaching influence on service life, likewise expert and regular servicing of the individual system sections are required.

Even air treatment systems of optimum design become ineffective if minimum requirements of the dryer and filter system are not adhered to. Optimum service life of a compressed air treatment package consisting of prefilter, adsorption dryer and downstream filter is only reliably achieved when reference conditions are adhered to. When considering the service life of air treatment equipment, the generation of the compressed air is often overlooked. The compressor and dryer as a unit are only as reliable as the weakest link in the chain.

9.6 Energy requirement

To save energy, to use it sensibly or even to re-use it, is a priority today and takes first place when selecting an adsorption dryer. Compressed air dryers consume energy directly and indirectly.

- Direct consumption of heat regenerated dryers in the form of electrical or steam energy as well as power consumption for the blower motor.
- Indirect consumption through pressure loss, leading to higher pressure in the compressor calling for increased power consumption
- Compressed air purge consumption for the regeneration of dryers with heatless or heated regeneration.

In most cases, the purge air consumption of adsorption dryers concerns compressed and already dried compressed air.

Closed loop systems regenerated by heat of compression indirectly use energy through the unavoidably increased pressure loss of the system.

Expensive operating energy can sensibly be saved through dewpoint or load dependent control systems. However, this is a very complex subject and is described elsewhere (see Section 8).

One must accept the principle that energy consumption of a particular system varies widely. It is, therefore, recommended that, in each case, an expert energy system comparison is carried out. The compressed air cost derived from the comparison of the dryer systems, being the result.

It is expedient to tailor this system comparison to the consumption requirements. Energy awareness is, however, not only a benefit for the operator but usually justified regarding the capital to be invested. Thus the system comparison preceding the selection of the correct process definitely avoids bad economic decisions.

9.7 Comparison of systems

The following sequence shows the structure of a system comparison of adsorption dryers. The system assessment is based on the following performance range :

Compressed air output	Q =	1000 - 5000 m^3/h
Operating pressure	p =	5 - 10 bar
Inlet temperature	ti =	25 - 45° C

This output range is of interest because it is relevant to all dryer systems and not based on idealistic values. The characteristic compressed air cost parameter to be established for adsorption dryers is based on £/1000 m^3. The design data is based on the average values of the overall range with

volume flow at inlet	3000 m^3/h
operating pressure at inlet	8 bar absolute
inlet temperature	35°C
relative humidity	100%

and subsequently indicated in the form of diagrams.

a) Design data

The design data within the assumed performance range is available without the need for calculations. The individual basic parameters are :

Volume flow at inlet	V	m^3/h
volume flow at outlet	V_o	m^3/h
inlet temperature	T_i	°C
relative humidity	rH	%
operating pressure at inlet	p_a	bar abs.
pressure dewpoint	P_{dp}	-°C

The pressure dewpoint for this comparison is laid down at P_{dp} -40°C. Heatless and heat regenerated adsorption dryers achieve this pressure dewpoint reliably throughout their service life. However, closed loop systems will only achieve this pressure dewpoint for limited periods under favourable conditions.

b) Cycle times

Differing periods for the adsorption and desorption processes are established depending on the system and laid down as minimum values for optimum drying. All time periods of importance for a comparison can be determined by means of the formulae (see part 7) as individually stated. For a general estimate, the following cycle periods apply under normal conditions[2]:

Subdivided Cycle Times	Heatless Regeneration	Heat Regeneration		
		Internal	External	cl.loop System
Adsorption Period t_B	1,00	1,00	1,00	1,00
Regeneration Period t_r	0,80	0,96	0,82	0,40
Heating Time t_h	-	0,65	0,54	0,27
Cooling Time t_c	-	0,31	0,11	0,13
Flushing Time t_f	-	-	0,18	-
Holding Period t_H	-	-	0,18	0,60
Pressure Build Up Time t_P	0,20	0,04	0,04	-

Table 9.7.1

With an optimum layout of heat regenerated adsorption dryers, the heating period th will not exceed 0.65 times the adsorption period t_B, so that the required temperature decrease can be reached within the remaining cooling time t_C.

c) Installed electrical capacities

Physical laws as well as the heat allowance determine the values of the installed electrical capacities and are to be obtained using the formulae for heating energy P_h (see Formula 7.2.7.2) and blower power P_b (see Formula 7.2.7.3).

These values can also be obtained from the adsorption dryer sales literature. Table 9.7.2 shows the installed electrical capacity requirement P_{iel} of the adsorption dryer systems[3] without the component used by the control system.

2p = 7 bar, t_{in} = 35°C; D_{dp} = -25°C

Design	Power Requirement P_{iel} $kW/m^3/min$	
Adsorption Dryer	Heating	Blower
Heatless Regeneration	-	-
Regeneration by Internal Heat	0,27	-
Blower Regeneration	0,61	0,13
Closed Loop System	-	-

Table 9.7.2

The difference between the values for internal heat regeneration systems as opposed to external blower regeneration is based on the fact that heat is applied to the desiccant bed in different ways. Adsorption dryers with internal heat regeneration permit direct contact between the heating element and the drying material with optimum heat transfer accompanied by minimum losses. With blower regeneration, the ambient air drawn in and heated by the blower is the means of conveying externally generated heat. Heat losses arise from the heating element to the air and, additionally, from the air to the drying material.

d) Air quantities

The air requirement for regeneration as well as for purge air has been explained (see Part 7) with the calculations for adsorption dryers. The quantity for regeneration and/or purge air, which is withdrawn from the volume of dried compressed air, i.e. purge air is no longer available to the process. For adsorption dryers with blower regeneration, not only cooling air but also additional purge air from the system is required and has to be taken into account when costs are compared.

The quantity of purge air V_{fl} with the unit m^3//h depends on the heat allowance and the blower running time. Table 9.7.3 shows the regeneration and purge air requirement at reference conditions[4].

---

[3] res. for $p = 7$ bar; $t_{in} = 35°C$; $D_{dp} = -25°C$

Regeneration/ Purging Air Requirement	Heatless Regeneration	Regeneration by Internal Heat		
in %		Internal	External	cl.loop System
Adsorption Period t_B	-	-	-	-
Regeneration Period t_r	14,2	-	-	-
Heating Time t_h	-	5,0	-	-
Cooling Time t_c	-	4,0	-	-
Purging Time t_f	-	-	5,0	-
Holding Period t_H	-	-	-	-
Pressure Build Up Time t_P	-	-	-	-

Table 9.7.3

e) Differential pressures

In order to establish the differential pressures, i.e. the pressure drops, in an accurate manner, a theoretical balance sheet has to be drawn up in detail, looking separately at regeneration, adsorption and cooling.

Differential pressures of the filters, regeneration coolers and separators are taken from technical data sheets. The pressure losses within the adsorber are obtained by means of diagrams (see Diagram 7.2.1.13). Individual pressure losses for fittings and pipe connections are also considered by the manufacturers and generally applicable values taken from specialist literature offer sufficient information. The sum of individual pressure losses, if added up, provides the total pressure loss of the adsorption dryer installation including all pre and after filters (when new),

$$\boxed{\Delta p_{\text{tot}} = \Sigma \Delta p_n}$$

Formula 9.7.1

so that the effective operating pressure at the outlet of the drying installation can be determined through:

$$\boxed{p_o = p_i - \Delta p_{tot}}$$

Formula 9.7.2

This theoretical differential pressure loss can be equated with the loss of compressor performance. The power requirement through pressure loss is allocated to the total compressor performance. This also makes it possible to determine the pressure loss as a component of the comparable electrical performance as an objective value.

$$\boxed{\Delta p_i = \left(1 - \frac{p_o{}^2}{p_i{}^2}\right) \text{x}\, P_c}$$

Formula 9.7.3

The pressure loss through adsorption dryers including pre and after filters proportionally reduces the compressed air output which is passed to the compressed air system. This value should not be underestimated as a critical comparison criterion.

f) Compressor performance

Using the tables and equations of this Part, the listed performance components can be specified. The performance values have to be determined for differing regeneration and purging volumes as well as differential pressures in relation to the required compressor performance.

Thus two items have been allocated as a standardised form of energy, items which had, previously been ignored and not applied in practice. Manufacturers of compressors quantify the specific performances (see Part 3) of compressors, which are then used as basic parameters in the course of system comparison between adsorption dryers. For approximations, the following value from Table 9.7.4 was used, referred to the operating pressure p = 8 bar abs.

---

[4] $p = 7$ bar; $t_{in} = 35°C$; $P_{dp} = -25°C$

Design	Energy Requirement E_{fl}
Compressor	kW/m³/min
Piston Compressor	
Oil Free	5,38 - 5,89
Oil Lubricated	4,82 - 4,87
Screw Compressor	
Oil Free	5,89
Oil Injected	6,02
Turbo Compressor	5,89 - 6,92

Table 9.7.4

The appropriate basic value from Table 9.7.4 is multiplied by the volume flow of regeneration, purging and cooling air quantity. The product is the comparable performance P_C allocated to the compressor in accordance with Formula 9.7.4.

$$\boxed{P_c = V \times E_{fl}}$$

Formula 9.7.4

g) Average performance requirement

Derived from the compressor shaft power, needed to achieve the volume flow at the inlet to the adsorption dryer, differentiated performances are established.

Taking into account adsorption and regeneration time, the average performance requirement for regeneration air has to be established by:

$$\boxed{P_c = V \times E_{fl}}$$

Formula 9.7.5

For the purging air by:

$$\boxed{P_{rs} = V_{fl} \times E_{fl} \times \frac{t_{sp}}{t_B}}$$

Formula 9.7.6

The average performance requirement for the performance loss through the pressure differential is calculated by:

$$\boxed{P\Delta p_l = \Delta p_l \times P_v}$$

Formula 9.7.7

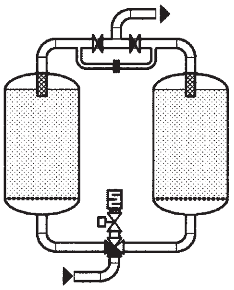
The method for system comparison shown here, an old and questionable analysis has been eliminated and replaced with a well founded, consistently logical approach.

The specified topics are supplemented by the formulae 7.2.7.4, respectively 7.2.4.5 (see Part 7) for average energy requirement for heating and blower, and allocated to the appropriate adsorption dryer system wherever this applies. For each adsorption dryer, the sum of average performance is established in accordance with:

$$\boxed{P_{v\text{tot}} = \Sigma P_{vn}}$$

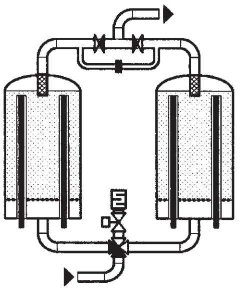
Formula 9.7.8

The energy and performance data can be established by this scheme and is qualitatively comparable. Through the mathematical determination of these well founded values, we can in principle do without the random figures for the costs of compressed air. The following overall view reproduces the most important basic data for the different adsorption dryer systems.



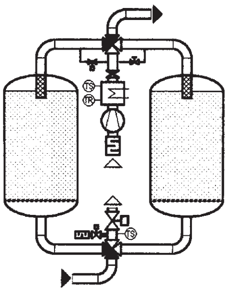
Heatless Regeneration

V_e	=	100	[%]	At Inlet	
p_e	=	8	[bar]		
t_e	=	35	[°C]		
rF	=	100	[%]		
F	=	40	$[g/m^3]$		
D_{tp}	=	-40	[°C]	At Outlet	
V_a	=	85,7	[%]	Loss	14,3%
p_a	=	7,73	[bar]	Loss	7,4%
E_{sp}	=	0	$[kW/m^3/min]$		



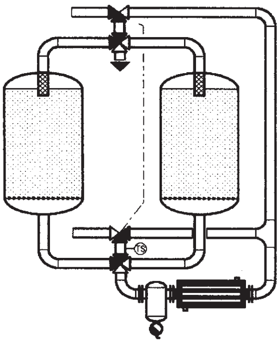
Heat Regeneration

V_e	=	100	[%]	At Inlet	
p_e	=	8	[bar]		
t_e	=	35	[°C]		
rF	=	100	[%]		
F	=	40	$[g/m^3]$		
D_{tp}	=	-40	[°C]	At Outlet	
V_a	=	95	[%]	Loss	5.0%
p_a	=	7,74	[bar]	Loss	7,3%
E_{sp}	=	0,18	$[kW/m^3/min]$		



Regeneration by blower

V_e	=	100	[%]	At Inlet	
p_e	=	8	[bar]		
t_e	=	35	[°C]		
rF	=	100	[%]		
F	=	40	$[g/m^3]$		
D_{tp}	=	-40	[°C]	At Outlet	
V_a	=	98,5	[%]	Loss	1,5%
p_a	=	7,74	[bar]	Loss	7,3%
E_{sp}	=	0,34	$[kW/m^3/min]$		



Closed Loop System

V_e	=	100	[%]	At Inlet	
p_e	=	8	[bar]		
t_e	=	35-170	[°C]		
rF	=	20-100	[%]	at T_u 25°C	
F	=	40-110	$[g/m^3]$	at T_u 25°C	
D_{tp}	=	-30	[°C]	At Outlet	
V_a	=	100	[%]		
p_a	=	7,43	[bar]	Loss	15,6%
E_{sp}	=	0	$[kW/m^3/min]$		

The following table shows the characteristic specific energy requirement of adsorption dryer systems.

Design	Energy Requirement E kW/m^3/min		
Adsorption Dryers	Elect. Energy	Reg. Air	Flush Air
Heatless Regeneration	-	0,697	-
Heated Regeneration	0,176	0,203	-
Blower Regeneration	0,342	-	0,053
Heat of Compression System	-	-	-

Table 9.7.5

Other energy requirements, such as steam, hot water, heated oil, for externally heat regenerated adsorption dryers, or even cooling water (see Diagram 5.6.1.2) for adsorption dryers with closed loop systems, are taken into account when calculating operating costs.

A system comparison is not the same as an operating cost calculation. The system comparison is used in order to select the best adsorption dryer. The operating cost calculation is used to find the ideal supply of energy for the particular application.

h) Cost of energy

The energy costs C_O for electrical power, steam, hot water, heated oil or cooling water, must be entered by the operator. With the input data of energy costs and the sum of the average performance from Formula 9.7.9, the energy costs per hour of operating time are calculated through :

$$\boxed{K_{Eh} = K_E * P_{vges}}$$

Formula 9.7.9

To form a uniform parameter, the energy costs per unit of volume of compressed air are determined as a basic value in £/1000 m^3. This basis of comparison has proved its worth in practice.

$$\boxed{C_{o1000} = C_{oh} \times \frac{1000}{V_e}}$$

Formula 9.7.10

Regarding energy costs, the result will generally correspond to the expectation that adsorption dryers with heatless regeneration are less economical, while adsorption dryers with heat regeneration are more economical. This conclusion refers to the result in accordance with the performance ranges as indicated at the beginning of Section 9.7.

The apparently high cost of compressed air purification must be set against the benefits derived from the compressed air treatment. The operating cost calculation is only complete when the difference between cost of investment including operating costs and effective cost savings have been established.

The diagrams in the following section show how the differentiated energy costs have to be allocated to the differing adsorption dryer systems.

i) Energy costs diagram

At the beginning of this section, the performance ranges of adsorption dryers valid for this comparison were specified. Using the formulae presented and the solution procedures indicated, an evaluation on the basis of industrially based values involves relatively complex work. The data are evaluated by computer analysis and the result presented in a clear manner in the form of diagrams.

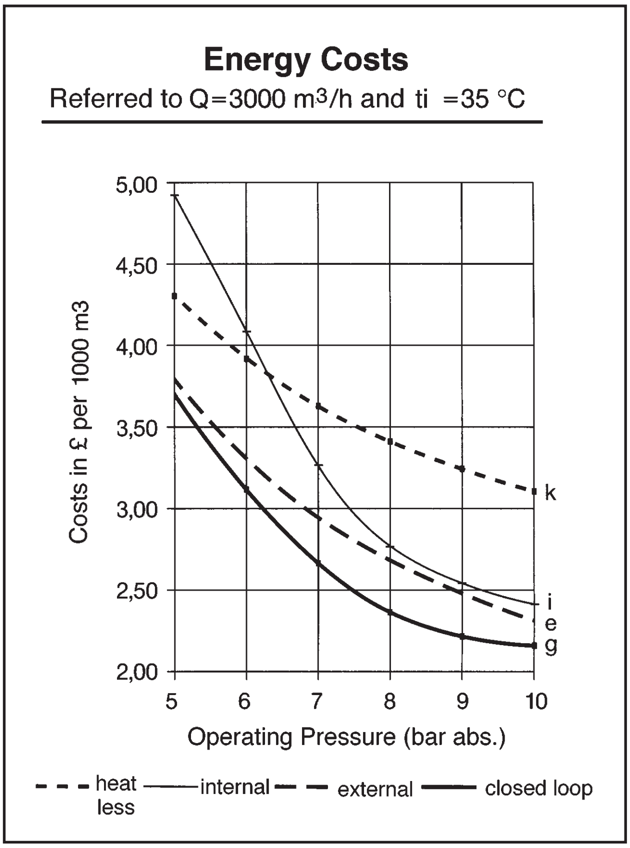


Diagram 9.7.1

Diagram 9.7.1 shows the energy costs of compressed air systems in £/1000 m^3 at constant volume and unchanging inlet temperature but variable pressure.

This diagram establishes clearly that heat regenerated adsorption dryers used for higher operating pressures are assessed more favourably than adsorption dryers with heatless regeneration, when used at the same high pressures.

In the case of adsorption dryers with heat regeneration, the higher operating pressure not only leads to an optimum relationship between volume flows from the inlet to the operating state but, at the same time also to a more favourable load factor through the pressure dependent secondary relative humidity (see Formula 7.2.1.7). This factor does not apply in the case of adsorption dryers with heatless regeneration.

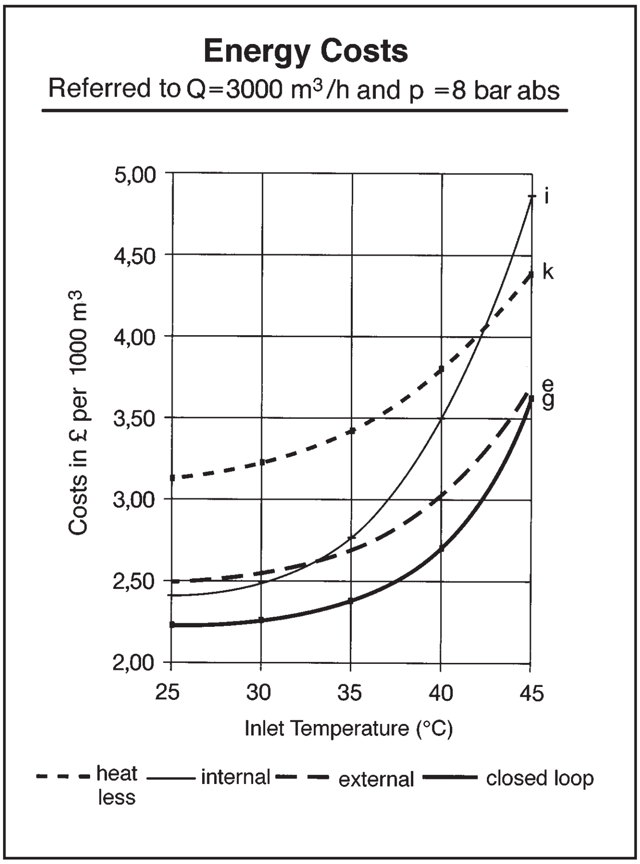


Diagram 9.7.2

Diagram 9.7.2 shows the energy costs of compressed air systems in £/1000 m^3 at constant volume and pressure but various inlet temperatures.

It is clear from all the curves that, at higher inlet temperature, adsorption dryers with heatless regeneration should operate more favourably than adsorption dryers with heat regeneration. In the case of adsorption dryers with heat regeneration, the higher inlet temperature influences the secondary relative humidity (see Formula 7.2.1.7) and leads to an unfavourable load factor.

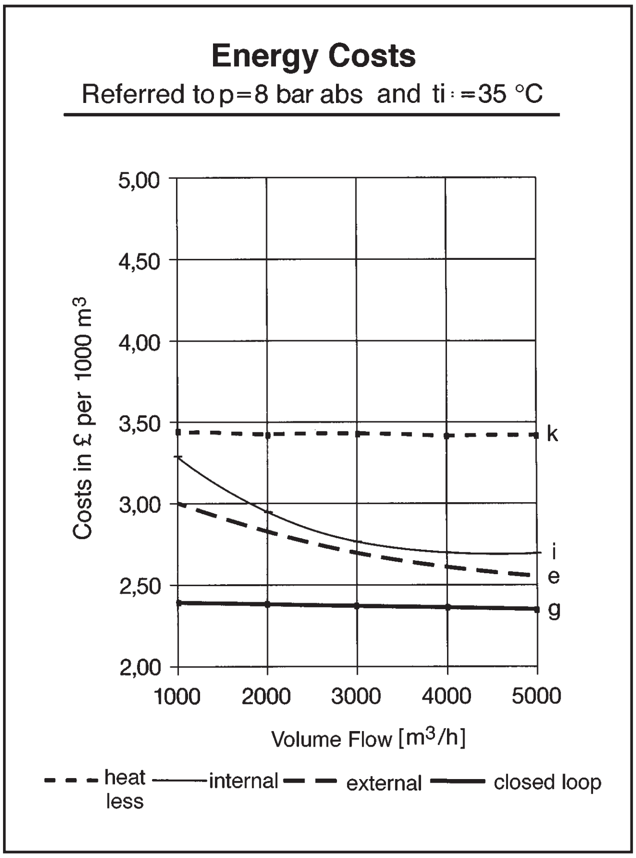


Diagram 9.7.3

In Diagram 9.7.3, the curves for adsorption dryers with heatless regeneration and closed loop adsorption dryer systems remain about the same, for these systems the change in volume results in a change in energy cost. Heat regenerated adsorption dryers with internal and external regeneration show a reducing cost per 1000m^3 as flowrate increases.   This is due to the differences in the equipment and the combined types of regeneration such as electric heater and regeneration air requirement. The quantity of these regeneration energies, electrical energy and compressed air requirement, is caused by different factors and results in a different shape of the curves.

There are three widely differing diagrams which, make clear statements about the energy costs of the individual dryer systems, based on a differentiated but factual assessment.

j) Capital service

Before an adsorption dryer is installed, capital resources for the investment have to be made available. For a comparison which includes investment, capital costs have to be incorporated in the evaluation. The annual capital amortisation is calculated while taking into account equipment costs A, writing off period n and the interest rate p (z = p / 100) as follows :

$$\boxed{C = \frac{z \times (1+z)^n}{(1+z)^{n-1}} \times A}$$

Formula 9.7.11

Operational running time and differentiated flows at the outlet of the adsorption dryer systems have to be determined by converting the capital service K distributed over the service life t_{Oa} per year and expressed in capital amortisation per hour.

$$\boxed{C_h = C \times \frac{t_{Bh}}{t_{Ba}}}$$

Formula 9.7.12

System comparisons claiming to arrive at an objective evaluation can be meaningful only if arrived at on the basis of a uniform framework. Due to their design, adsorption dryers with heatless regeneration are cheaper to manufacture than systems using hot regeneration. With these systems, capital and energy costs move in opposite directions.

k) Maintenance/spare parts costs

Maintenance and spare parts costs should also be included in any comparison. For reasons of simplification, these values are expressed as percentages, depending on the cost of the installation and on the basis of data gathered from experience.

Independent of the numerical values arrived at through estimated flat rate costs, differentiated tabulations concerning the service life of adsorption dryers can contain accurate costs per unit of time. The following values are realistic as guideline values:

Maintenance and spare parts costs

Maintenance Costs Spare Parts Costs	Heatless Regeneration	Heat Regeneration		
		internal	external	closed loop system
Maintenance costs	2,0 %	4,0 %	4.0 %	3,0 %
Spare Parts Costs	1,0 %	2.0 %	2,0 %	1,5 %
Prefilter Element	0,1 %	0,1 %	0,1 %	0,1 %
Outer Filter Element	0,1 %	0,1 %	0,1 %	-

Table 9.7.6

percent values stated in the table for maintenance and spare parts costs are based on the manufacturers' standard. Adsorption dryers based on a different specification have to be separately assessed. The maintenance costs C_{mh} per operating hour t_{Oh} taking into account the annual operating hours t_{Oa} have to be established by :

$$\boxed{C_{wh} = C \times i_w \times \frac{t_{Bh}}{t_{Ba}}}$$

Formula 9.7.13

The spare parts costs C_{sph} per operating hour t_{Oh} are to be calculated by:

$$\boxed{C_{eh} = C \times i_e \times \frac{t_{Bh}}{t_{Ba}}}$$

Formula 9.7.14

l) Total costs

The sum total of energy costs C_{eh}, capital servicing C as well as maintenance and spare parts costs C_{sph} are to be collated for the annual operating period as follows :

$$\boxed{C_{tot} = C_{Eh} + C_{h} + C_{wh} + C_{eh}}$$

Formula 9.7.15

The total costs £/1000 m^3 of treated compressed air referred to the usable volume flow at the outlet of the dryer find their definitive determination through the concluding formula.

$$\boxed{C_{1000} = C_{tot} \times \frac{1000}{V_a}}$$

Formula 9.7.16

Only the energy obtained by multiplying volume V_o x pressure po at the outlet of the adsorption dryer is at the disposal of the user. The data indicated at the inlet to the dryer is relevant for determining the size of the adsorption dryer and, for this reason, only of secondary importance for comparison purposes.

Figures on their own are informative but can, nevertheless, lead to flawed decisions if the comparison of systems does not take into account the subjective, and thus variable, decision criteria for the adsorption dryer in question.

The system comparison contains a numerical result from the values supplied from the basic data. Diagram 9.7.4 shows the energy and capital costs of compressed air systems in £/1000 m^3 at constant inlet temperature and pressure but variable volume.

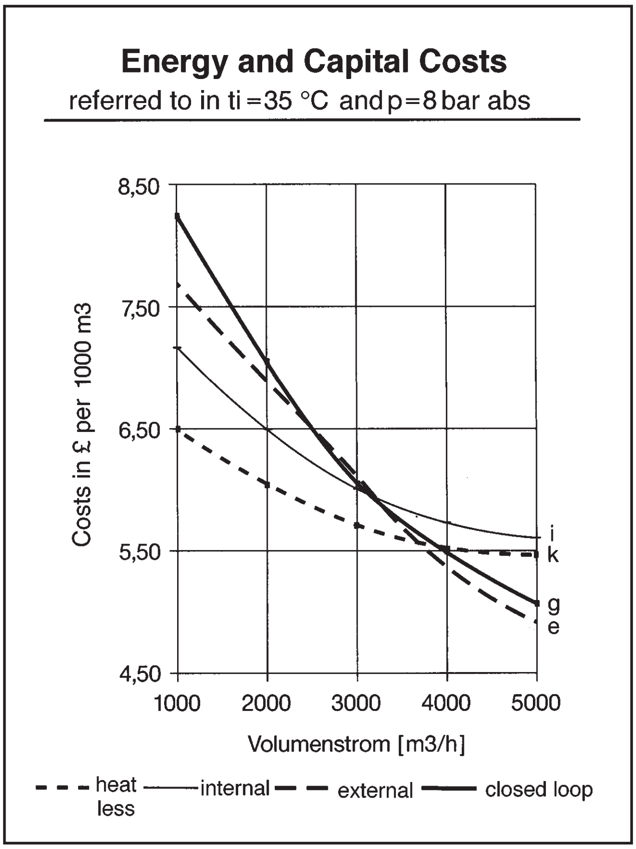


Diagram 9.7.4

Capacities above 5000 m^3/h are intentionally not shown as, above this performance range, we enter the field of heat regenerated adsorption dryers. This range was established on the strength of realistic assessment aids, so that unbiased evaluations could be built up with other basic data in a reproducible manner.

The decision for or against a particular adsorption dryer system should not be taken on the basis of energy and capital costs calculation alone. What does make sense, is an application catalogue, by means of which all aspects are weighted and assessed, always with the actual requirement in mind. There is no uniform and universally valid answer to the question of “Which adsorption dryer system is the best one?”. For each case and application there is only one correct dryer which, must be individually evaluated following the various criteria.

m) Cases of application

The question of which adsorption dryer system should be utilised can, generally be assessed by the following scheme. This scheme does not replace a system comparison, but makes a general and preliminary selection possible.

Typical application case

Application Case		Heatless Regen.	Hot Regeneration		
			Internal	External	Cl. Loop System
Volume flow up to	**200 m^3/h**	yes	no	no	no
Volume Flow	**200 - 5000 m^3/h**	yes	yes	yes	yes
Volume flow from	**5000 m^3/h**	no	no	yes	yes
Inlet temperature from	**45 °C**	yes	no	no	no
Inlet temperature	**25 - 45 °C**	yes	yes	yes	yes
Inlet temperature	**5 - 25 °C**	yes	yes	yes	yes
Operating temperature	**16 - 350 bar**	yes	no	no	no
Operating temperature	**5 - 16 bar**	yes	yes	yes	yes
Operating temperature	**3 - 5 bar**	no	yes	yes	yes
Pressure dew-point to	**-20°C pdp**	no	yes	yes	no
Pressure dew-point to	**-40°C pdp**	yes	yes	yes	no
Pressure dew-point to	**-70°C pdp**	yes	yes	yes	yes

Table 9.7.7

Part 10

10.0 Compressed air installations

The earlier parts of this work deals with the individual components of compressed air supply and treatment, dealing with the subject as a whole and focusing on the crucial points. However, an efficiently functioning compressed air installation is created only by combining all components to form a complete system. A simple compressed air installation consists of a compressor and air consuming equipment connected downstream by interconnecting piping.

This simple combination of compressor and air using equipment, cannot be considered suitable as far as compressed air quality is concerned. A ‘compressed air installation’ of this type may be adequate for the simplest works operations but, cannot satisfy the quality requirements of suitable compressed air.

If compressed air is dried by cooling only and not by adsorption, a further cooling of the air can occur in long and non-insulated pipes. The formation of condensate will then be the consequence. At temperatures below 0°C, this will lead to freezing of the compressed air lines. If the pipe cross-section is large, layers of ice will, in the first instance, form on the inner pipe walls. These will become progressively thicker and constrict the pipe cross-section. Smaller diameter tubing will freeze completely. As soon as thaw sets in, the layers of ice will become detached and may cause blockages, interrupting the compressed air supply.

In contrast to winter, hot summer days may lead to the compressed air being warmed in the piping. Rust particles, previously formed through the condensate, dry out and are conveyed to the air using equipment as fine dust, leading to potential malfunction of equipment.

In order to prevent the flooding of the distribution piping by condensate, condensate separators must be installed in the system at suitable points. In winter, additional trace heating of the separators is necessary. The piping must always be installed at a downward gradient towards the drainage points.

Because of high levels of rust and dirt, the separators should not be fitted with automatic draining devices and must be capable of manual operation. Unsuitable drains can cause leakage losses amounting to 5 - 10% of the total compressed air. In addition, this formation of condensate causes air lines to be corroded from the inside.

Such problems will not occur, if the compressed air is appropriately dried at the source. The economic advantages of effective compressed air drying are clear.

The largest benefit is derived from the elimination of the need for drainage, both in the main and the operational network.

Maintenance and servicing costs of the numerous drainage points in the compressed air system are drastically reduced. As a compressed air dewpoint of -25°C can be maintained throughout all seasons, small drying devices for instrument and control air become superfluous. Energy costs for heating the condensate separators during the winter period are also saved. Corrosion within the pipelines, icing up of working machinery and distribution network and malfunctions of the compressed air using equipment are eliminated.

If compressed air is used for conveying powder, fine materials or hygroscopic substances, a dryer is essential. Adsorption dryer installations need little maintenance and have a lower energy consumption compared with other methods of drying air.

It is also expedient to subdivide the types of contamination in the compressed air, using separators and dryers installed in accordance with the quality requirements. Purification should therefore be carried out in steps, from coarse to fine. Solids, water and oil in the droplet state, are taken out of the compressed air by means of filters\separators. Oil and water vapour are removed from the compressed air by means of absorbers and dryers respectively.

The question of which filters and dryers should be used, can be answered by “as much as necessary and as little as possible”. This generally valid answer is true, as each particular application must be assessed from other specific points of view. Help is provided by appropriate standards such as DIN 3188 or recommendations such as PNEUROP 6611 and ISO 8573. However, the ultimate decision as to what quality of compressed air must, be achieved, is that of the operator, who will judge this in relation to the application.

10.1 PNEUROP 6611

The various applications of compressed air quality supply are considered. Previously, it was sufficient to install individual elements of compressed air generation and treatment. The differentiated quality requirement for various production needs was achieved through successive, staged system adaptations. This has evolved into practical application guide lines.

The application guidelines with the recommended quality classes according to PNEUROP 6611 are based on classification for:

- Particle size
- Highest oil content
- Pressure dewpoint.

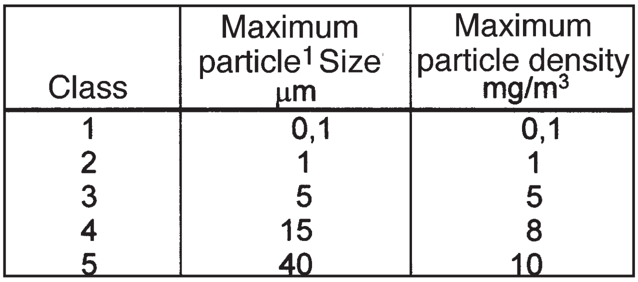
Appropriate values are allocated to the individual application examples. A compressed air quality requirement is thus specified in the form of an application related recommendation.

Industrial applications are subject to periodic changes, affecting the compressed air treatment. Application guide line PNEUROP 6611, Part 1, specifies recommended quality classes, depending on the purpose for which the compressed air is used, with regard to solids, oil content and water. In practice application recommendations to PNEUROP 6611 lacked sufficiently accurate detail with regard to the important area of pressure dewpoint. As a result, PNEUROP 6611 was revised and has since been replaced by ISO 8573-1 which includes pressure dewpoint grades.

10.2 ISO 8573

Compressed air for general use, Part 1 “Contaminants and Quality Classes” is the title of DIN ISO 8573-1. The application guidelines with the recommended quality classes to ISO 8573 were drafted by ISO committee TC 118 Compressors, Pneumatic Tools and Pneumatic Machines, and are based on:

Maximum particle size and density of solid contaminants



Class	Maximum particle[1] Size µm	Maximum particle density mg/m^3
1	0,1	0,1
2	1	1
3	5	5
4	15	8
5	40	10

Table 10.2.1.1

Maximum pressure dewpoint

Class	Max. pressure Dew-point[2] °C
1	-70
2	-40
3	-20
4	+ 3
5	+ 7
6	+10
7	not defined

Table 10.2.1.2

Maximum oil content

Class	Maximum Concentration[3] mg/m^3
1	0,01
2	0,1
3	1
4	5
5	25

Table 10.2.1.3

This makes it possible to recommend the quality required from the compressed air to the user in a more differentiated manner.

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[1] referred to a filtration rate flN = 20

[2] referred to p = 1 bar abs.; t = 20°C; rpD = 0.6

[3] referred to p = 1 bar abs.; t = 20°C; rpD = 0.6

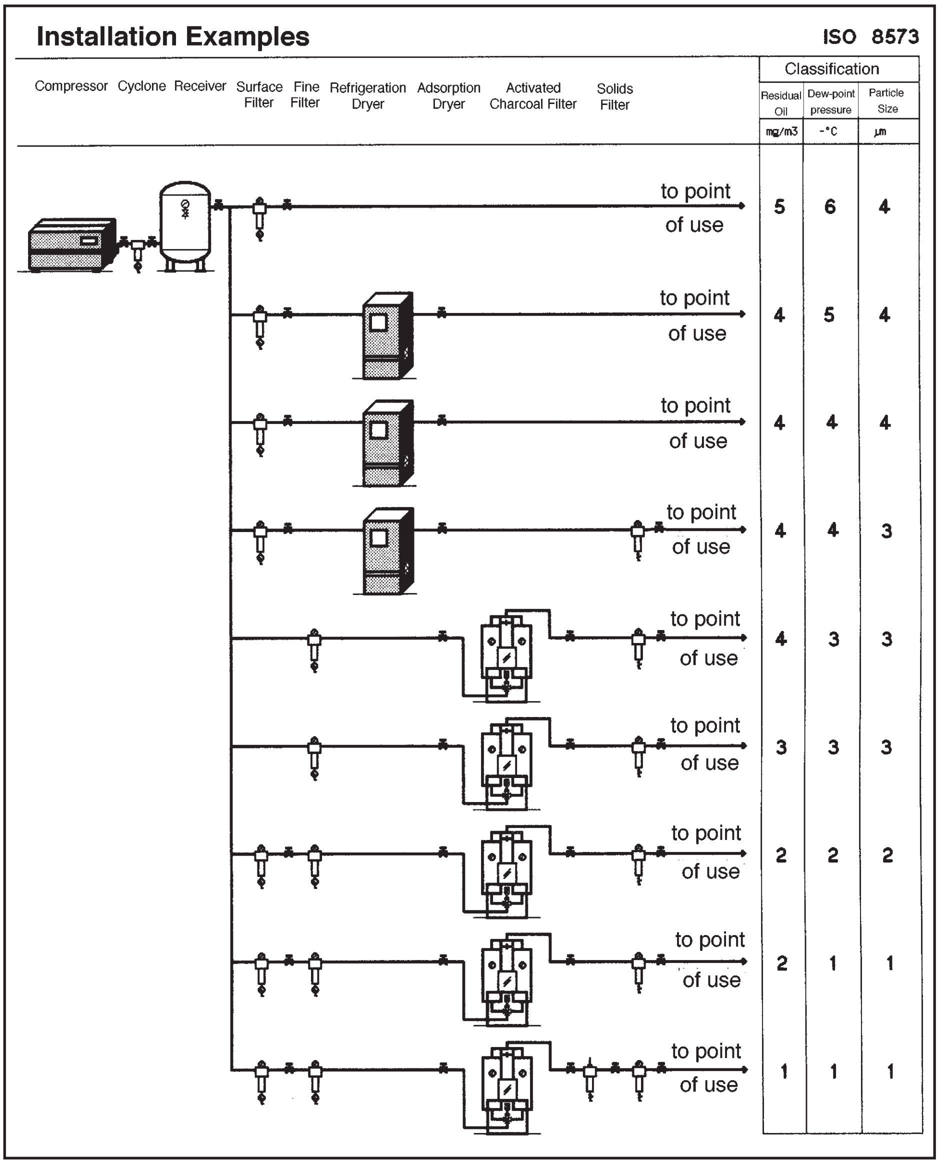


Fig. 10.2.1

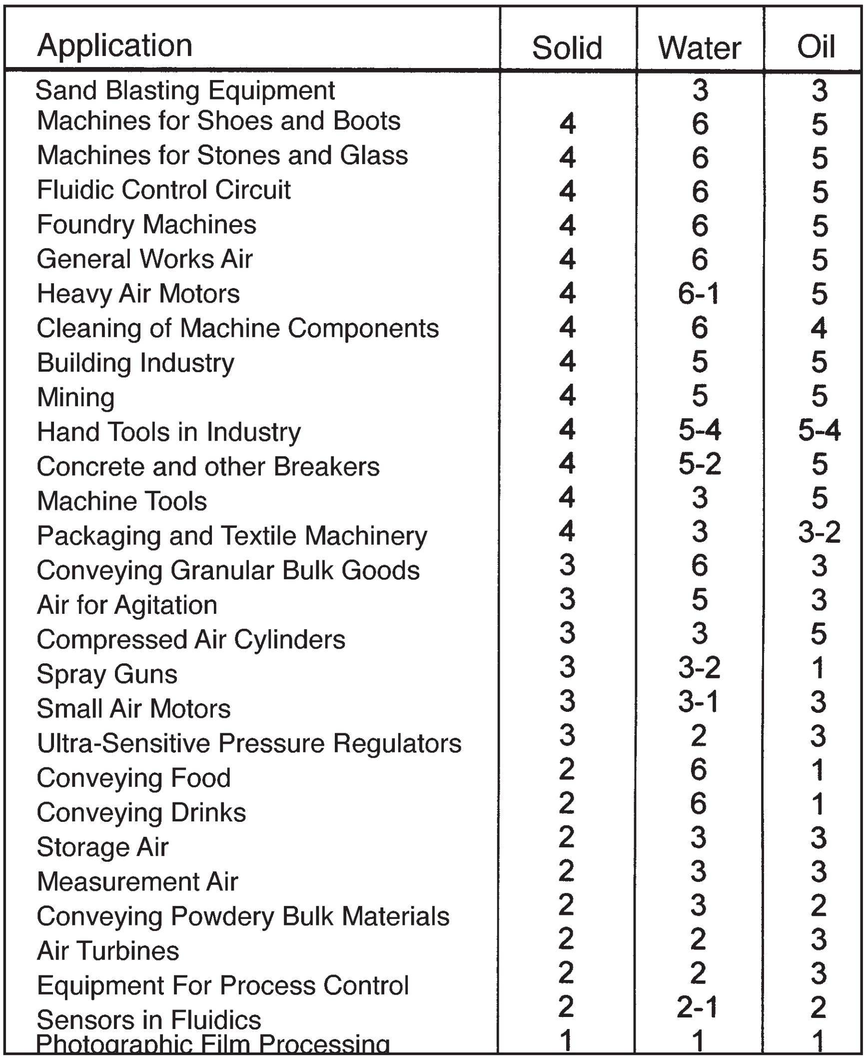
The quality class notation indications must be in the following sequence :

Air of quality class a) solid contaminants
b) water content
c) total oil content

10.2.1 ISO quality classes

ISO 8573-1 specifies a modern application guide line which, improves on PNEUROP 6611, making possible a differentiated break down of typical applications. However, this classification does not apply to sterile and breathing air.

Recommended quality classes - typical applications



Application	Solid	Water	Oil
Sand Blasting Equipment		3	3
Machines for Shoes and Boots	4	6	5
Machines for Stones and Glass	4	6	5
Fluidic Control Circuit	4	6	5
Foundry Machines	4	6	5
General Works Air	4	6	5
Heavy Air Motors	4	6-1	5
Cleaning of Machine Components	4	6	4
Building Industry	4	5	5
Mining	4	5	5
Hand Tools in Industry	4	5-4	5-4
Concrete and other Breakers	4	5-2	5
Machine Tools	4	3	5
Packaging and Textile Machinery	4	3	3-2
Conveying Granular Bulk Goods	3	6	3
Air for Agitation	3	5	3
Compressed Air Cylinders	3	3	5
Spray Guns	3	3-2	1
Small Air Motors	3	3-1	3
Ultra-Sensitive Pressure Regulators	3	2	3
Conveying Food	2	6	1
Conveying Drinks	2	6	1
Storage Air	2	3	3
Measurement Air	2	3	3
Conveying Powdery Bulk Materials	2	3	2
Air Turbines	2	2	3
Equipment For Process Control	2	2	3
Sensors in Fluidics	2	2-1	2
Photographic Film Processing	1	1	1

Table 10.2.1

10.3 Installation planning

When planning a compressor installation, the user must specify the minimum quality the compressed air should achieve with regard to solids, residual oil and water content. Highly purified compressed air for less sensitive applications has to be equally avoided. The cost and time implications of compressed air treatment should bear a sensible relationship to the application, in certain cases the purification of small branched-off compressed air flows (ie. terminal applications) is sufficient.

Oil free compressed air, generated by oil-free compressors are used for many applications in the chemical, pharmaceutical and food & beverage industries. However, not every compressor with oil free compressing chambers does, in reality, feed oil free compressed air into the network. From the ambient air, solids, moisture, hydrocarbons and other contaminants are drawn into the compressor.

It is not sufficient to expect better compressed air quality solely through the use of oil-free compressors. Special requirements must, therefore, be implemented by the installation of downstream equipment such as separators, coolers, dryers and receivers.

The question of the required quality of compressed air has to be answered by the:-

- Moisture content of the compressed air
- Oil content of the compressed air
- Solids content of the compressed air

It is correct to say that compressed air treatment is necessary. It is likewise correct to say that the resources in cost and time devoted to the purification of compressed air must always bear a sensible relation to the application concerned. While solutions are possible, it is also disproportionately cost intensive. Every step in the improvement of compressed air quality is costly. However, deterioration in compressed air quality through inadequate treatment is often far more expensive through product rejection and machine/equipment downtime.

10.3.1 Compressed air receivers

Compressed air is used for numerous applications, naturally, the basis of a compressor installation is the compressor itself. This compresses ambient air up to the required delivery pressure.

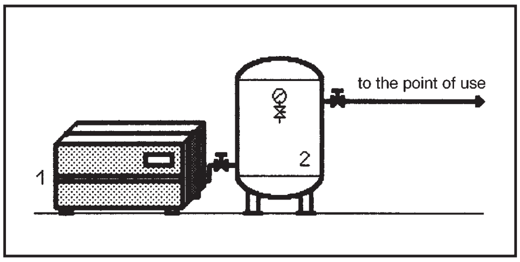


Fig. 10.3.1.1

Within a compressed air system, it is the primary task of the compressed air receiver to even out pressure fluctuations occurring in the system.

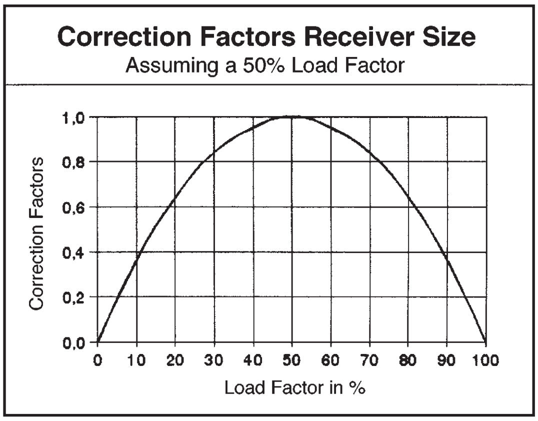


Diagram 10.3.1.1

If the effective volume flow generated by the compressor is greater than the actual air consumption, the compressor, sensed by a pressure monitor, switches over to idle running or non-running for a certain time interval, depending on the selected mode of operation. During this period, the unwanted compressor output does not cause a pressure rise in the system. When maximum operating pressure is reached, the compressed air receiver supplies compressed air to points of use, until the lower switch-on point of the pressure system has been reached.

The receiver size needed for a compressed air system is calculated or taken from appropriate diagrams. The receiver design in Diagram 10.3.1.1 is based on a load factor of a = 50 %, the consumption is half the amount of the volume flow of the compressor. The receiver volume can be calculated in accordance with the following formula :

$$\boxed{V_r = \frac{60 \times V}{z \times \Delta p} \times \frac{a(100-a)}{10000}}$$

Formula 10.3.1.1

Here Q = receiver volume in m3 and V = volume flow m3/min. Values z = number of switching cycles and dp = pressure difference. With a = 50 %, switching frequency for the compressor motor is at its highest. Once the actual loading is known, the receiver volume can be reduced by the factor f.

It is often desirable to use a pressure vessel to cope with short periods of peak demand at specific points in the network. In such cases it is not always expedient to place the receiver next to the compressor but, instead place it near the point of use.

The compressed air is taken to the points of use via the piping system.

10.3.2 Distribution piping

The question of the location of a compressor installation is closely linked to being able to call this an ideal installation. The compressed air has to be ducted to individual points of consumption, some of which are located at considerable distances from each other. Practical experience shows that the expansion of a factory is usually linked to an extension of the compressed air installation and to wider compressed air distribution. The traditionally evolved network with a central compressor station becomes an expanded network of higher output. The way in which the network is extended, and the associated question of where to locate further compressors, requires careful evaluation.

In principle, there are several potential solutions, three of which are outlined as follows:-

- Central compressor station with economically operating large compressors and air distribution eminating from one point.

- **Advantage:**
  Low investment costs, lower requirement of operating personnel.

- **Disadvantage**:
  Unfavourable air distribution, large piping diameters or increased pressure loss. If repairs have to be carried out in the distribution network, compressed air supply cannot always be ensured.

Decentralised compressed air generation at principal points of consumption and thus a small distribution network.

Advantage: Favourable pressure conditions, low distribution costs

Disadvantage: A larger number of compressor installations, possibly more expensive reserve provisions to ensure continuity of the compressed air supply.

Compressed air generation at two principal points and feeding into a ring main. If the network is very large, a compressor with output regulation can be connected to the point of highest pressure loss in the mains in order to maintain pressure.

Advantage: The compressors are large enough to be operated within an economical range as basic output providers as well as topping up compressors. By arranging a ring main, compressed air distribution is ensured even if there is a breakdown at one point.

Disadvantage: Increased costs of the ring mains, as larger cross sections have to be selected. Should one station drop out, the station at the opposite point has to satisfy the entire demand.

The operator has to consider the advantages and disadvantages of various piping materials for the compressed air network. Here, too, the decision will be a compromise between optimum procedure and that which is economically and technically acceptable.

There is a choice of materials for the distribution network and the following selection provides a survey of the most frequently used materials:

Copper pipes

Advantage : Non rusting, easily worked material
Disadvantage : Expensive, possibility of oxide formation
Utilisation : For smaller outputs

Plastic pipework

Advantage : No corrosion, smooth surfaces
Disadvantage : Temperature sensitive, maximum standard bore 100 mm
Utilisation : Temperatures up to te = 50°C
Operating pressure p = 8 bar

Threaded tubing

Advantage: Quick assembly, can be dismantled
Disadvantage: Maximum bore R 6”, possibility of leakage
Utilisation: Low quality requirements

Seamless steel pipes

Advantage: Favourable costs combined with absolutely leak tight connections
Disadvantage: Has to be assembled by welding, liable to corrode
Utilisation: Medium quality requirements

Galvanised steel piping

Advantage: No surface corrosion
Disadvantage: Autogenous (gas) welding required
Utilisation: Higher quality requirements

Stainless steel piping

Advantage: No corrosion, low flow resistance
Disadvantage: Very expensive, welding shielded by protective gas
Utilisation: Highest quality requirements

When sizing the piping, pressure loss should be kept as low as possible. An ideal pressure loss would be a maximum value of 0.1 bar. However, this value is only rarely met in practice. From the planning stage, every effort should be made to achieve the lowest possible pressure loss.

10.4 Installation examples

This section deals with the various options for installations including adsorption dryers. The examples mentioned represent a limited selection of typical installations found in industry.

These installation examples, serving as models, cover a large range of user problems.

The step by step recording of problems arising with individual installations are at the centre of these observations, not the basic scheme. By-pass lines were intentionally not drawn into the schemes. The valves shown in the layouts can be manually, electrically or pneumatically actuated.

Each application has its own, often concealed, problem arising from a specific requirement. This must always be considered so, for this reason these installation examples should be regarded as guides as to how to identify the problem. “We have always done it this way” is the surest way to overlook problems at the planning stage.

The logical starting point for a new installation is the specification by the user of the compressed air requirement for quality, quantity and pressure. ISO 8573-1, with its’ recommended quality classes relative to the application forms the basis for selecting an application case similar to the planned project.

Each case is individually examined with regard to the quality class and the maximum residual values for solids, water and oil are prescribed. In order to achieve these values, the separator and dryers to be used need to be specified.

The adsorption dryer must always be installed with a pre-filter and a downstream filter. The pre-filtration and preparation at the inlet to the dryer is necessary in order to separate condensed moisture, oil aerosols and solid particles from the gas flow. The downstream filter at the outlet of the dryer protects the equipment connected downstream from desiccant dust.

Filters and dryers have very different construction, degree of separation and mode of operation. These differences were explained in the preceding chapters.

Possible installation schemes for adsorption dryers with heatless regeneration are explained in the following sections. It is not possible to reduce installation examples for adsorption dryers with heat regeneration, as these dryer systems call for a fundamentally different form of consideration due to the heat which has to be applied and extracted in the course of regeneration.

10.4.1 Receivers/adsorbers

Should the receiver be installed upstream or downstream from the dryer? While this question appears ambiguous both forms of installation are potentially correct, however, there must be a full evaluation of the installation requirements if there is any likelihood of high short term demands, installation of both upstream and downstream receivers should be considered.

Without considering marginal cases or abstract theories, the installation of receiver/dryer is operationally most practical. The precondition is that the dryer must be sized to the maximum compressed air consumption.

Installing (Fig. 10.4.1.1) an adsorption dryer (item 4) downstream from the receiver (item 2) is expedient if an even, continuous loading through the compressed air is assured. The dryer is then system sized to this even compressed air consumption.

A positive aspect of this arrangement is the additional cooling of the compressed air by the large receiver surface. Lowering the temperature accompanied by simultaneously reduced inlet humidity means theoretically that the dryer system fitted downstream can be reduced in size, at the same time achieving a saving in regeneration energy. With such an installation, sudden demand for compressed air has to be avoided in order to prevent an overload of the adsorption dryer. One also comes across plants with an intermittent compressed air consumption pattern. Sometimes the compressed air demand equals zero, i.e. there is no compressed air requirement. The adsorption dryer without dewpoint dependent switching with a rigid time cycle control will, however, permanently consume regeneration air during this low demand period.

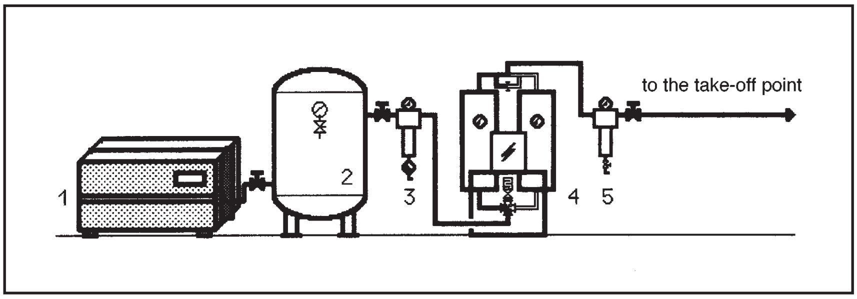


Fig. 10.4.1.1

There is a simple method of counteracting energy losses of this kind. The poor compatibility between zero load operation of the compressor and full load regeneration of the adsorption dryer is resolved by interlinking of the control system to the operational pattern.

One simple solution for an installation with adsorption dryers with heatless regeneration consists of linking compressor (item 1) and adsorption dryer electrically so that simultaneous running of both components is maintained. The electrical supply of the dryer is linked to the pressure monitor of the compressor as signal emitter. Both compressor and adsorption dryer are simultaneously switched on or off, depending on the demand. For this, the pressure monitor must be arranged in such a way that the pressure in the piping system is detected.

For an adsorption dryer with normally open inlet valves (see Fig. 5.2.3.1), the pressure monitor can be fitted to the compressor or to the receiver. For an adsorption dryer with normally closed inlet valves (see Fig. 5.2.1.1), the pressure monitor must be fitted downstream from the adsorption dryer, as otherwise, compressed air generation would be separated from the compressed air network through the closed dryer inlet valves in the power off condition.

However, all this linkage achieves is an adaptation of the regeneration air consumption in relation to compressor running periods. Adaptation to fluctuations in pressure or temperature cannot be achieved through this control method.

For small and medium installations, the above solution is practicable and expedient, as every operator of a compressor installation is capable of establishing this linkage without difficulty.

For adsorption dryers in the high performance range, a Dewpoint Dependent Switching system (see section 5.2.6) should, ideally, be incorporated in the original project plan, with a view to achieving an economic balance between regeneration energy and a wide range of load situations.

10.4.2 Duty/standby compressor, receiver

With only one compressor and dryer, uninterrupted long term compressed air supply is improbable. This risk is reduced through the installation of a second compressor. Fig. 10.4.2.1 shows a typical installation with two compressors (item 1.0 and item 1.1) which are used in parallel. Compressor 1.0 is available as the base load, compressor 1.1 for covering peak loads.

Installing a duty/standby compressor, receiver or dryer will result in the dryer being subjected to a varied load of 0-50-100%.

In addition to the specified compressor performance of 0 - 50 - 100%, the receiver volume multiplied by pressure difference can, under certain circumstances, throw an additional load onto the adsorption dryer. This must be clearly identified and analysed from the outset in order to exclude undesired operating circumstances.

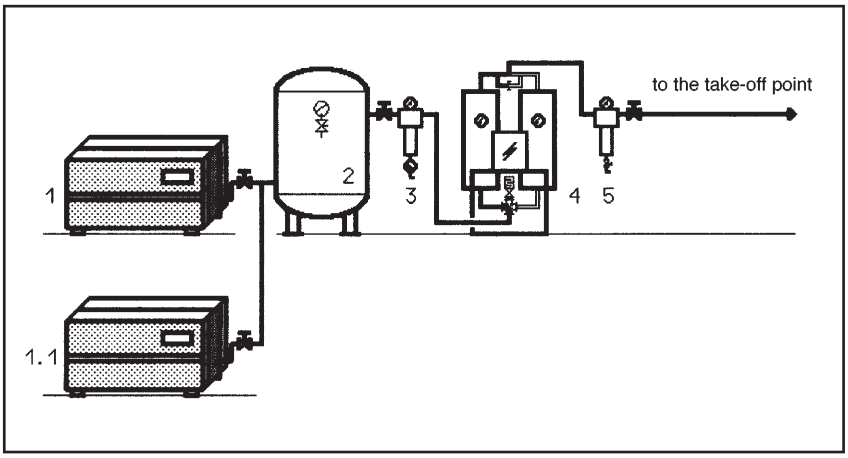


Fig. 10.4.2.1

As adsorption dryers are designed for maximum moisture loads, deviating loads are, part loads, and thus smaller than 100%. A Dewpoint Dependent control system compensates for these part loads. To adapt the regeneration output of the adsorption dryer to the actual compressed air requirement calls for a continuous assessment of the load situation by means of the Dewpoint Dependent control system. A dewpoint meter adjustable with dewpoint sensor at the outlet of the adsorption dryer permanently registers the true pressure dewpoint of the compressed air.

The pre-set dewpoint is used as a signal for switching over the dryer from adsorption to regeneration. The loading time is inversely proportional to the part load. Working on the assumption that every part load operation is immediately followed by full load working, the regeneration period is set at a constant value corresponding to full load operation. Thus the regeneration air requirement will be inversely proportional to the load situation, in contrast to the regeneration air quantity which remains constant. The ratio of regeneration time to loading time determines the saving in regeneration energy.

When a Dewpoint Dependent control system is used, the adsorption dryer must be switched on throughout the entire operating time. Shutting off the compressed air from the system through the adsorption dryer is thus made impossible and continued operation guaranteed.

With adsorption dryers in the smaller ranges, the economic viability of employing load depending control systems has to be carefully scrutinised. For such cases, there is an alternative to a Dewpoint Dependent control system in the form of a direct linkage dryer/compressor, the principle has been described in section 10.4.1. When setting up such an interdependence, the following must, be considered:

The adsorption dryer must be linked to the base load compressor. With standby or operation of both compressors sufficient control is achieved. However, 50 % load also means a 50% waste of regeneration energy as far as the adsorption dryer is concerned.

The compressors alternate as the base load. In this case, an OR-linkage for the dryer control must be installed. Also, when one compressor is running, 50 % of the regeneration energy of the adsorption dryer must be regarded as an unnecessary waste.

10.4.3 Duty/standby installation with cross-over

The installation of a duty/standby plant (Fig. 10.4.3.1) consists of two compressors and two adsorption dryers and offers optimum assurance of the compressed air supply. Such an installation can be utilised in different ways :

Depending on demand, compressor and adsorption dryers are switched on as required.

The duty machines (items 1 - 5) take over the entire compressed air provision,

The standby machines (items 1.1 - 5.1) are available as reserve.

Receiver siting should be considered as in the example in section 10.4.1 and is, therefore, not detailed here.

However, when considering this installation scheme, an automatic logic linkage between compressors and dryers provides a more effective solution. Both compressors (item 1.0 and item 1.1) and dryers (items 4 and 4.1) are connected in series and cross-over via one air receiver (item 2), but with interchangeably for automatic operation so that, should one unit fail, whether this be a compressor or a dryer, the stand-by unit takes over the supply of the compressed air.

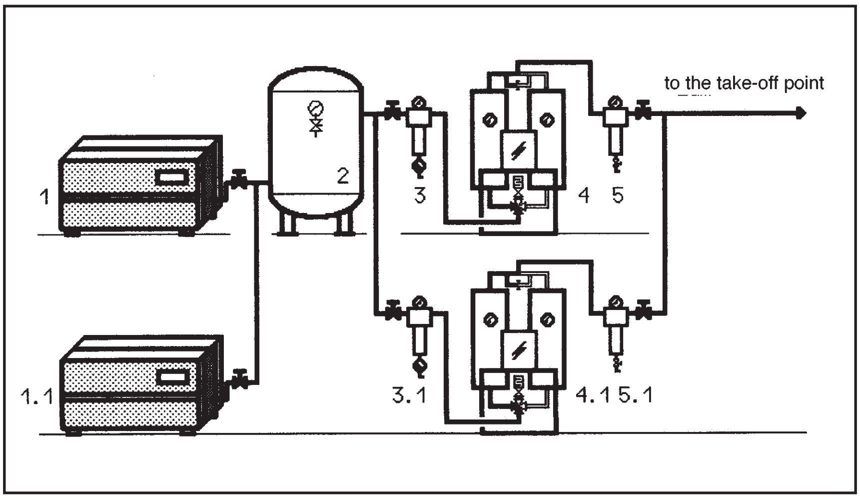


Fig. 10.4.3.1

So that the system automatically fulfils this task, both adsorption dryers must be equipped with a Dewpoint Dependent control system. Compressor 1 takes on the base load, compressor 1.1 is stand-by operation via a change-over switch,. The adsorption dryers are linked electrically via a programmable logic controller, which then signals the automatic operation.

During operation, the pressure dewpoint is measured at the outlet of dryer 4 and the limiting value used for the load governed fully automatic control of the dryer. As long as the dewpoint is lower than the set limiting value, the valve behind the downstream filter (item 5) remains open so that there is free flow towards the points of use. However, as soon as the dewpoint falls off and reaches the set switching point, the valve of the first line is closed and dryer 4.1 activated at the same time. The latter then takes over the drying of the compressed air.

It is necessary for automatic continuous operation that dryer 4 be regenerated. To achieve this, this adsorption dryer is regenerated at a predetermined interval until the pressure dewpoint is reached. Once the pre-set pressure dewpoint is reached at dryer 4, this line switches over to standby and becomes available again for operation if required. Regeneration takes place in parallel to the operation of dryer 4.1. Of course, other solutions may be selected as well. However, alternatives either call for more electro-technical resources or are limited in their degree of automatic response.

Altering the control system to other operating conditions presents no problem. The increasing demand for compressed air for production, is covered by the parallel operation of both lines with automatic adaptation to a load in the range of 0 - 100%.

10.4.4 Adsorber/receiver

Installation of adsorber/receiver is the second variant. With the equipment installed in this order, adsorption dryer size solely matches the compressor output so that an accurately specified load situation can be allocated to the dryer. With this installation overloading, the adsorption dryer through sudden high compressed air demand from the compressed air receiver is not possible, provided the design is correct.

Piston compressors compress the air in a pulsating manner and may have a more significant effect on the adsorption dryer. These pulsations do not exert a damaging influence on the adsorption dryer if the volume between compressor and dryer corresponds to 50 times the final stage of the compressor, or if pulsations are removed by pulsation dampers between compressor and dryer.

To install the adsorption dryer upstream of the receiver is possible but irregular, as varying demand for compressed air is to be expected. While irregular compressed air demand is not always totally evened out by a large compressed air receiver, it is balanced between suitable limits.

Arguments presented for this type of installation is the reduced corrosion of the receiver, as the compressed air enters the system in a dry state once it leaves the dryer, no further moisture is precipitated, so elaborate condensate traps are not necessary.

Varying load situations are possible for the operation of the adsorption dryer, i.e. continuous operation as well as partial loading, caused either by pressure and/or temperature fluctuations at the inlet of the dryer. In the unfavourable situation where, no compressed air is drawn off but there is a steady consumption of regeneration air.

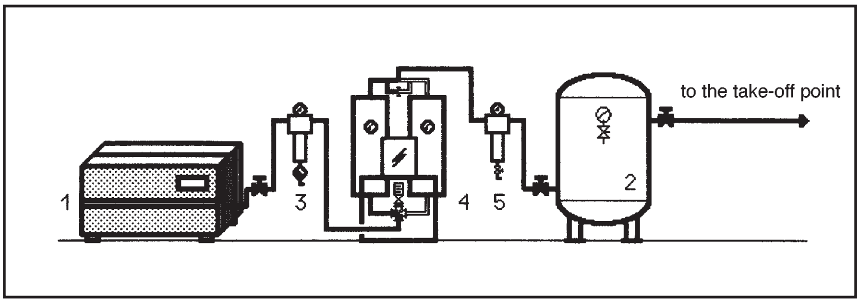


Fig. 10.4.4.1

As shown in section 10.4.1, the aim should be to achieve optimum performance from no load operation to full load regeneration between the adsorption dryer and the compressor.

To this end, heatless adsorption dryers are electrically linked to the pressure monitor of the compressor system, thus forming a matched running unit. However, with this adaptation, the dryer running time is dependent on the compressor running time. Other criteria, such as temperature variations and/or pressure fluctuations, cannot be catered for by this linkage. This solution is expedient for small to medium installations and can often be arranged on site.

With this linkage, the following is worth considering as a possible variant :

The compressor pressure monitor emits the unload signal for compressor/dryer when the upper switching point is reached. The purge valves of the adsorption dryer (see Fig. 10.4.4.2) close when this status is reached, to block the escape of regeneration air into the atmosphere. The main valves remain open allowing the pressure build up at the receiver to feedback to the compressor pressure monitor.

Pressure equalisation inside the adsorber will take place by the regeneration air repressurising the empty vessel. After pressure equalisation inside the adsorption dryer, the pressure may be lower than the minimum operating set at the compressor sensor non-return valves. The non-return valves in the outlet of the adsorption dryer prevents full pressure equalisation. In the worst case, the system is restarted.

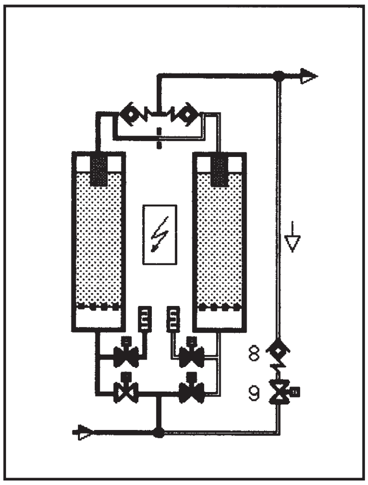


Fig. 10.4.4.2

The pressure level after pressure equalisation, depends on the volumes of both adsorbers, this forms a criterion for checking and, if necessary, correcting the pressure difference set at the pressure monitor. The pressure drop inside the adsorption dryer is compensated for by an additional compressed air return feed, Fig. 10.4.4.2. This return feed by-passes the non-return valves of the adsorption dryer. The direction of flow is controlled by an non-return valve (item 8). A leak proof valve (item 9) prevents dewpoint degradation in the course of normal operation.

Alternatively, the pressure monitor is not fitted to the compressor but to the receiver. In this case, the pressure drop inside the adsorber can be ignored (excepting that it is not too high to cause the safety valve to blow off). With this arrangement, direct coupling of compressor and adsorption dryer cause no difficulty, and the return feed becomes unnecessary.

However, for large heatless adsorption dryers (see Fig. 5.2.6) the adaptation to varying operating conditions can be achieved only by a Dewpoint Dependent control system. Using a governed control system with pre-set automatic regeneration, for long standby periods, one has to supply the regeneration air requirement of the adsorption dryer via a return feed line. Regeneration by means of dry air from the receiver, provided this has a sufficiently large volume, can be assured without compressor restart.

10.4.5 Duplicate compressor, dryer

In line with the installations described, the following applies to differing load situations according to Fig. 10.4.5.1:

One compressor (item 1) is available for the duty output, the second compressor (item 1.1) as standby.

Both compressors remain in standby, with the variants:

Two-compressor operation	100 % dryer load
One-compressor operation	50 % dryer load
Compressor standby	0 % dryer load

The varying running periods of the compressors call for an adaptation of the adsorption dryer (item 4), to maintain economic performance. In order to match the regeneration performance with the load, the loading from 0 - 50 - 100% must be coped with.

This is achieved in practice by means of a modified Dewpoint Dependent control of the dryer system. Deviating load ranges are always part loads. A load governed control system caters for this part load and adapts the dryer running periods in an effective manner.

Full load operation can follow immediately after a part load use. For this reason, the length of the regeneration period has to be set in such a way that continuous drying is possible when changing over from part load to full load operation without a dewpoint peak (dewpoint collapse) during continuous operation.

Regeneration time and regeneration air quantity remain constant. In the partial load range, the loading time will be inversely proportional to the load, i.e. with 50 % load, the loading time will be made longer by the factor 2. Regeneration air requirement is likewise inversely proportional to the loading. The ratio of regeneration time to loading time determines the regeneration air requirement and economic utilisation of the adsorption dryer.

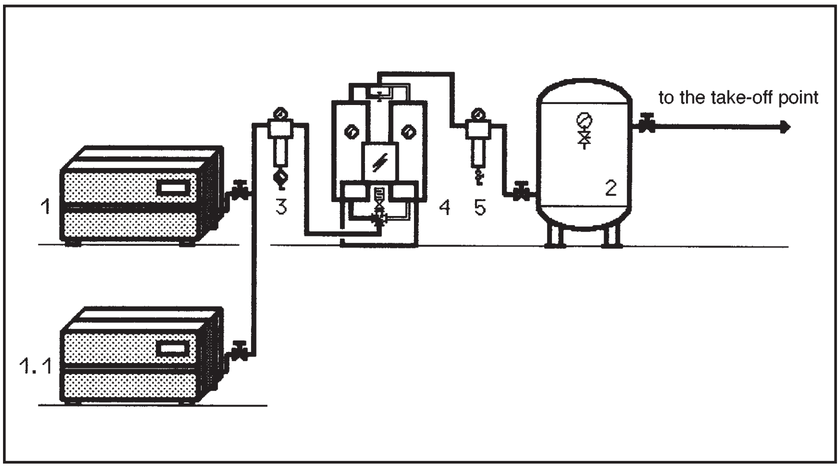


Fig. 10.4.5.1

Using a load governed control system, the power supply to the dryer must be ensured at zero loading, i.e. the dryer remains open allowing the pressure monitor in the compressor to trigger the pre-selected lower switch-on and upper switch-off point as limiting values for operation.

As an alternative to load depending control, it is possible to link the compressors directly to the dryer. Dryer/compressor simultaneous running have been discussed in section 10.4.2. As varying load situations are unpredictable, the following assumption applies:

Compressor 1 supplies points of use for brief periods only, remaining off-load for long periods, compressor 1.1 is required as a standby.

These conditions, long periods of standby and short periods of operation have a detrimental effect upon the pressure dewpoint.

Long standby periods call for additional regeneration phases. With connection of the dryer/compressor, automatic regeneration can be simply achieved. Two additional time relays are included in the control system. Relay 1 has the maximum period of availability and relay 2 the time of regeneration. Setting these relays is based on the acceptance of a pressure dewpoint peak. The return feed for regeneration air from the receiver has to be provided with this installation scheme also.

10.4.6 Duplicate installation in parallel

The operation of two compressors and two dryers, operated in parallel, is shown on Fig. 10.4.6.1 and can be regarded as ideal.

Line 1 (item 1 - 5) takes on the base load and
Line 2 (item 1.1 - 5.1) is for stand-by operation

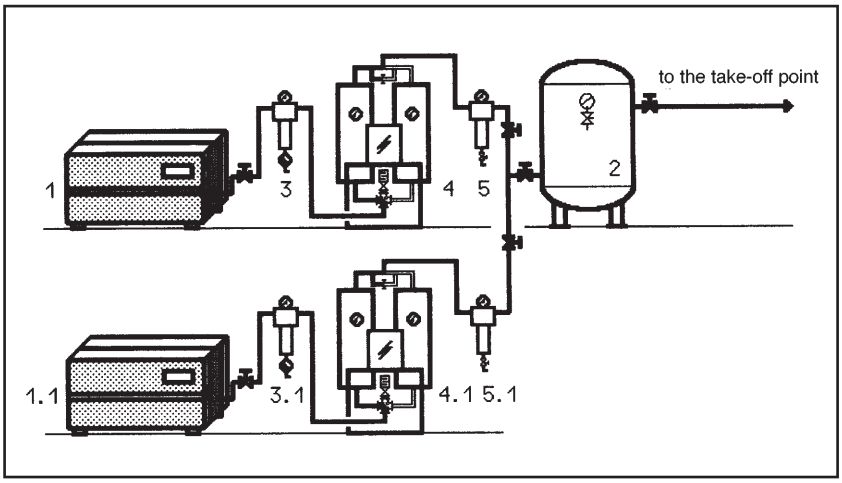


Fig. 10.4.6.1

As desired, duty periods are allocated to the compressors via a base load change-over switch. Should one line fail, the second line takes over the total supply. Also see section 10.4.4.

A further development of dryer control is called for if the system is meant to run fully automatically. Both dryers are fitted with a load depending control system and linked to the compressors.

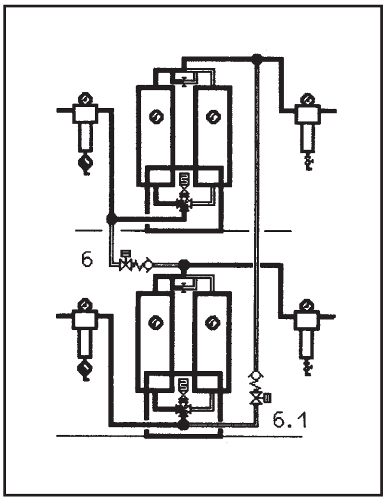


Fig. 10.4.6.2

Line 1 operates, the dewpoint at the outlet of the dryer is better than the set point. The valve after the downstream filter (item 5) is opened to the take-off point. If the dewpoint rises and reaches the set point, line 2 becomes automatically activated. Depending on the loading, each line can take on 50 % or line 2 takes on the entire load when required.

Regeneration of line 1 is timed and automatic. One option for timed regeneration is shown with Fig. 10.4.6.2. External regeneration lines (item 6 and item 6.1) connect the dryers of line 1 and line 2. As required, regeneration air is taken to the dryer to be purged.

10.4.7 Stand-by adsorber

As the last variant of this type, installation Fig. 10.4.7.1 is shown.

Two compressors (item 1 and item 1.1) and two dryers (item 4 and item 4.1) upstream of a receiver (item 2) are cross linked to each other and should be suitable for automatic operation as, if one unit fails, whether compressor or dryer, the parallel unit takes on the total supply of the compressed air. The system operates automatically without manual switching, both dryers are fitted with a load governed control system. Here, too, compressor 1 takes on the base load, compressor 1.1 is meant for stand-by operation. The compressors operate as selected via a base load change-over switch.

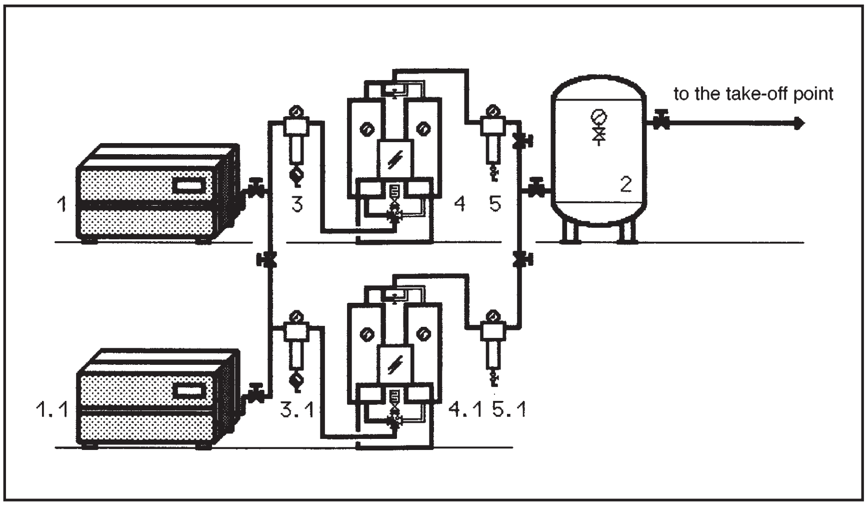


Fig. 10.4.7.1

Layout and sequence can be understood from the examples 10.4.3 and 10.4.6. For an installation of this type, i.e. cross-over connection of compressor and adsorption dryer, fitting a load depending control to each adsorption dryer is the correct and optimum solution.

With dewpoint sensing at the outlet of each adsorption dryer, the output signal ensures quality remains constant for all load situations. Adaptation to varying load levels takes place automatically.

From the multitude of possibilities, three fundamental rules emerge and these must always be followed.

Rule 1:

With a Dewpoint Dependent control system, automatic operation for each dryer can be achieved, as the dewpoint is utilised as the control signal.

Rule 2:

If a load governed control system is used ie. compressor and adsorption dryers are linked up for simultaneous running, free passage of the pressure to the pressure monitor must be ensured, irrespective of how the dryers are installed.

Rule 3:

If the adsorption dryer is mounted upstream of the receiver, a return feed of compressed air for pressure equalisation has always to be considered.

10.4.8 Refrigeration dryer/adsorber

If an adsorption dryer is installed downstream of a refrigeration dryer, the criteria changes. With this layout, pre-dried compressed air is fed to the adsorption dryer. The refrigeration dryer removes part of the moisture from the compressed air. As a rule, the pressure dewpoint at the outlet of the refrigeration dryer is between 2 - 5°C. The compressed air at the inlet to the adsorption dryer is no longer 100% saturated, typically 15 - 30%. Formula 10.4.8.1 is used for determining the relative humidity.

$$\boxed{{}_{r}H = \frac{h_n \times 100}{h_s}}$$

Formula 10.4.8.1

Should the relative humidity at the inlet to the adsorption dryer be below 20%, particular care should be taken in the selection of the drying medium. Not all drying materials display a constant loading factor (see section 6.3.1) with a relative humidity of below 20%. Drying medium, such as molecular sieve (see Diagram 5.3.1.2), is recommended.

If reliable operation of the refrigeration dryer is assumed for the layout, the adsorption dryer can be load dependently adapted to the lower level of moisture loading, but rarely reduced in size. Size selection depends primarily on the dwell time of the compressed air in the adsorber bed, the load level, however, on the low moisture loading.

The fixed loading cycle of adsorption dryers is determined on the basis of the moisture to be dried. Should the refrigeration dryer no longer reach the desired pressure dewpoint in the course of operation or, even fail completely, the adsorption dryer is challenged with a correspondingly higher moisture level and almost certainly overloaded. At such a critical moment, dried compressed air is then not available from the refrigeration dryer or from the adsorption dryer.

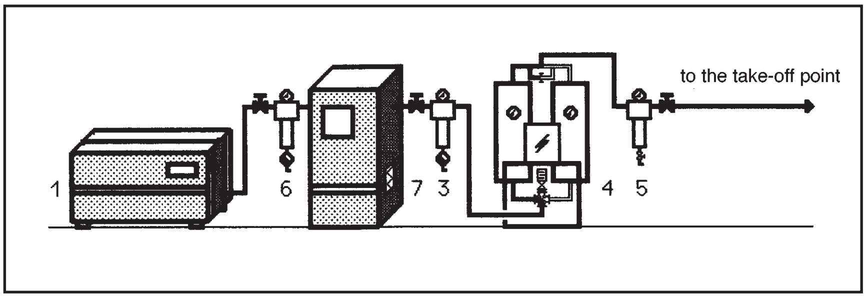


Fig. 10.4.8.1

When sizing the adsorption dryer, one can alternatively proceed as if the refrigeration dryer were not operating, then compensation through the adsorption dryer is achieved even in the case of refrigeration dryer failure. The operating load of the adsorption dryer is based on the pressure dewpoint of the refrigeration dryer. Optimum operation of the adsorption dryer downstream of a refrigeration dryer is achieved by using a Dewpoint Dependent control system. The real water loading of the adsorption dryer is at about 20 % and, through the adaptation from a load governed control system, an adsorption period of about 5 cycles with a regeneration time of 1 cycle is obtained.

Economic viability is achieved through the saving of cycles in which no regeneration takes place. Dewpoint fluctuations and failure of the refrigeration dryer are compensated for by the adaptation of the adsorption time of the dryer. Using a load governed control system is the logical solution if safety, reliability and economy are considered.

Alternatively, a refrigeration dryer fault signal sent to the adsorption dryer can be used for triggering a change-over from cycle time 1 to fixed cycle time 2 for the refrigeration dryer. However, this alternative is not absolutely reliable for overload protection for the adsorption dryer fitted downstream, as such a signal cannot be considered equivalent to a constantly maintained pressure dewpoint at the outlet of the refrigeration dryer.

10.4.9 Refrigeration dryer/part-flow adsorber

Using an adsorption dryer in a branch line for the purpose of drying a portion of the overall flow which has been pre-dried by the refrigeration dryer, is sketched in Fig. 10.4.9.1

In the preceding examples, installation of an adsorption dryer into a branch line is subjected to basic consideration regarding:

- Moisture load
- Selection of the drying medium
- Refrigeration dryer operation
- Automatic control
- Adsorption dryer size

Automatic control of the adsorption dryer operation in relation to the pressure dewpoint of the refrigeration dryer is achieved if the adsorption dryer is equipped with Dewpoint Dependent control. The variable cycle times adapted to the current operating state at any time, justify such a control system even for smaller adsorption dryers.

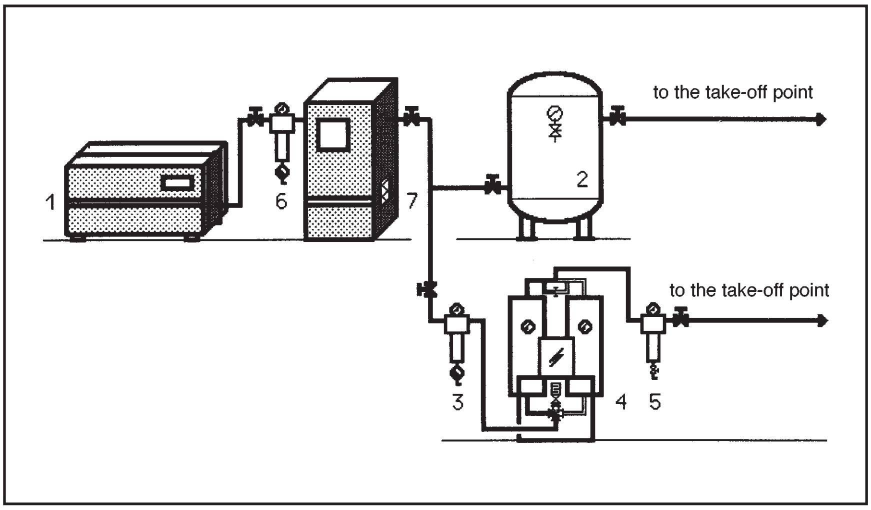


Fig. 10.4.9.1

The refrigeration dryer fault signal is not always available to the adsorption dryer as signal for switching over the cycle times. Distances between the centrally installed refrigeration dryer and the decentralised mounting of the adsorption dryer can, in practice, be very far apart and thus practically exclude direct electrical connection.

10.4.10 Adsorber/part-flow adsorber

A rare application is one where compressed air is further dried after already having been dried to a low pressure dewpoint. This occurs when, downstream of an adsorption dryer, a proportion of the total compressed air must have an even lower pressure dewpoint.

Compressed air with an inlet temperature of about ti = 35°C into the adsorption dryer (item 4) has a humidity level of hi = 39.9 g/m^3. At the outlet from the dryer, a pressure dewpoint of Pdp = -25°C is achieved. At this pressure dewpoint, the remaining humidity level is to about ho = 0.55 g/m^3.

The moisture content at the inlet to the adsorption dryer (item 4.1) in the branched-off air flow is less than 1%. Such a low relative humidity at the inlet of the adsorber calls for a completely new way of reviewing at the design criteria of the dryer.

Having selected a suitable drying medium and looking at dimensional criteria, this type of application always calls for a check whether flow takes place in an intermittent turbulent state and the dwell time in the adsorber is sufficient.

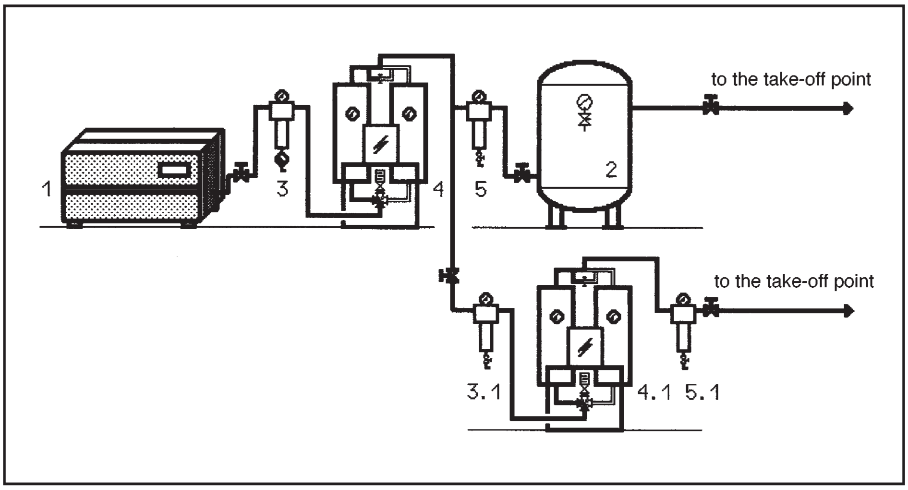


Fig. 10.4.10.1

These considerations may lead to an adsorber which is larger than in a standard installation. Dwell time depends on the pressure drop of inlet to outlet of the air dryer.

However, in extreme cases the intermittent flow in the turbulent flow, adequate dwell time, or high pressure drop, cannot be resolved. Under these circumstances, reliable after-drying is questionable.

Regeneration has be to looked at from the same points of view. Logically, the quantity of regeneration air must be higher.

For these part flow dryers, time and load depending control systems are used. These must be set with a safety margin and also fitted with a time cut-off.

Part 11

11.0 Condensate treatment

The purpose of compressors is to generate compressed air. Depending on air humidity and temperature, this is accompanied by a by-product, a large quantity of condensate. Significant technical resources are engaged in order to extract this condensate from the compressed air. Aftercoolers, separators, filters and adsorption dryers serve only one purpose, the achievement of a specified compressed air quality and the removal of condensate.

This condensate is the outcome of.pollutants drawn in from the atmosphere, absorbed by water aerosols. All components of the aspirated air, such as hydrocarbons from the lubricating oil of the compressor, flue gas emissions (ie. sulphur dioxide) and solvent vapour as well as diverse microdusts, form an oily and greasy or highly aggressive condensate in conjunction with the precipitated moisture and the oil component, depending on the type of compressor used.

Oil free condensate resembles distilled water and therefore readily absorbs mineral substances. Atmospheric air contains large quantities of acid components released by the combustion of fossil fuels. Enriched through concentration, the pH-value of the condensate can be reduced to around pH 4. With oil lubricated compressors, the concentration enrichment factor of the condensate can cause up to a 300 times higher proportion of oil than in the air. Some compressor oils partly neutralise the pH-value of the condensate. Most condensates precipitate at a pH of 4 - 6.

The problems of condensate treatment assume increasing significance through growing environmental consciousness and ever strict legislation. Oil containing compressor condensates, in particular, must be treated before being allowed to enter the drainage system.

According to § 7a of the German water treatment law, operators of oil lubricated compressors are obliged to dispose of the oil containing condensate in accordance with state of the art technology. As this is always a question of water which contains oil, in dispersed, emulsified, or soluble form, there are two possibilities :

- Collection in tanks and disposal through specialised companies or, preferably.
- Treatment by condensate trap, oil/water separator and emulsion separating equipment.

For chemically generated emulsions, emulsifying agents are used. Emulsifying agents are substances which lead to a homogeneous emulsion and prevent separation into two phases. They enable unpolarised substances such as oils, greases, hydrocarbons, solvents and petrol, etc. to be stably bound up in polarised liquids such as water. To purify such wastes or water, it is often required to de-activate the emulsifying agent, i.e. to split the emulsion.

Compressor condensates are mechanically generated emulsions.

By adding flocculating agents, finely emulsified oil droplets are adsorptively tied to microflocs generated by the flocculating agent. For further enhancing flocculation, auxiliary flocculating agents are used in addition to the main agents. These permeate the forming microflocs, leading to macro flocculation and an improved sedimentation process or, alternatively, facilitate separation by causing the pollutant to float.

Emulsions can also be separated by another process, ultrafiltration (see Section 11.3). This process does rely on the addition of flocculating agents. The equipment is relatively expensive but it creates filtrates of a high degree of purity (less than 1mg/L). Ultrafiltration is particularly suitable for removing the larger types of molecule. Under pressures of 2.5 - 4 bar1, smaller molecules can pass through the membrane whereas larger particles are retained. Ultrafiltration is suitable therefore for the wider field of waste water purification.

This is not the place to explain separating plant in further detail as the field of application extends far beyond that of condensate treatment.

The units of far greater interest in connection with condensate treatment, such as static Oil/Water Separators and emulsion separating equipment (Ultrafiltration), form the subject of subsequent sections.

11.1 Types of condensate

Oil/Water mixtures as compressor condensates occur in various forms:

- Coarsely dispersed mixtures
- Finely dispersed mixtures
- Emulsions
- Solutions

In the case of coarsely dispersed mixtures, individual oil droplets in the condensate are sufficiently large, by nature of their difference in density compared with water, to rise to the water surface if in a calmed zone of low flow velocity. In practice, these coarsely dispersed mixtures are in a frequently occurring form of oil containing compressor condensate which is treated by gravity separation followed by selective adsorption through activated charcoal in an Oil/Water Separator connected downstream of the equipment producing the condensate.

In finely dispersed mixtures, separation through gravity takes place to a limited extent only. Given an appropriate impingement surface, these can, to some extent, be coalesced through coalescing pre-filters, provided that adequate attention is paid to effective presedimentation. The residual oil content present in such mixtures is trapped by means of activated charcoal.

Emulsions are significantly different to dispersed mixtures. For a better understanding, further details about the chemical structure of compressor oils are given here.

Oil usually consists of long chain hydrocarbons without a polar centre. As water is partly polar, there are no significant interactions between oil and water molecules. Oil behaves hydrophobically (water repellent).in principle.

Part of the function of a compressor oil consists of binding condensate water which is being formed. For this purpose, the oil is supplemented with additives containing polar groups with a view to binding water. Such characteristics are provided by amine compounds or sodium salts of fatty acids. These substances promote the formation of stable emulsions with the oil via long chain constituents. These polar constituents form bridges to the water molecules.

Emulsions arise through water binding additives or through the application of mechanical energy. Both forms occur in the case of compressor condensates, the major cause of the emulsions being due to mechanical generation. The water phase of such emulsions still contains finely distributed oil droplets with diameters of less than 50 microns. These oil droplets are electrically charged with the same polarity and this prevents coalescing of the droplets. Pre-cleaning through gravity and coalescing filters is thus excluded, and a cleaning phase with activated charcoal is also not economical. The input of energy takes place not only in the compression of the compressed air as the draining of the condensate also adds considerable energy.

Timed condensate drain valves for example are in practice set with a safety margin in such a manner that the maximum possible quantity of condensate is

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[1] reverse osmosis on the other hand p = 20 - 80 bar

pushed out with a blast of compressed air. Given a low level of condensate and constant time setting, the blast of compressed air grows proportionately and unnecessarily.

When the timed condensate drain valve opens, the condensate is, in the first instance, pushed into the condensate pipe network and highly turbulent currents are formed because of the small cross-section. Upon impingement, the oil droplets are microscopically fragmented and dispersed, as the compressed air flowing out of the solenoid valve with high kinetic energy accelerates the droplets to a high velocity.

Friction against the internal walls of the piping and in the air stream provides additional electric static charges on the oil droplets. The result is a highly stable emulsion. The mode of distribution of the smallest oil droplets in the condensate phase decides whether an emulsion is formed or not. Given an oil droplet diameter of 100 microns or smaller, a limiting value has been reached at which only poor phase separation by purely physical means is possible.

Stable emulsions can be specific to a compressor under certain conditions only. Fresh oil lubricated rotary compressors of older design, reliable and robust as far as their construction is concerned, are in practice commonly lubricated by means of engine oil containing high levels of dispersants. In conjunction with very high temperatures of compression, conventional oil/water separation is practically impossible.

Almost the same circumstances apply to large air cooled piston compressors, as well as high pressure compressors, as strong thermal input has a negative influence on the demulsification characteristics of highgrade compressor oils.

Oils with a strong inclination towards emulsion are fundamentally those engine oils described by the classification HD or SAE as the requirement to emulsify is of great importance for the original fields of application of these oils. Also, oils capable of demulsification may behave similarly to HD oil for the following reasons:-

- Excessive oil change intervals, followed by too high mechanical.shear, combined with intensive exposure to oxygen from the air and to ageing. Antioxidation additives, foam formation preventors and demulsifying agents lose their capabilities. Within hours, stable emulsions can be formed.

- Effects upon the oil through drawn in emulsion forming agents, where this symptom can, under certain conditions, occur after a short period of oil use. One has to investigate whether emulsifying substances are drawn in with the inlet air and whether these change the characteristics of the compressor oil. Examples could be emissions of combustion plant (catalytic effort) or PVC processing (formation of hydrochloric acid).

Describing compressor condensate is never straightforward. The question is: Is this solely an oil/water mixture or a genuine emulsion?

Oils contained in condensate are only to a very limited extent bio-degradable and endanger life in standing or flowing water, interfere with the operation of cesspits and impede oxygen penetration as well as compost putrefaction. For this reason, the law demands appropriate treatment of the oil containing water where the maximum limiting value of hydrocarbons is < 20 mg/L (or even less in some areas). For example, the German water treatment law prohibits dilution in order to diminish toxicity, therefore the oil and water have to be separated.

Low viscosity liquid separators to DIN 1999, which are usually employed in drainage, or simple sedimentation basins with some diverting baffles, are not suitable for the treatment of air compressor condensate. The water emerging after treatment in such equipment usually contains an unacceptably high content of residual oil of about 30 - 200 mg/L.

11.2 Oil/Water Separators

Oil/Water Separators with integrated activated charcoal filters continuously separate oil containing condensates into oil and water from compressor installations. The residual oil content of the treated water only maintains its level below the limiting value of 20 mg/L over a long period of operation, if the condensate feed is a true mixture of oil and water. Oil/Water Separators are not suitable for the treatment of stable emulsions.

The condensate should be piped to the Oil/Water Separator from the compressed air system via level controlled condensate drains (see Fig. 4.10.1.2). Automatic drains such as those based on floats or timed solenoid drain valves as sources for feeding the Oil/Water Separator can be used to a limited extent provided that large bores prevent highly turbulent flow and that the oil droplets are not fragmented and dispersed by shearing and impingement.

Oil/Water Separators are most successful with oil/water mixtures which can be separated by gravity only. The polluting ingredients drawn in via the air compression process (e.g. dusts, solvent vapours, pollen, etc.) can exert an unfavourable influence on the separation characteristics between the oil and water phase so that condensate separating systems are capable of separating the oil and water of such condensates to an unsatisfactory degree only.

The feeding of condensate to the oil/water separator (Fig. 11.2.1) takes place under pressure. Pressure release takes place in an expansion and separating chamber (item 1). This causes the surface of the main settlement tank to remain calm.

The condensate passes into a primary settlement chamber 2. Solid particles are trapped by the dirt trap forming the primary settlement chamber. The condensate then passes into the secondary settlement chamber.

The cleaned water from the base of the secondary settlement chamber is fed into the activated charcoal filters, which are configured to flow either singularly or in parallel.

In this way, even the finest oil droplets are retained. Very long dwell times guarantee the particularly high efficiency and the striking effectiveness of oil/water separators. The service life of the activated charcoal depends on the degree of emulsification of the oil in the water.

The oil content of the clean water at the outlet of the Oil/Water Separator should be checked periodically.

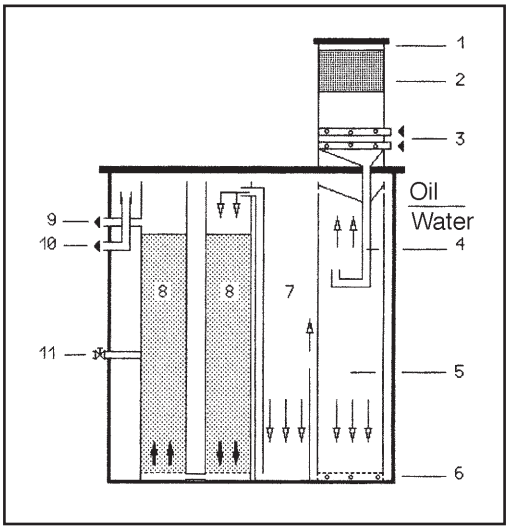


Fig. 11.2.1

As the density of the oil is lower than water, the oil floats on the surface. The oil outlet funnel (item 3), the height of which can be adjusted, is situated 0.5 - 1 cm above the water level. As soon as sufficient oil has settled on the water surface, (approximately 5-10 cm) the oil flows automatically from the Oil/Water Separator into a waste oil container.

Via the water outlet (item 9), the purified water can be channelled directly into the foul drain. The residual oil content of the drained water is less than 10 mg/L. The maximum condensate throughput, the residual oil content and the service life of the activated charcoal filters are largely determined by the type of compressor and the lubricating oil used.

As can be seen from Diagram 11.2.1, condensates from piston compressors are more problematic, because of the higher temperature of compression, than those from rotary or screw compressors. Compressor oils, resulting in the formation of emulsions, only then yield acceptable results if the condensate throughput is considerably reduced.

For Oil/Water Separators operating according to the principle of gravity, the vessel volume and the dwell time resulting from this, form a significant process technological parameter. Equally decisive for the effectiveness of separation is the number of directional diversions within the systems. Both features set a limit to the design size of the oil/water separator. Activated charcoal as a material for oil/water separation, is justified solely for oil/water mixtures which could be separated by the force of gravity only and are capable of removing only the final traces of oil.

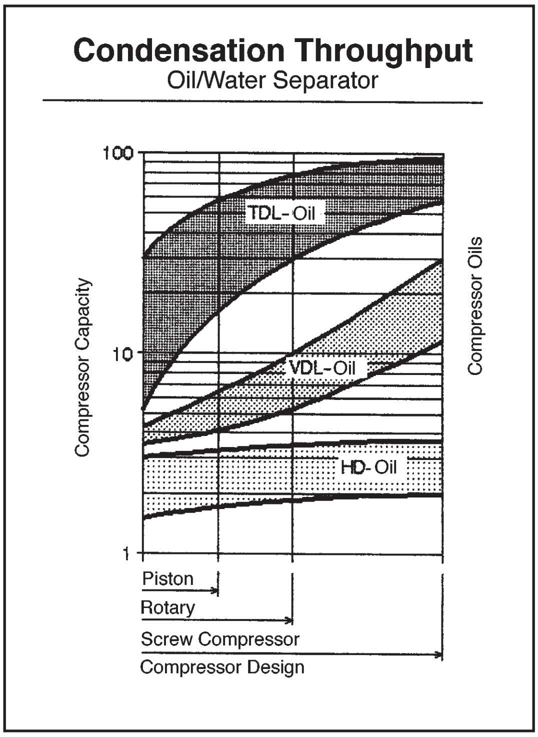


Diagram 11.2.1

When using Oil/Water Separators for emulsions, the oil separation must, be accomplished by activated charcoal filters. Transferring this function from gravity separation to activated charcoal adsorption calls for more frequent changes of activated charcoal filter and consequently additional costs of equipment maintenance, apart from the extremely high costs of responsible disposal.

Figures based on experience confirm that the disposal of 1 tonne of used activated charcoal costs about £690 with, in addition, the issue of the accompanying certificate, the declared analysis and the drawing up of the proof of responsible disposal. The changeover of the principle of oil/water separators to adsorption by activated charcoal for critical condensates cannot be regarded as a solution to these problems.

Photo 11.2.1

11.3 Ultrafiltration installations

Breaking up an emulsion of compressor condensate into oil and water can take place using cross-flow filtration. This purely physical separation process takes place selectively without additives. A semi-permeable membrane retains the larger oil molecules, thus separating them from the smaller water molecules which can pass through.

Through varied and successful applications, membrane technology occupies a secure place in waste water treatment. Extreme applications show the robustness of silicon carbide membranes.

The emulsion under pressure flows at high speed parallel to the filtration surface of the membrane, largely preventing a rapid contamination of the fine membrane pores.

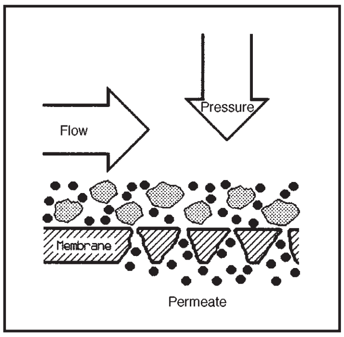


Fig. 11.3.1

The treatment of condensate emulsions from air compressors therefore poses no unusual challenge to membrane technology. It is the task of the plant designer to adapt the peripherals of the design to match the harsh conditions of the application and requirements. These include:

- Ceramic membranes
  Silicon carbide guarantees high filtration performance with constant quality of filtration and long service life of the membrane.

- Cyclic back flushing with compressed air
  Through cyclic reversal of the direction of flow of the purified condensate through the membranes, the filtration surface is effectively cleaned and the filtration performance kept at a constant level for a long period of time.

- Cyclic membrane cleaning
  Membranes automatically regenerate themselves after treating a quantity of condensate which has been specified beforehand.

- Integrated oil separator with coalescing stage
  The free oils carried from the compressor are safely and reliably separated. This greatly reduces the load on the membrane, and increases the filtration capacity.

- Fully automatic programmed control
  All necessary functions of the installation are performed automatically with the most important parameters monitored. This can only be achieved by the use of programmable logic controllers.

The pore diameter of the ceramic membrane used is such that even the finest emulsified oil droplets are retained, whereas water permeates the membrane and flows away as pure water.

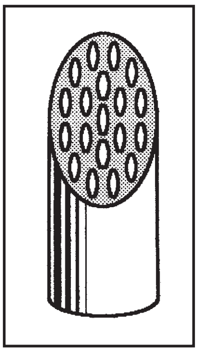


Fig. 11.3.2

The service life of the membrane is an essential factor. The filtration membrane consists of the inorganic material silicon carbide. This extremely robust material is characterised by high thermal and chemical resistance as well as extreme longevity.
A number of successful applications such as, the thickening of biomass or the pre-cleaning of cesspool water seeping through the ground are proof that even biologically highly loaded waste water can be treated reliably without the membranes blocking up.

To achieve correct sizing of emulsion separating installations, the compressor capacity, the periods of use and, possibly, installed dryers and their parameters are of significance. On this basis, the annual quantity of condensate can be determined with a reasonable degree of accuracy. Differing conditions should, however, be taken into account. The module contains up to five silicon carbide membranes. Filtration takes place automatically via programmed control. The sequence of separation is made clear by Fig. 11.3.3.

In the integrated oil separator (item 1) with dirt trap, oil floats to the top of the emulsion and is separated. A two-stage coalescing filter element improves the efficiency of separation. Overflowing emulsion is stored in the buffer container (item 2) and is pumped, into the process container (item 3). As soon as the process container is filled up to the maximum level, the concentration cycle commences.

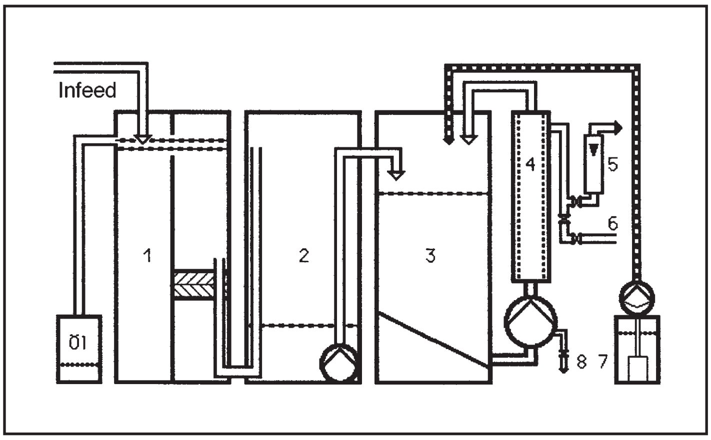


Fig. 11.3.3

In a closed loop operation, the emulsion is pumped through the filtration module (item 4). A flow meter (item 5) with a minimum flow switch monitors the quantity of permeate (quantity of purified water) flowing to drain. For cyclical membrane cleaning, the direction of flow of the permeate is reversed for a brief time by the back flushing unit (item 6). After the content of the process container has been treated, the float controlled process pump reverses.

Photo 11.3.1

The emulsion collected in the buffer container during the processing of the process tank is now pumped back into the process vessel, and the next concentration cycle commences. A pre-selected number of cycles specifies the degree of concentration. When this number of cycles has been carried out, the concentrate is pumped into a collecting vessel.

After this, the cleaning cycle starts again automatically. From a fresh mains water connection, the process container is filled up with the required quantity of rinsing water. From the cleaning solution dispensing device (item 7), the cleaner is fed in. The rinsing water cleans the membrane. After the rinsing time has elapsed, the charge concentration process commences again.

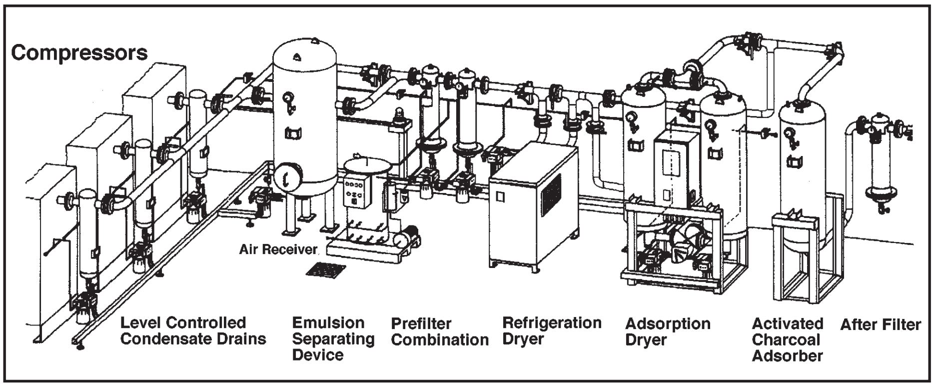


Fig. 11.3.4

Condensate drain lines from the individual drainage points to the emulsion separator operate under the following conditions, depending on the particular application.

Under pressure :
Mounted inside compressors (Fig. 11.3.4), where the condensate is fed in by means of level controlled condensate drains via flexible connections.

Through pump pressure :
Through use of a condensate collecting tank, a submerged pump in the collecting tank fills up the emulsion separator tank batch by batch.

Without pressure :
From a condensate collecting tank, the outlet of which is higher than the inlet of the emulsion separator. The inlet quantity of emulsion must be controlled to match the outlet quantity of clean water.

A concentrated oil/water emulsion remains as residue. Compressor condensates can reach an oil content of approximately 500 mg/L. The oil content within the concentrate from an emulsion separator can reach about 30 % or 300 000 mg/L. Volume reduction by a factor of 600 means that, theoretically, 1000 L of condensate emulsion results in a residual concentrate of only 1.6 L which has to be disposed of responsibly.

There can be no doubt that emulsion separating plants represent a future trend. The further development of ceramic membranes will make new applications possible in the future.

In direct comparison to flocullating equipment which uses powder or liquid means for splitting emulsions, emulsion separators offer a considerably higher operational reliability. The difference in pore size enables the membrane to retain oil particles while permitting water particles to pass through. This means that, even with high fluctuations of oil content in the condensate, there will be no deterioration in the quality of the purified water.

Drain water treatment systems operating on the basis of the filtration principle are the only ones, from the process technological point of view, which do not use any chemicals, bentonite, etc. This means that the condensate to be treated remains in its original state, and is not chemically modified or irreversibly occluded through an additive.

This largely eliminates the problems of residue disposal. The condensate remains in a fluid state and is therefore convenient to handle during intermediate storage and for later disposal through a specialist company. Moreover, when concentrating through filtration equipment, the disposal company has the possibility of splitting the concentrate into water and oil to a degree of nearly 100 %, thus utilising the oil for recycling.

One should note that, under normal circumstances, 1 m^3 of condensate leads to maximum 10 L of concentrate. The possibility of recycling the residue resulting from condensate treatment will exist in the near future.

Part 12

12.0 Tables of Information

Humidity of air in the saturated state

g/m^3	°C	g/m^3	°C	g/m^3	°C	g/m^3	°C	g/m^3	°C
0.000010	-100	0.0111	-60	0.89	-20	17.30	20	129.54	60
0.000013	-99	0.0126	-59	0.97	-19	18.34	21	135.23	61
0.000017	-98	0.0144	-58	1.06	-18	19.43	22	141.13	62
0.000022	-97	0.0163	-57	1.16	-17	20.58	23	147.24	63
0.000029	-96	0.0185	-56	1.27	-16	21.79	24	153.57	64
0.000037	-95	0.0209	-55	1.39	-15	23.06	25	160.12	65
0.000047	-94	0.0236	-54	1.52	-14	24.39	26	166.90	66
0.000059	-93	0.0267	-53	1.66	-13	25.79	27	173.92	67
0.000075	-92	0.0301	-52	1.81	-12	27.25	28	181.19	68
0.000095	-91	0.0339	-51	1.97	-11	28.79	29	188.70	69
0.000119	-90	0.0381	-50	2.14	-10	30.39	30	196.47	70
0.000141	-89	0.0428	-49	2.33	-9	32.08	31	204.50	71
0.000166	-88	0.0481	-48	2.53	-8	33.84	32	212.80	72
0.000195	-87	0.0540	-47	2.75	-7	35.68	33	221.38	73
0.000229	-86	0.0605	-46	2.98	-6	37.61	34	230.24	74
0.000268	-85	0.0678	-45	3.24	-5	39.63	35	239.40	75
0.000312	-84	0.0758	-44	3.51	-4	41.73	36	248.85	76
0.000364	-83	0.0846	-43	3.80	-3	43.93	37	258.60	77
0.000422	-82	0.0944	-42	4.11	-2	46.23	38	268.67	78
0.000489	-81	0.1052	-41	4.45	-1	48.64	39	279.06	79
0.000566	-80	0.1171	-40	4.81	0	51.14	40	289.77	80
0.000667	-79	0.1308	-39	5.16	1	53.76	41	300.82	81
0.000785	-78	0.1459	-38	5.53	2	56.48	42	312.22	82
0.000923	-77	0.1626	-37	5.92	3	59.32	43	323.96	83
0.001081	-76	0.1811	-36	6.33	4	62.29	44	336.07	84
0.001265	-75	0.2014	-35	6.77	5	65.37	45	348.54	85
0.001476	-74	0.2238	-34	7.23	6	68.59	46	361.39	86
0.001719	-73	0.2485	-33	7.73	7	71.93	47	374.62	87
0.001999	-72	0.2755	-32	8.25	8	75.41	48	388.25	88
0.002319	-71	0.3052	-31	8.80	9	79.04	49	402.28	89
0.002686	-70	0.3378	-30	9.38	10	82.81	50	416.72	90
0.003119	-69	0.3735	-29	10.00	11	86.73	51	431.57	91
0.003617	-68	0.4127	-28	10.65	12	90.80	52	446.86	92
0.004186	-67	0.4554	-27	11.33	13	95.03	53	462.58	93
0.004836	-66	0.5022	-26	12.06	14	99.43	54	478.75	94
0.005577	-65	0.5532	-25	12.82	15	103.99	55	495.38	95
0.006421	-64	0.6090	-24	13.63	16	108.73	56	512.47	96
0.007380	-63	0.6697	-23	14.47	17	113.65	57	530.03	97
0.008468	-62	0.7358	-22	15.37	18	118.76	58	548.08	98
0.009702	-61	0.8079	-21	16.31	19	124.05	59	566.62	99

Water vapour table

p	T	r	p	T	r	p	T	r
bar	°C	$\frac{\text{kcal}}{\text{kg}}$	bar	°C	$\frac{\text{kcal}}{\text{kg}}$	bar	°C	$\frac{\text{kcal}}{\text{kg}}$
2.0	119.4	527.0	5.0	150.1	500.2	12.0	186.8	475.9
2.1	120.8	525.5	5.2	151.6	499.1	12.2	187.6	475.5
2.2	122.3	524.1	5.4	153.0	498.0	12.4	188.4	475.0
2.3	123.6	522.8	5.6	154.4	497.0	12.6	189.1	474.6
2.4	124.9	521.5	5.8	155.8	496.0	12.8	189.9	474.2
2.5	126.2	520.3	6.0	157.1	495.1	13.0	190.6	473.8
2.6	127.5	519.2	6.2	158.4	494.1	13.2	191.3	473.4
2.7	128.7	518.0	6.4	159.7	493.2	13.4	192.1	473.0
2.8	129.9	517.0	6.6	160.9	492.4	13.6	192.8	472.6
2.9	131.0	515.9	6.8	162.1	491.5	13.8	193.5	472.2
3.0	132.1	515.0	7.0	163.3	490.7	14.0	194.2	471.8
3.1	133.2	514.0	7.2	164.4	490.0	14.2	194.9	471.4
3.2	134.3	513.1	7.4	165.6	489.2	14.4	195.6	471.0
3.3	135.3	512.2	7.6	166.7	488.5	14.6	196.2	470.7
3.4	136.3	511.3	7.8	167.8	487.7	14.8	196.9	470.3
3.5	137.3	510.5	8.0	168.8	487.0	15.0	197.6	469.9
3.6	138.3	509.6	8.2	169.9	486.3	15.2	198.2	469.6
3.7	139.2	508.9	8.4	170.9	485.7	15.4	198.9	469.2
3.8	140.2	508.1	8.6	171.9	485.0	15.6	199.5	468.9
3.9	141.1	507.3	8.8	172.9	484.4	15.8	200.1	468.5
4.0	142.0	506.6	9.0	173,9	483.8	16.0	200.8	468.2
4.1	142.8	505.9	9.2	174.8	483.2	16.2	201.4	467.9
4.2	143.7	505.2	9.4	175.8	482.6	16.4	202.0	467.6
4.3	144.6	504.5	9.6	176.7	482.0	16.6	202.6	467.2
4.4	145.4	503.9	9.8	177.6	481.4	16.8	203.2	466,9
4.5	146.2	503.2	10.0	178.5	480.9	17.0	203.8	466.6
4.6	147.0	502.6	10.2	179.4	480.4	17.2	204.4	466.3
4.7	147.8	502.0	10.4	180.3	479.8	17.4	205.0	466.0
4.8	148.6	501.4	10.6	181.1	479.3	17.6	205.6	465.7
4.9	149.4	500.8	10.8	182.0	478.8	17.8	206.2	465.4
5.0	150.1	500.2	11.0	182.8	478.3	18.0	206.8	465.1
5.1	150.9	499.7	11.2	183.6	477.8	18.2	207.3	464.8
5.2	151.6	499.1	11.4	184.5	477.3	18.4	207.9	464.5
5.3	152.3	498.6	11.6	185.3	476.9	18.6	208.5	464.2
5.4	153.0	498.0	11.8	186.1	476.4	18.8	209.0	463.9

Critical molecule diameter in Angström

Material	Symbol	Molecular diameter *f*
Acetylene	C_2H_2	2,4
Ammonia	NH_3	3,6
Argon	Ar	3,8
Benzol	C_6H_6	6,8
Carbondioxide	CO_2	2,8
Carbonmonoxide	CO	2,8
Chloro-difluoromethane	R22	4,9
Cyclohexane	C_6H_{12}	6,1
Dichloro-fluoromethane	R12	4,9
Ethane	C_2H_6	4,4
Ethanol	C_2H_3	4,4
Ethylene	C_2H_4	4,2
Ethylmercaptane		5,1
Helium	He	2,0
Hydrogen	H_2	2,4
Hydrogen sulphide	H_2S	3,6
i-Butane		5,6
i-Hydrocarbons		5,6
Methane	CH_4	4,0
Methano	CH_3	4,4
Methylemercaptane	CH_3SH	4,5
n-Butane	C_4H_{10}	4,9
n-Hydrocarbon		4,9
Nitrogen	N_2	3,0
Oxygen	O_2	2,8
Propane	C_3H_8	4,9
Propylene	C_3H_6	5,0
Water	H_2O	2,8

Application of activated charcoal

Acetaldehyde	2
Acetic acid	1
Acetone	3
Acetylene	1
Acroleine	1
Acrylaldehyde	2
Acrylic acid	1
Alcohol	1
Amine	3
Ammonia	3
Amyl alcohol	1
Amyl ether	1
Aniline	1
Benzol	1
Benzoldehyde	1
Butadiene	3
Butane	2
Butyl acetate	1
Butyl alcohol	1
Butyl chloride	1
Butyl ether	1
Butylene	2
Camphor	1
Caproldehyde	1
Caprylic acid	1
Carbolic acid	1
Carbon disulphide	2
Cellosolve	1
Chlorine	2
Chlorobenzol	1
Chlorobutadiene	1
Chloroform	1
Crontonaldehyde	1
Cyclohexane	1
Cyclohexanol	1
Cyclone hexanon	1
Decane	4
Detergents	2
Diaethyl amine	2
Diathyl ketone	1
Dibromo-ethane	1
Dichloro-benzol	1
Dichloro-ethane	1
Dimethyl amine	2
Dimethyl-sulphate	1
Dioxane	1
Dipropyl-ketone	1
Ethane	4
Ethyl acetate	1
Ethyl acrylate	1
Ethyl amine	2
Ethyl chloride	2
Ethyl ether	2
Ethtylene	4
Ethylene formate	2
Ethylene oxide	2
Formaldehyde	3
Formic acid	2
Freon	3
Putrefied substances	1
Heptane	4
Heptylene	3
Hexane	2
Hexylene	3
Indol	1
Iodine	1
Iodoform	1
Lactic acid	1
Leather	1
Mercaptane	1
Mesityl oxide	1
Methane	4
Methanol	2
Methyl acetate	2
Methyl bromide	2
Methyl chloride	2
Methyl ether	2
Methyl formate	2
Nephtaline	1
Nicotine	1
Nitric acid	2
Nitro-benzol	1
Nitro-ethane	1
Nitroglycerine	1
Nitromethane	1
Nitropropane	1
Nitrotoluol	1
Nonane	4
Octane	4
Octylene	4
Palmitinic acid	1
Pentane	2
Perfume	1
Phenol	1
Phosgene	2
Polymers (plastics)	1
Propane	3
Propionaldehyde	2
Propionic acid	1
Propyl acetate	1
Propyl alcohol	1
Propyl ether	1
Propylchloride	1
Propylene	2
Pyridine	1
Rancid fats	1
Rancid oils	1
Rosin	1
Rubber	1
Scatol	1
Sulphur dioxide	3
Sulphuric acid	1
Tar fumes	1
Tobacco smoke	1
Toluidine	1
Toluol	1
Turpentine	1
Urea	
Uric acid	1
Valeraldehyde	1
Valerian acid	1
Vinegar	1
Vinylchloride	2
Wood alcohol	2
Xylol	1

Key

1 very good
2 good
3 weak
4 hardly

Material parameters for gases and vapours

at 0°C and 760

Gas	M	$\tau_{,,}$	$\frac{\tau_{,,}}{\tau_{Luft}}$	v’	R	x
	$\frac{kp}{Mol}$	$\frac{kp}{Nm^3}$		$\frac{Nm^3}{kg}$	$\frac{mkp}{kggrad}$	$\frac{c_p}{cv}$
Acetone	17,03	0,771	0,597	1,296	49,78	1,313
Acetylene	26,04	1,171	0,906	0,854	32,57	1,245
Air	28,96	1,293	1,000	0,774	29,27	1,404
Ammonia	17,03	0,771	0,597	1,296	49,78	1,313
Argon	39,94	1,784	1,378	0,561	21,23	1,665
Benzol	78,11	3,485	2,695	0,287	10,86	1,127
Butane	58,12	2,593	2,005	0,386	14,59	1,114
Carbon dioxide	44,01	1,977	1,529	0,506	19,27	1,300
Carbon monoxide	28,01	1,250	0,967	0,800	30,27	1,401
Carbondisulphide	76,14	3,397	2,628	0,294	11,14	1,230
Chlorine	70,91	3,164	2,447	0,316	11,96	1,329
Ethane	30,07	1,356	1,049	0,738	28,20	1,201
Ether	72,12	3,307	2,558	0,302	11,44	1,085
Ethylene	28,05	1,261	0,975	0,793	30,23	1,255
Generator gas	25,70	1,150	0,866	0,873	33,00	1,388
Helium	4,00	0,179	0,138	5,602	211,80	1,665
Hydrogen	2,02	0,090	0,070	11,120	420,50	1,415
Hydrogen chloride	36,47	1,639	1,268	0,610	23,25	1,397
Hydrogensulphide	34,08	1,251	1,191	0,650	24,88	1,324
Methane	16,04	0,717	0,555	1,395	52,85	1,316
Neon	20,18	0,900	0,696			
Nitrogen	28,02	1,250	0,967	0,800	30,26	1,425
Oxygen	32,00	1,429	1,105	0,700	26,50	1,400
Propane	44,09	2,019	1,562	0,495	19,23	1,138
Smoke gas	29,30	1,340	1,033	0,749	28,30	1,380
Sulphur dioxide	64,07	2,926	2,264	0,342	13,24	1,284
Top gas	28,33	1,260	0,977	0,791	29,90	1,410
Town gas	11,70	0,520	0,390	1,920	72,70	1,369

Conversions

Pressure	Pa	bar	at (tech.)	atm (phys.)	mmHg
Pa	1	$1*10^{-5}$	$0,102*10^{-4}$	$0,987*10^{-5}$	0,0075
bar	$1*10^{5}$	1	1,02	0,987	750
at (tech.)	98100	0,981	1	0,968	736
atm (phys.)	101325	1,013	1,033	1	760
mmHg	133	0,00133	0,00136	0,00132	1

1Pa = 1N/m^2 1at = 1kp/cm^2 1atm = 760Torr

Output	W	kW	kcal/s	kcal/h	kpm/s	PS
W	1	0,001	$0,239*10^{-3}$	0,86	0,102	0,00136
kW	1000	1	0,24	860	102	1,36
kcal/s	4186	4,186	1	3600	427	5,69
kcal/h	1,16	0,00116	0,000277	1	0,119	0,00158
kpm/s	9,81	0,00981	0,00234	8,43	1	0,0133
PS	736	0,736	0,176	632	75	1

1W = 1Nm/s = 1J/s

Work	J	kWh	kcal	kpm	PSh
J	1	$0,278*10^{-6}$	$0,239*10^{-3}$	0,102	$0,378*10^{-6}$
kWh	4186	1	860	$0,367*10^{6}$	1,36
kcal	4186	$1,16*10^{-3}$	1	427	$1,58*10^{-3}$
kpm	9,81	$2,72*10^{-6}$	$2,34*10^{-3}$	1	$0,37*10^{-6}$
PSh	$2,65*10^{6}$	0,736	632	$0,27*10^{6}$	1

1J = 1Nm = 1Ws

prefixes

G	Giga	10^{9}	one thousand million times
M	Mega	10^{6}	one million times
k	Kilo	10^{3}	one thousand times
h	Hecto	10^{2}	one hundred times
da	Deca	10^{1}	ten times
d	Deci	10^{-1}	one tenth
c	Centi	10^{-1}	one hundredth
m	Milli	10^{-2}	one thousandth
µ	Micro	10^{6}	one millionth
n	Nano	10^{9}	one thousandth of a millionth

12.1 Diagrams

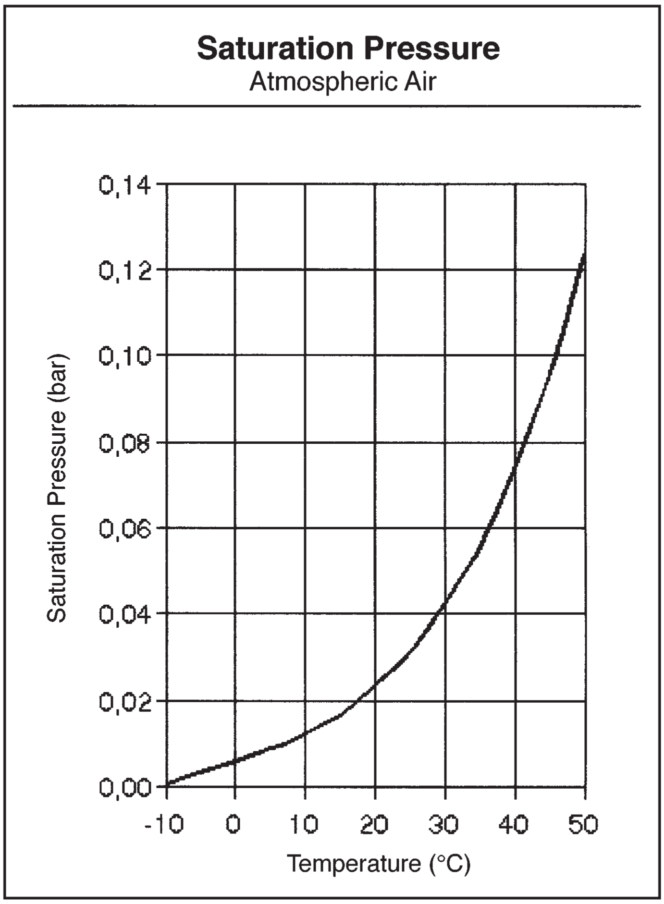


Diagram 1.7.1

Evaporation and condensation are in mutual balance if the vapour pressure of a liquid is as large as that part of the external pressure which is generated by the water vapour contained in the air. If both pressures are of equal magnitude, the air is saturated with moisture.

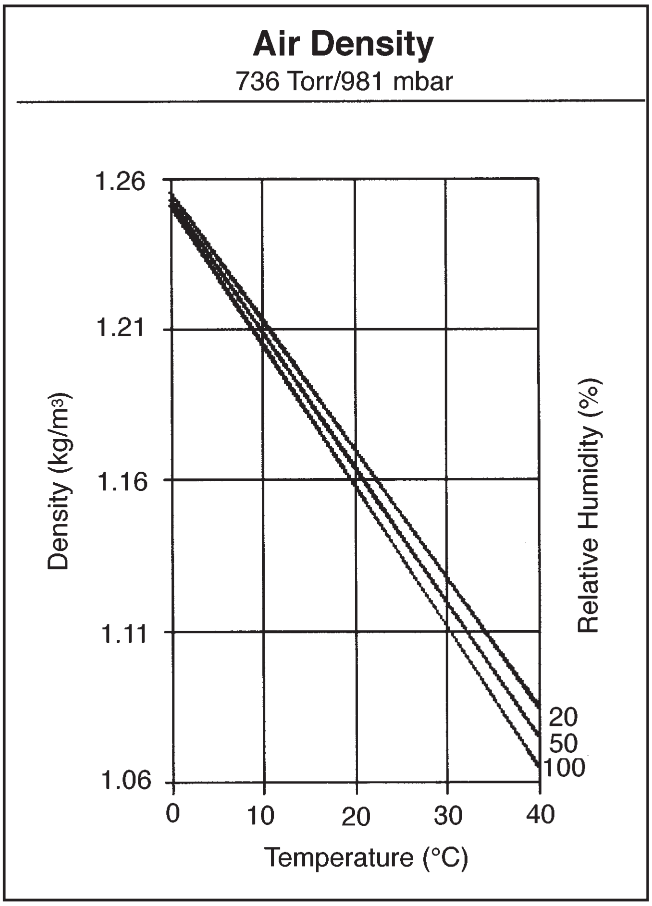
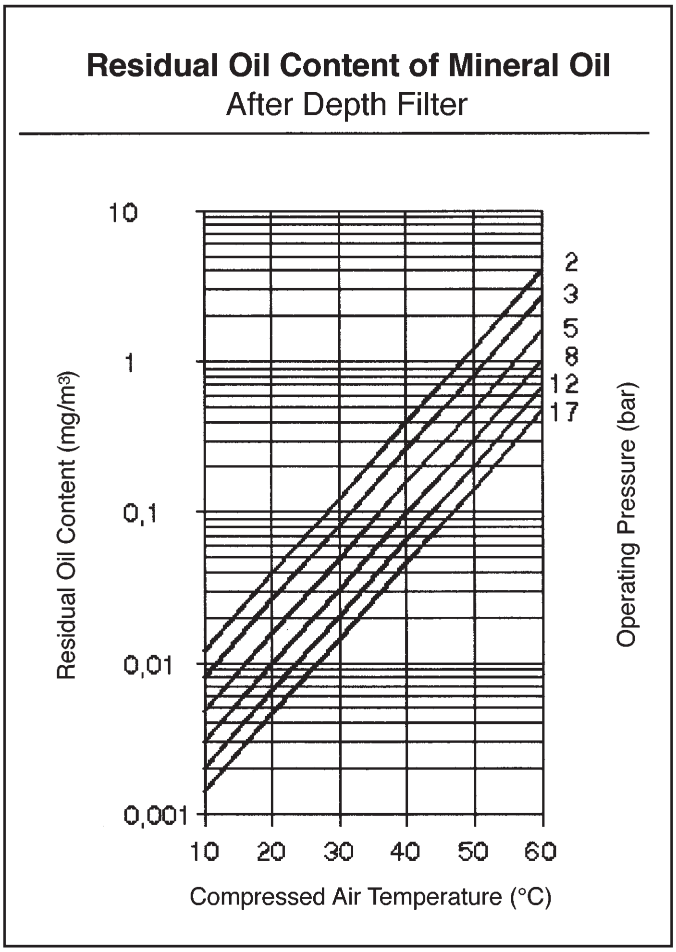


Diagram 2.3.2.1

In most cases the mass of air in kg is not known but the quantity delivered in volumetric values per unit of time, e.g. in m^3/min. Using the values from the diagram, the mass of air is calculated on the basis of the volume.



Residual Oil Content of Mineral Oil
After Depth Filter

Diagram 4.7.4.1

The milligramme figures indicating residual oil content refer, according to ISO 554, to the unpressurised volume (atmospheric pressure) in m^3. The residual oil content of the oil still in its vapour phase is not taken into account. Every compressor oil has its own characteristic and correspondingly deviating values. This diagram is based on a compressor oil with a mean molecular weight of 300.

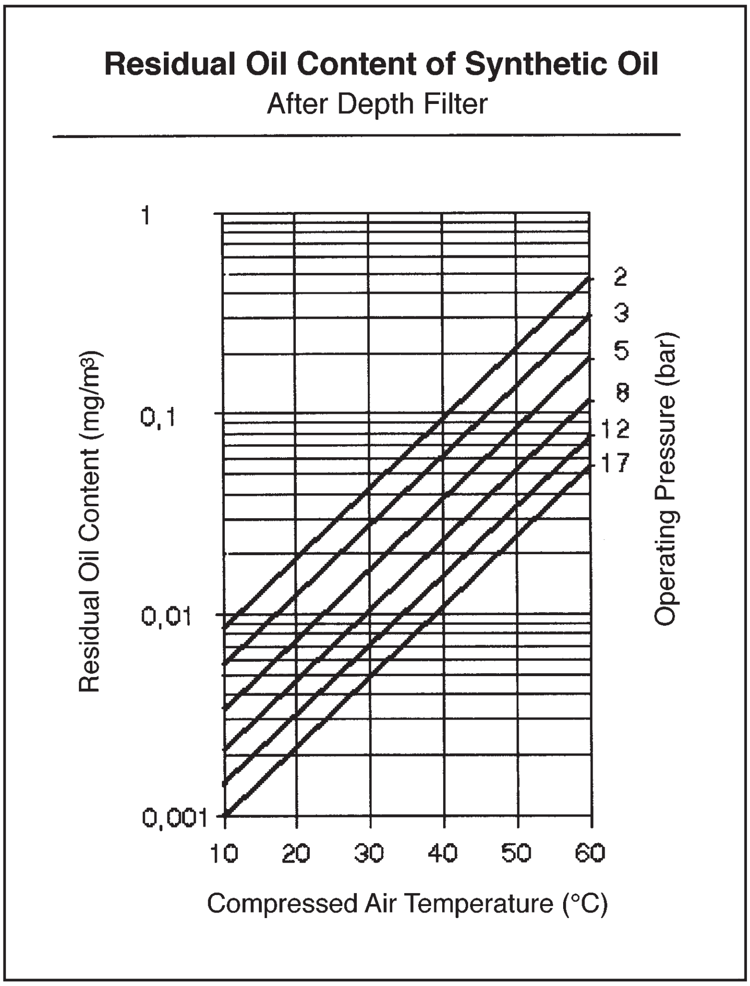
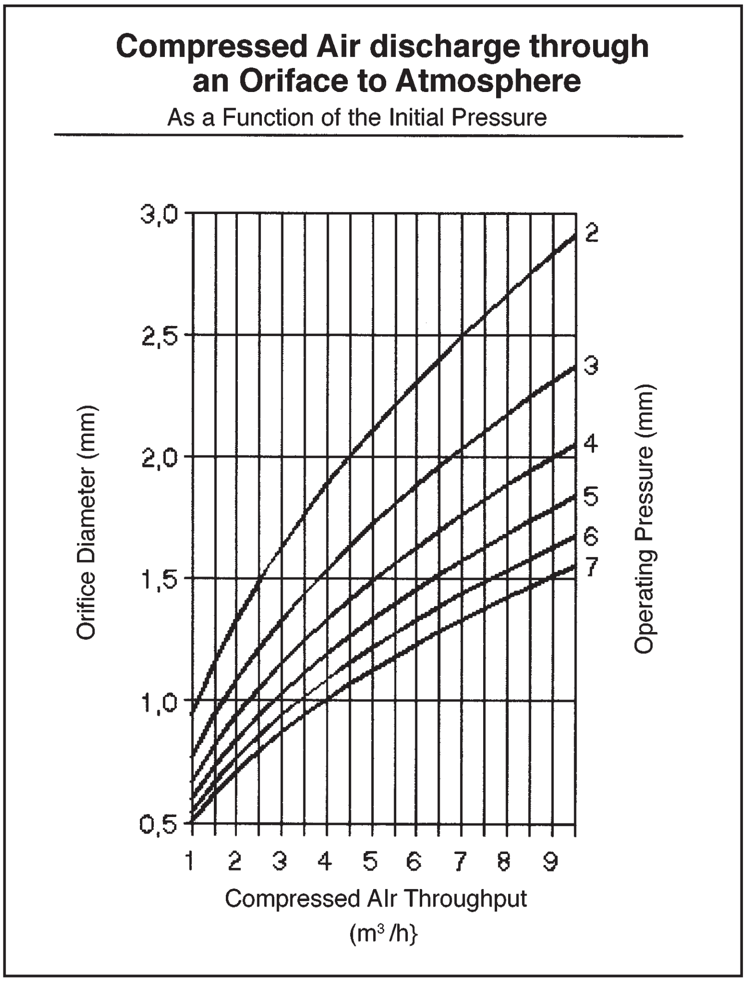


Diagram 4.7.4.2

The milligramme figures for the residual oil content refer, according to ISO 554, to the unpressurised volume (atmospheric pressure) in m^3. The residual oil content of the oil still in its vapour phase is not taken into account.
Every compressor oil has its own characteristic and correspondingly deviating values.

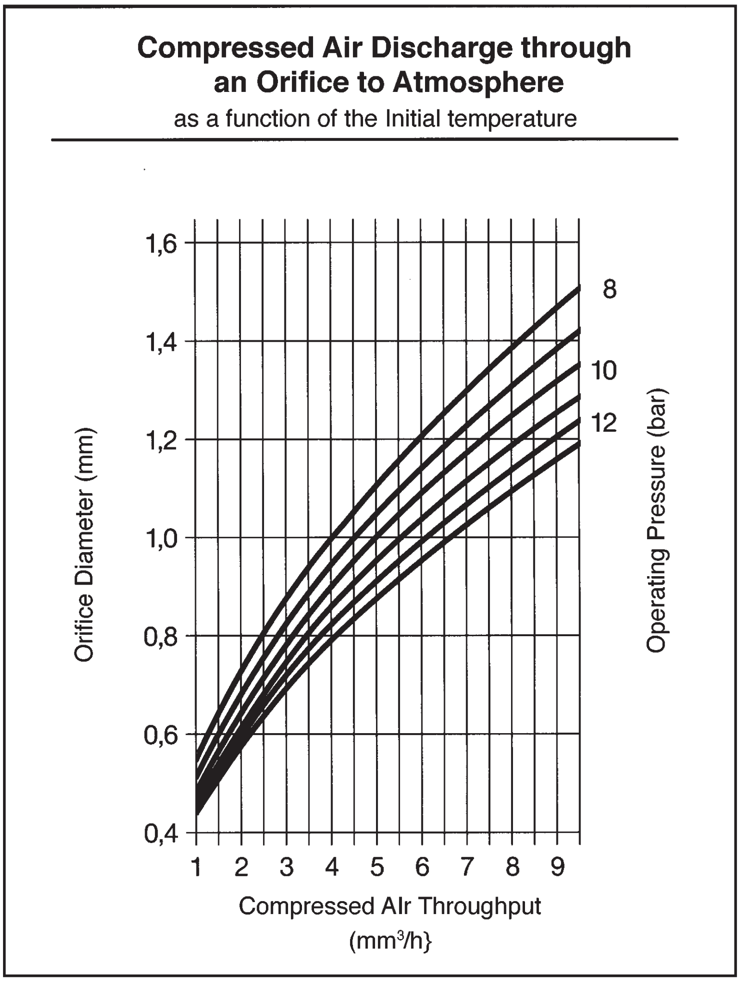


Compressed Air discharge through an Oriface to Atmosphere

As a Function of the Initial Pressure

Diagram 7.1.4.1

The efficiency quotient of the orifice is less than 1 and not taken into account by the diagram. This causes the quantity of air flowing out of the orifice to be smaller than the amount obtained on the basis of theory. In practice, a factor derived from the proportion between loading time and pressure build-up time is taken into account when designing the orifice.



Compressed Air Discharge through an Orifice to Atmosphere

as a function of the Initial temperature

Diagram 7.1.4.2

The efficiency quotient of the orifice is less than 1 and not taken into account by the diagram. This causes the quantity of air flowing out of the orifice to be smaller than the amount obtained on the basis of theory. In practice, a factor derived from the proportion between loading time and pressure build-up time is taken into account when designing the orifice.

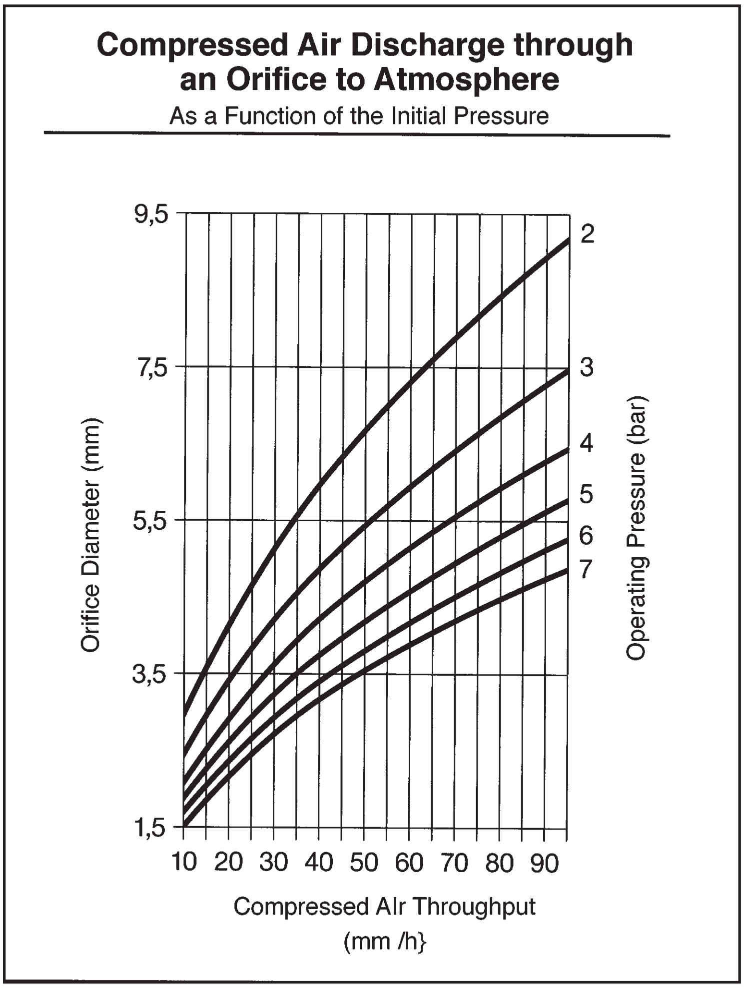
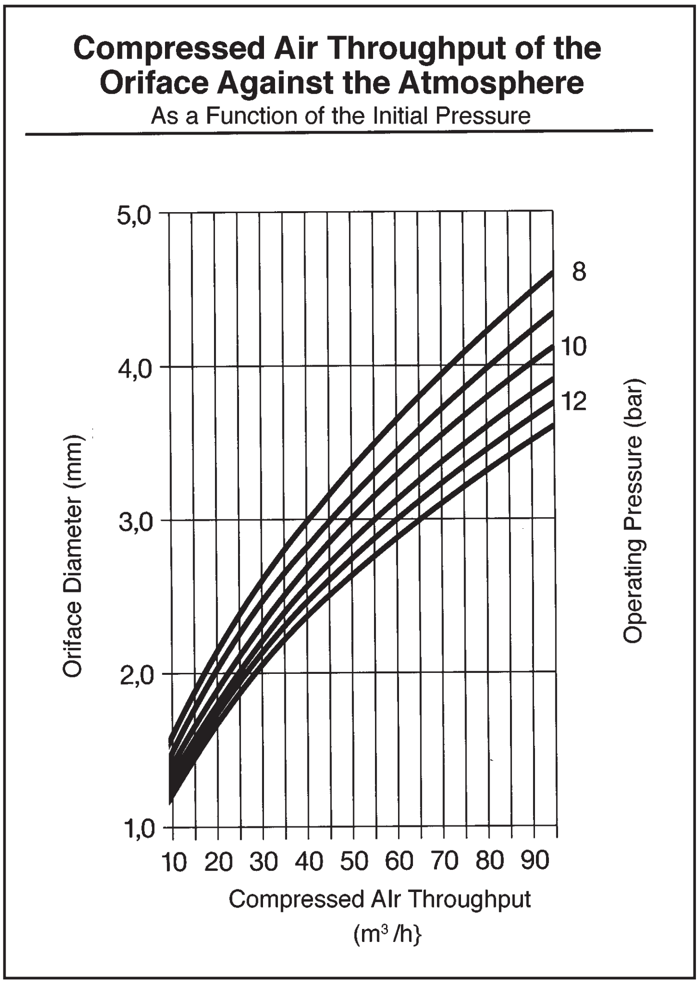


Diagram 7.1.4.3

The efficiency quotient of the orifice is less than 1 and not taken into account by the diagram. This causes the quantity of air flowing out of the orifice to be smaller than the amount obtained on the basis of theory. In practice, a factor derived from the proportion between loading time and pressure build-up time is taken into account when designing the orifice.



Compressed Air Throughput of the Oriface Against the Atmosphere

As a Function of the Initial Pressure

Diagram 7.1.4.4

The efficiency quotient of the orifice is less than 1 and not taken into account by the diagram. This causes the quantity of air flowing out to be smaller than the amount obtained on the basis of theory. In practice, a factor derived from the proportion between loading time and pressure build-up time is taken into account when designing the orifice.

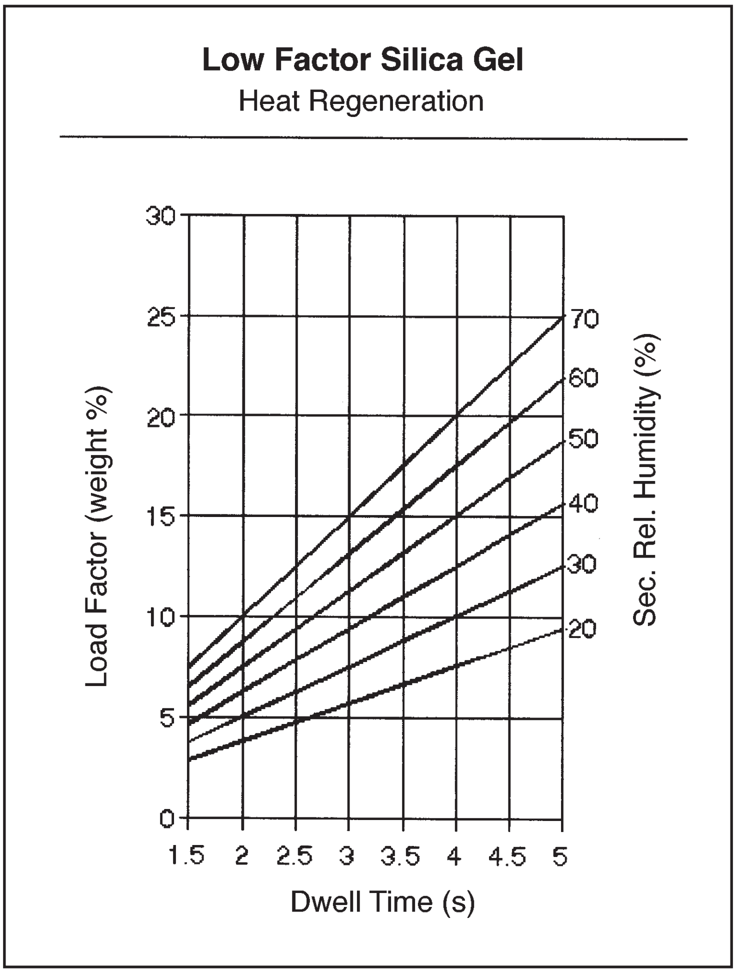


Diagram 7.2.1.2

By load factor one understands the quantity of water in kg adsorbed per kg of drying medium under certain operating conditions. The diagram relates to the achievement of a dewpoint of -40°C measured at 1 bar gauge at the end of the drying period.

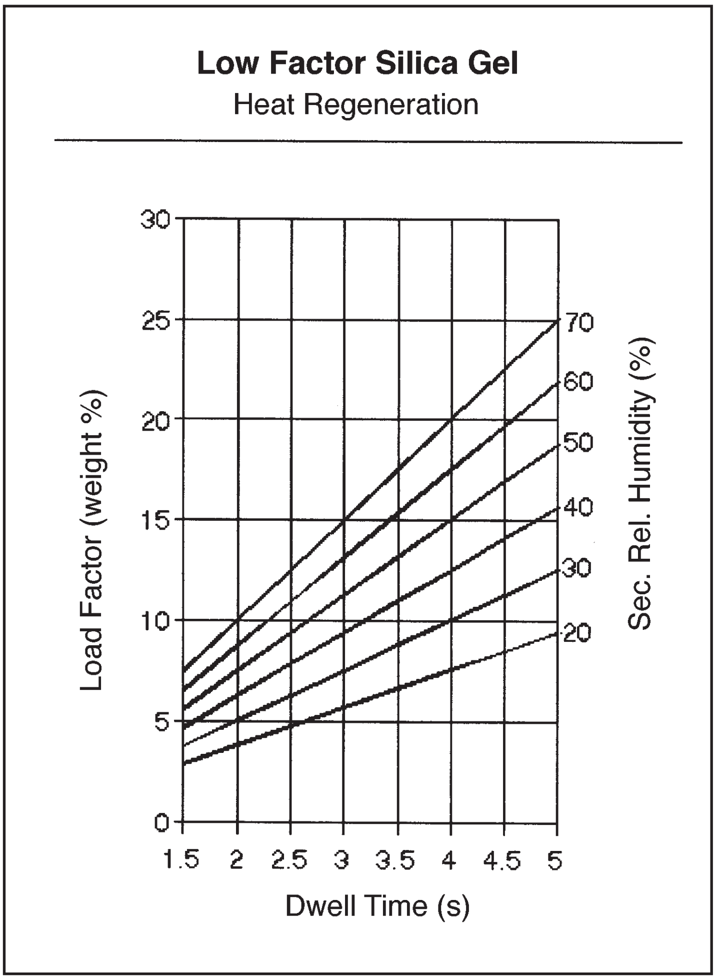


Diagram 12.1

Equilibrium relationship of
inlet temperature and inlet humidity as well as
regeneration temperature and dewpoint temperature
valid for water resisting WS pearls.

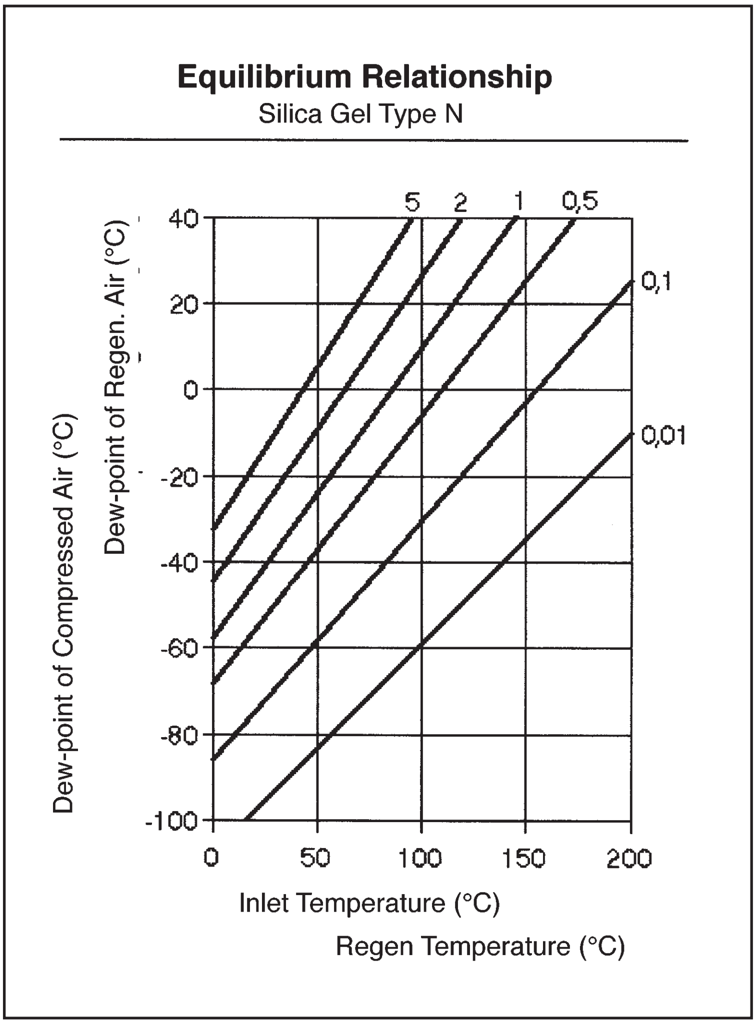


Diagram 12.2

Equilibrium relationship of
inlet temperature and inlet humidity as well as
regeneration temperature and dewpoint temperature
valid for intensely drying N pearls.

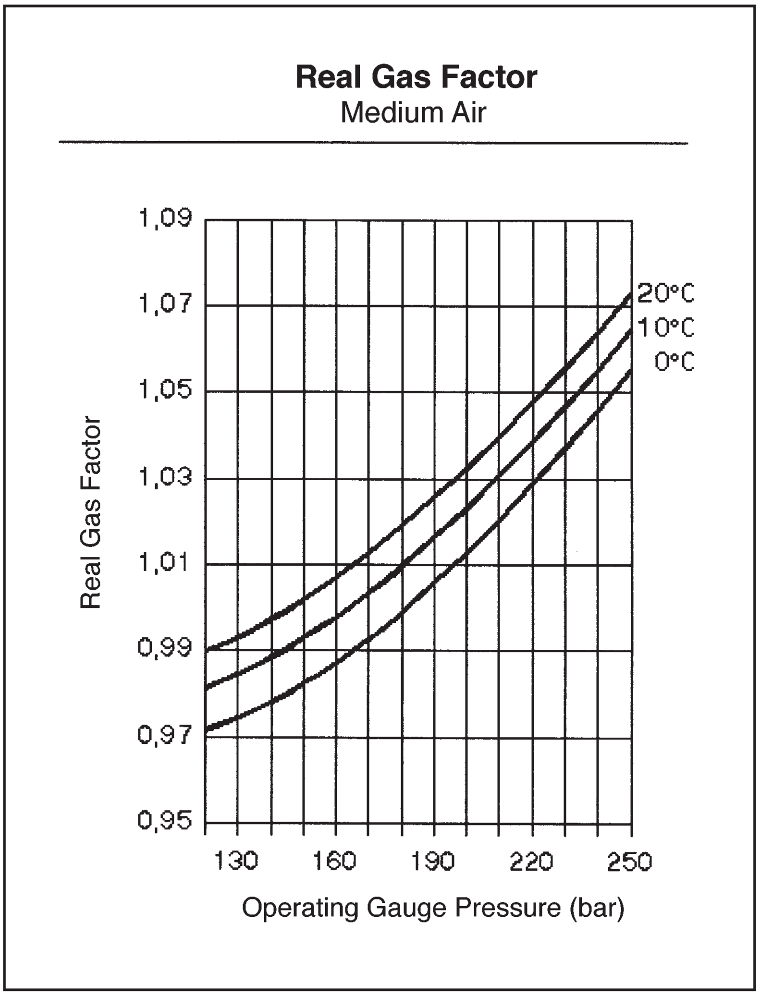


Diagram 12.3

Equilibrium relationship of inlet temperature and inlet humidity as well as regeneration temperature and dewpoint temperature
valid for molecular sieve.

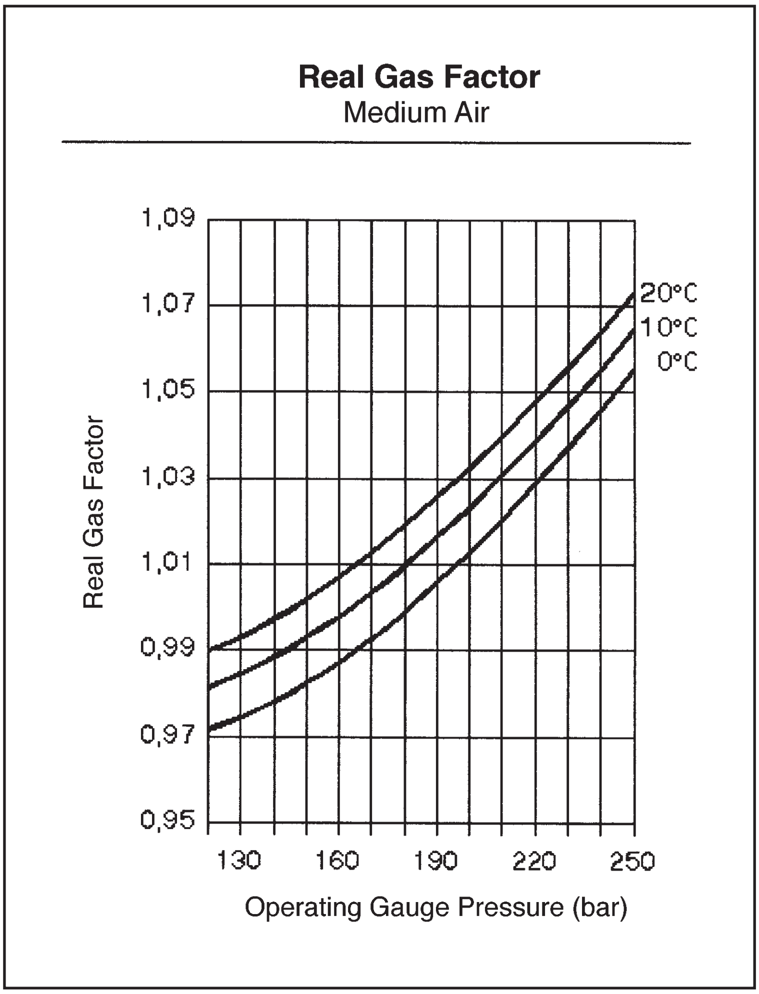


Diagram 12.4

The calculations were carried out with synthetic air composed of 79 % nitrogen and 21 % oxygen.

12.2 Index of Key Terms

24 hour effect: 276

A

absolute air humidity: 29, 32, 265, 266, 267, 270
absolute pressure: 33, 43, 47, 110, 276
absolute vacuum: 11
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