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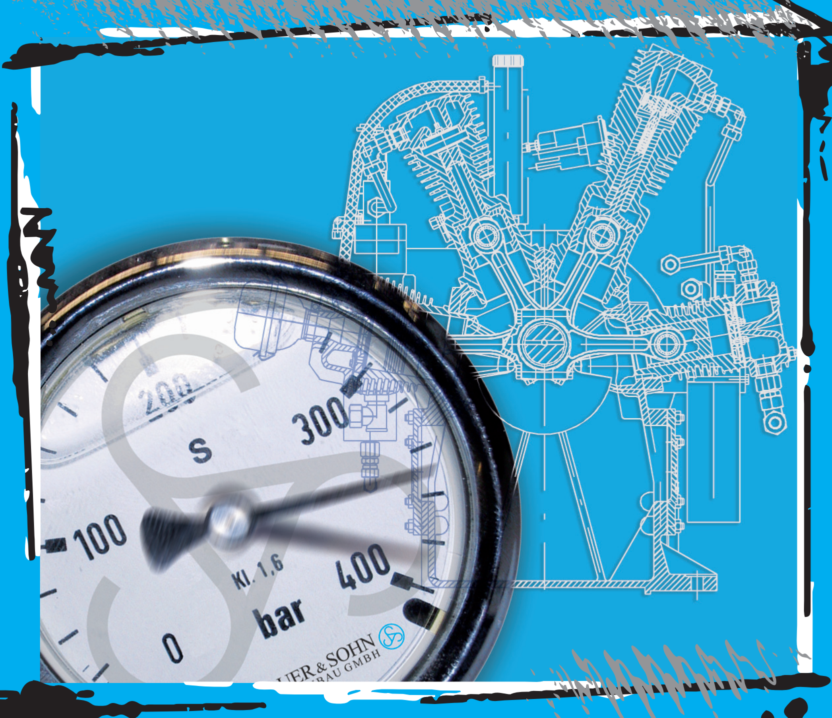
High-pressure Industrial Compressors

A practical guideline on selection, operation and maintenance



Sauer Compressors

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High-pressure Industrial Compressors

A practical guideline on selection, operation and maintenance

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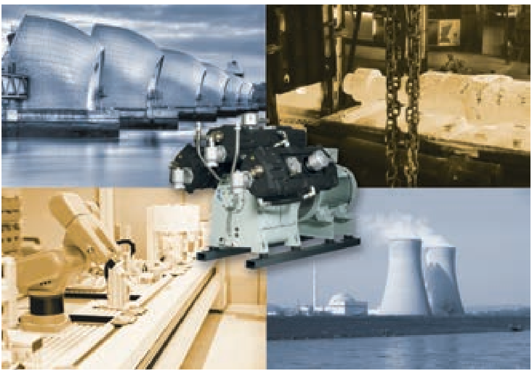

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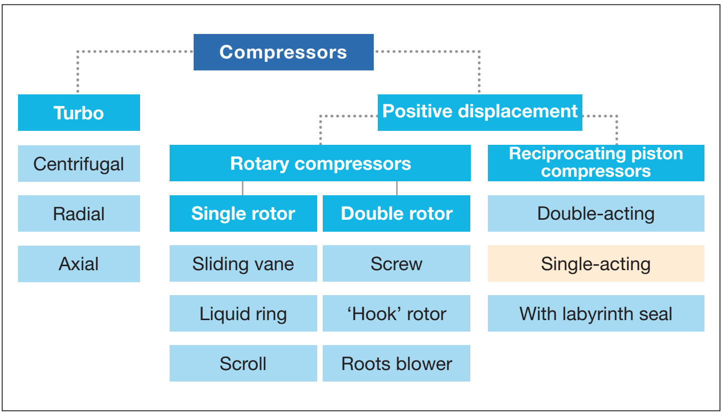
Contents

Introduction

Guidelines

This book was written by engineers for the guidance of readers who lack a compressor construction background and need assistance with the selection, planning, erection, installation, operation, maintenance and fault diagnosis of a compressor designed to meet the needs of their application. Six chapters within this book emphasise practical considerations, giving readers ready access to knowledge relating to the industrial use of compressors.
One of the oldest energy carriers – compressed air – is the subject of many specialised books. Most publications, however, focus primarily on pressure levels ranging from 4 bar to 15 bar overpressure (*pressure above atmospheric pressure [barg]; in the remainder of the book referred to using only the unit "bar"*) because most compressed air applications are in this low-pressure range. Many users make the mistake of applying the rules and related strategies for the 'low-pressure range' to, for example, safety measures,

Fig. 1: Overview of compressor designs



application concepts or possible energy savings in the 'high-pressure' range, although the technology and physics are not the same. This often leads to incorrect assumptions and designs for higher pressure compressed air systems which then fail to work at the desired level of efficiency. For this reason, this handbook focuses exclusively on high-pressure (from 30 bar to 500 bar) single-acting reciprocating piston compressors and outputs of 5 kW to 250 kW. Figure 1 shows reciprocating piston compressors in relation to all compressor construction types. There is no further discussion of other systems such as double-acting reciprocating piston compressors or crosshead compressors, which are also used for high-pressure applications. The compres-

Single-acting reciprocating piston compressors

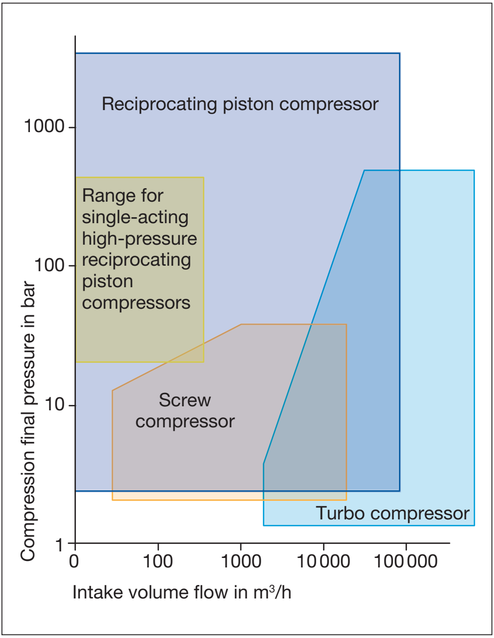


Fig. 2: Pressure-volume flow diagram for various compressor types

sion of gases such as helium or bio-methane is not examined closely either.

Greater risk potential

While safety plays an important role with all compressors, because of their high energy storage capability, compressors such as high-pressure compressors which generate pressures of 30 bar, 100 bar, 200 bar or even 500 bar (Fig. 2) can pose a greater risk compared to low-pressure compressors. With high pressure, in particular concerning safety aspects, a clear distinction from the low-pressure range is of particular importance.

Basic principles and design of reciprocating piston compressors

There are two basic types of compressors, namely positive displacement compressors and dynamic compressors. *Positive displacement compressors* include both reciprocating piston compressors as well as low-pressure screw-type compressors. *Dynamic compressors* include rotating types such as centrifugal compressors whose operating principle is based on the transfer of energy from a rotating impeller (shrouded propeller) to the air. Reciprocating piston compressors operate using positive displacement by reducing the volume and increasing the pressure within a closed space (i.e. piston, cylinder). This type of compressor offers the widest range of output (from < 1 kW to > 9000 kW) and pressure (from a low vacuum up to 1000 bar or more).

Positive displacement …

… and dynamic compressors

There are various types of reciprocating piston compressors defined by the following characteristics:

Distinctive features

- Number of compression stages
- Cooling method (air or water)
- Drive method (electric motor, combustion engine, other methods)
- Lubrication (oil lubrication, oil-free, non-lubricated service)
- Series design or custom built

Low-pressure compressors are primarily used for general service or instrument air (<10 bar), while the high-pressure reciprocating piston compressors (30 bar to 500 bar) discussed here are used in a variety of industrial applications.

Technical and thermodynamic basics

All compressor types have limiting operating conditions. For the reciprocating piston compressor, too great a compression ratio (discharge to intake pressure) may create excessive temperature or mechanical difficulties from too much cylinder load. It may, therefore, be necessary to complete the compression in two or more steps (*multi-stage compression*).

Multi-stage compression

In medium-pressure and high-pressure reciprocating piston compressors multi-staging is primarily used in order to:

- save power
- prevent the discharge temperature from becoming too high, and
- limit the pressure differential or ration for each stage.

A multi-stage air compressor compresses air from the intake pressure to the required final

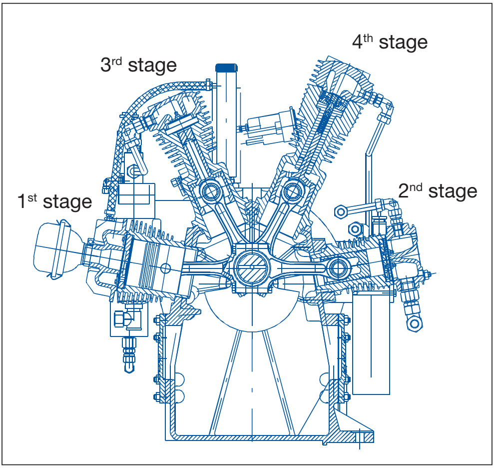


Fig. 3: Arrangement of compression stages in a compressor

pressure through a series of compression stages (Fig. 3). The cylinders are arranged so that the air passes through them in sequence until it is discharged into the final pressure air system. The air is cooled between the compression stages to reduce the temperature and the volume before the next compression stage.

Interstage cooling

The working principle of multi-stage compressors can be described in the following way: in the first stage as the piston moves downwards, air is sucked in (Fig. 4) and after

Suction

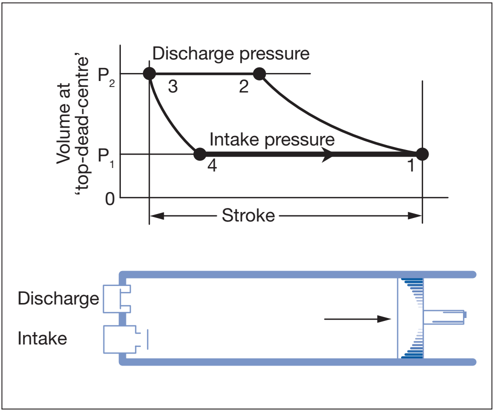


Fig. 4: Pressure-volume diagram (p - V diagram) at suction
- p_1 *Intake pressure*
- p_2 *Discharge pressure*
- *1-2 Compression process*
- *2-3 Discharge process*
- *3-4 Expansion process*
- *4-1 Intake process*

its subsequent upwards movement, the air is compressed by decreasing its volume (Fig. 5), is discharged from the cylinder (Fig. 6) and then conveyed to a cooler to remove the heat resulting from compression. The cooled air is then passed to a separator where any liquid oil and/or water present in the compressed air is separated and stored to be discharged at a later time. The dehydrated air then passes out of the separator and continues to the next compression stage where the process is repeated. Any air or gas which has remained in

Compression

Discharging

Separation

Fig. 5: p - V diagram for compression

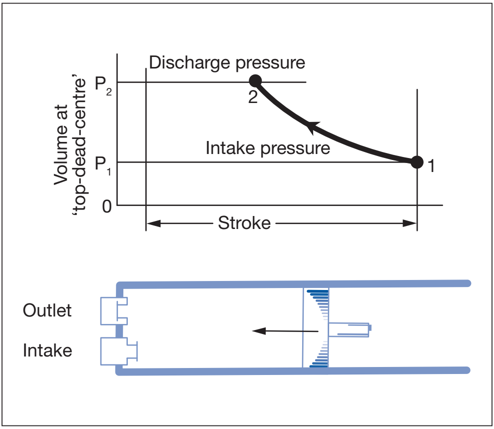
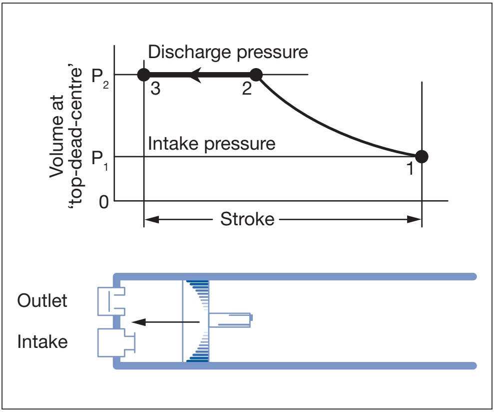


Fig. 6: p - V diagram at discharge



the cylinder is expanded back to the intake pressure (Fig. 7).

Limiting the discharge temperature …

With inter-cooling between stages, a reduction in the maximum gas discharge temperature is achieved. Limiting the discharge temperature at each compression stage is important for safety reasons when handling high-pressure compressed air, or gases, where distortion of cylinder parts could occur, and with oil-lubricated air compressors an oxidising air

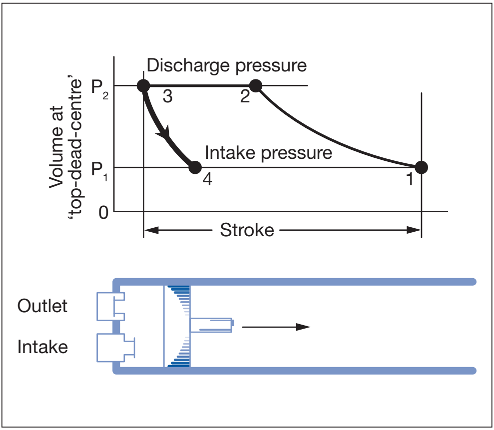


Fig. 7:
p - V diagram for expansion of the gas not discharged

mixture exists and oil decomposition accelerates with increasing temperature. A guideline for larger high-pressure compressors is a discharge temperature less than 160°C. Higher temperatures to 200°C are permissible for air or gases which contain no oxidising components.

… to less than 160°C

Increasing the number of compression stages to reduce the operating discharge temperature can also increase the compressor costs due to additional manufactured parts – however, these costs can be recouped over time. The stage pressure ratio, i.e. the ratio of intake to discharge pressure in each stage, is limited to avoid excessive running-gear loads and temperatures (Fig. 8). This lowers the running-gear loads and the compressor service life costs. Typical pressure ratios in the compression stages of multi-stage compressors are under 5:1. If the same pressure ratios are found in all stages, the same design for connecting rods and bearings can be used; only the piston sizes change. As pressure rises, smaller piston diameters are

Stage pressure ratio under 5:1

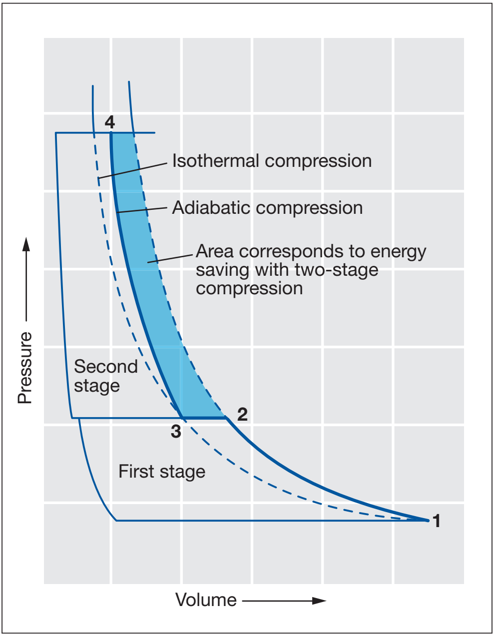


Fig. 8: Combined diagram of a two-stage piston unit with idealised interstage cooling. The real process (adiabatic compression) includes the following steps: 1 to 2 (air compression in the first stage); 2 to 3 (interstage cooling); 3 to 4 (air compression in the second stage). The outer dotted line to the left indicates the process path for optimal isothermal compression (theoretical only).

used in order to achieve the same gas load or force for each compression stage of the cylinder line.

Low clearance volume

To maintain a high volumetric efficiency, the clearance space – in other words the 'top-dead' volume in the cylinder essential to make sure that the piston does not strike the cylinder head – must be kept as small as possible. However, it cannot be completely eliminated. In practice this clearance space can vary between 4% and 20% of the total cylinder volume. This has to be accounted for when designing the compressor, but is of little importance to the end-user.

Formula for performance

The performance of a reciprocating piston compressor can be approximately described using the following formula:

$$P_{shaft} = 2{,}78 \cdot 10^{-4} \cdot Z_{avg} \cdot \left[\frac{Q_g \cdot T_S}{E}\right] \cdot \left(\frac{k}{(k-1)}\right) \cdot \left(\frac{p_L}{T_L}\right) \cdot \left[\left(\frac{p_D}{p_S}\right)^{\left(\frac{(k-1)}{k}\right)} - 1\right]$$

P_{shaft}	Shaft output per stage, kW
Z_{avg}	Average compressibility factor
Q_g	Volume flow-rate, m³/h
T_S	Intake temperature, K
E	Overall efficiency
k	Ratio of specific heats
p_L	Reference pressure, bar(a)
T_L	Reference temperature, K
p_D	Discharge pressure, bar(a)
p_S	Intake pressure, bar(a)

Total efficiency

The overall efficiency of a compressor is a value determined by experience which not only considers compression efficiency but also mechanical efficiency. The compression efficiency is dependent on many factors such as valve performance, compression ratio, gas composition, etc., while the mechanical efficiency is a function of cylinder proportions and speed. Typically, mechanical efficiency is 85% while compression efficiency can be between 65 and 75%.

Construction types and design variants

Drive via flexible coupling

Compressors are generally driven via a flexible coupling connected to the flywheel of the compressor and the shaft of an electric or diesel motor. The crankshaft with drive converts the rotary motion to reciprocating motion for the pistons.

Self-acting spring-loaded inlet/outlet valves on each cylinder regulate the flow of the compressed air. The intake stroke of the cylinder begins when the piston moves away from the valves. The internal pressure of the cylinder between the piston and the valves decreases, the inlet valve of the stage opens and air flows into the cylinder. As soon as the

Compression process

piston begins the compression stroke, the pressure inside the cylinder begins to increase, closing the inlet valve. The pressure continues to increase during the compression stroke until the outlet valve opens and the compressed air is passed to an inter-cooler and then to a separator. This operation is repeated in each of the compression stages, all of which are protected by a safety valve against overpressure.

Mineral oil or synthetic oil

A reciprocating piston compressor is commonly lubricated with oil. Either mineral oil or synthetic oil is used for both the drive (crankshaft bearings, etc.) and the cylinder and piston rings. However, there are applications where oil cannot be tolerated (e.g. oil

Oil-free operation or non-lubricated service

content < 0.001 ppm). Although such a requirement can be easily complied with by using an additional oil removal filter, ‘oil-free’ compressors or ‘non-lubricated’ compressors are also available.

Oil-less designs use no oil whatsoever, neither in the pistons nor the drive. Non-lubricated compressors, primarily destined for use in the process gas industry, use no lubricant in their compression cylinders, although oil is used to lubricate the drive bearings. The oil in

Separation of crankshaft oil

the crankcase is sealed via a piston rod in a crosshead-type design from the compression chamber and does not come into contact with the air or gas being compressed (Fig. 9). Crosshead-type designs use non-metallic piston rings and moving valve parts, together

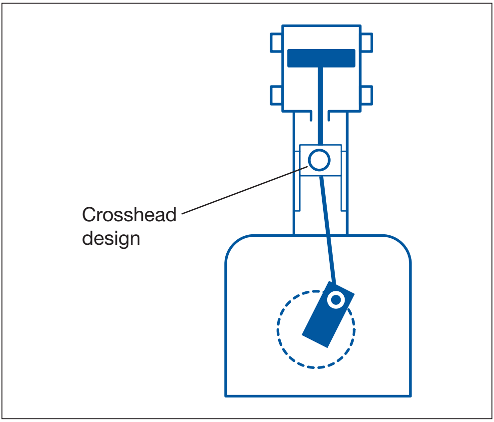


Fig. 9: Crosshead design variant

with a ‘distance piece’ to separate the crank-case oil from the sealed compression chamber. Non-lubricated compressors typically are more complex compared with oil-lubricated compressors with higher initial costs and higher maintenance costs.

Selecting a compressor

The core of any compressed air system is the compressor which generates the air pressure. All downstream systems are dependent on its proper design. To select the correct compressor for a given application speedily and easily, the following questions must first be answered:

List of questions

- What supply volume is needed?
- What pressure is required?
- What energy supply is available?
- What cooling medium is preferred?
- What accessories are required?
- What energy recovery is to be employed?

In the following section, the respective questions and points related to these questions will be examined more closely. Several of these points have a strong influence on the selection of a high-pressure compressor; some can be disregarded for high-pressure compressor applications.

What supply volume is needed?

Final pressure as reference value

The amount of air pumped by the compressor into the compressed air network is referred to as the supply volume. This should be indicated according to ISO 1217 Annex C or to standards corresponding to ISO 1217. The supply volume value should refer to the desired final pressure in order to ensure that different systems can be compared. The basis for this is the use of the same units of measure. Generally, the supply volume is specified using the unit cubic metres per hour (m^3/h) or cubic feet per minute (cfm), depending on what system of units is being used.

In order to determine the desired supply volume for the compressor, it is necessary to consider in advance what process the compressor is to supply. This includes a needs analysis as well as collection of data relevant to the desired process. The following should be considered:

Determining required work input

- What is the total volume of the consumer(s)?
- How often do the processes occur per hour?
- Do any processes take place simultaneously?
- What are the estimated compressed air system losses (generator, preparation, storage, compressed air distribution)?
- Is the supply volume required continuously or intermittently?

The work input identified through this list of questions should be supplemented by an additional reserve and possibly also a further amount for unknown conditions. The resulting value represents the minimum requirement for the supply volume of the high-pressure compressor.

What pressure is required?

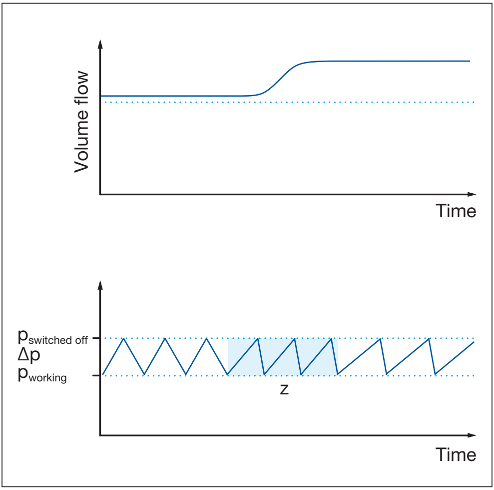
Process-dependent pressure level

A distinction should be made in high-pressure applications between what minimum pressure the process requires and what working pressure is required for the process. Attention should be paid to whether the process is continuous or intermittent.

For a continuous process (Fig. 10) in the high-pressure range, the difference in pressure, meaning the difference between the working pressure and the switch-off pressure of the compressor, should be kept as small as possible. The pressure differential

Fig. 10: Continuous process

$p_{switch\text{-}off}$	*Switch-off pressure*
Δ_p	*Differential pressure*
$p_{working}$	*Working pressure*
z	*Switch-on frequency of motor*



Optimising pressure differential

can be optimised by using appropriate high-pressure vessels. For an intermittent process (Fig. 11), it can be sufficient to supply the complete process only once, with the compressed air stored in a compressed-air vessel. When operational, the pressure existing in the storage vessel drops to the minimum pressure required for the process. During a pause in the process the compressor refills or recharges the required volume of compressed air which has to be available for the next process. Either the manufacturer of the compressor can help specify what differential pressure should be used, or this can be calculated based on the data collected during the needs analysis.

Pressure losses in the lines

Pressure losses in the pipelines caused by flow losses must be taken into account; these can often be attributed to incorrectly dimensioned pipe cross-sections or additional losses in valves, etc. As a general rule it can be stated “the lower the flow velocity the lower

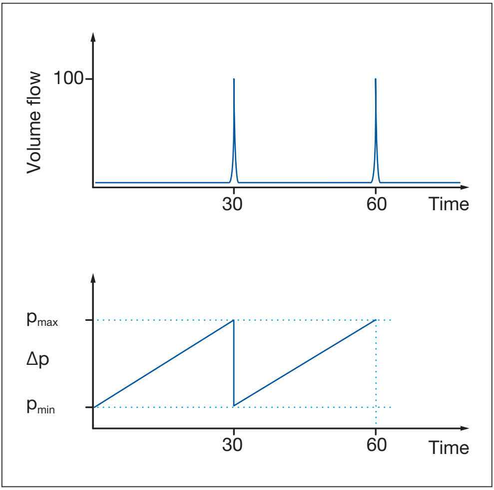


Fig. 11:
Intermittent process
p_{max} Maximum pressure
Δ_p Differential pressure
p_{min} Minimum pressure

the pressure loss". For this reason constriction in the pipeline system should be avoided wherever possible. As a guide, a flow velocity of 20 m/s for straight pipelines and a flow velocity of 5 m/s in fittings can be used. If at all possible neither value should be exceeded. On the other hand, the maximum cross-section for a pipeline is limited only by economic considerations.

Leaks do not remain concealed

Leakage tends to be a less important factor with high-pressure systems and does not have to be included in the differential pressure calculation. The reason for this is that, for example, a hole in a high-pressure system will make a very loud and annoying noise and will therefore not escape the user's notice as is frequently the case in low-pressure applications. That is why any leakage in a high-pressure system tends to be repaired in good time as soon as it occurs.

Unlike low-pressure systems, with high-pressure systems the final pressure does not play a decisive role in saving power. While 1 bar differential pressure in a low-pressure system requires about 6 to 8% greater input power; high-pressure systems only need 0.03% more power for each bar of differential pressure. For a 300-bar differential pressure, 10% more input power would be needed.

Function of the high-pressure vessel

As referred to above, a high-pressure compressor system nearly always includes a high-pressure vessel (Fig. 12). This vessel is used for storing the required process compressed air and also for dampening any pulsation which unavoidably occurs with reciprocating piston compressors. High-pressure vessels – also often referred to as high-pressure cylinders – must be designed for continuous or intermittent duty applications depending on

Fig. 12: High-pressure vessel to 600 bar

whether the process is constant or operates discontinuously.

Design for a continuous …

For a continuous process, the objective is to design the compressed-air vessel with an optimal balance between switching frequency and differential pressure of the high-pressure compressor. For high-pressure applications the industry practice is to set the differential pressure to 20% of the maximum pressure and then to optimise this value during operation. Various control strategies can offer more help in this regard (see chapter “Monitoring and control”, pp. 52 - 58).

… and for an intermittent process

For an intermittent process, the compressed-air vessel is designed to allow the process to be supplied from the available vessel volume. After completion of the process, the high-pressure compressor has a corresponding amount of time to refill the vessel before the next process run.

Dynamic load

Generally speaking, high-pressure vessels must be looked at much more carefully than low-pressure vessels. In high-pressure applications there is typically a dynamic, repetitive load, i.e. an interplay of pressures between the full and, where applicable, partially empty vessel. The vessels are designed for maximum repetitive loading and for this reason the user of vessels designed for service over 20 bar should inform the vessel supplier how often the pressure difference will take place.

What energy supply is available?

High-pressure compressors differ in their working principles and the drives they use. For electric drives, more and more highly efficient asynchronous motors are used today which should be categorized according to the

IEC standard (IE1-IE3). Additional information should be obtained from the motor manufacturer. A three-phase current system with a neutral conductor is required for use of a high-performance electric motor. If no neutral conductor is available, the manufacturer should be informed.

Use of four- or six-pole motors

Modern high-pressure compressors (Fig. 13) which have flexible direct-drive couplings are equipped with four- or six-pole motors and can then be operated at speeds of 1000 to 1800 rev/min. Speeds of 1000 to 1500 rev/min can be achieved with three-phase supplies with a frequency of 50 Hz, and those with a frequency of 60 Hz attain speeds of 1200 to 1800 rev/min. This allows adjustment of the desired volume flow rate which is directly related to the motor speed and thus the compressor crankshaft. A more flexible adjustment of the desired volume flow can be achieved by using a frequency

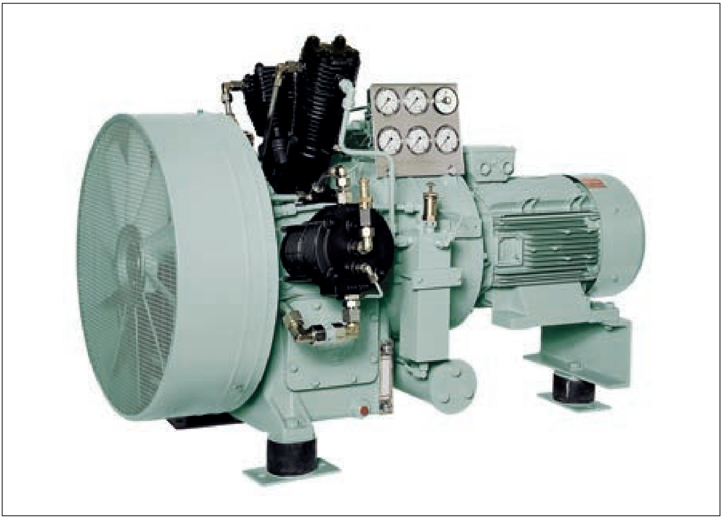


Fig. 13: Modern high-pressure compressor

inverter. With high-pressure compressors, this is only used to match a defined speed and not in the way it is used for low-pressure compressors to optimise the differential pressure and related energy savings. No energy-saving effect results from this with high-pressure compressors.

Flexible adjustment

In a few cases belt-driven compressors are still in use, but because of increased demands for safety and energy savings, these are steadily losing significance.

Voltage range

In the case of modern electric motors, the supply voltage plays a minor role because modern variable-voltage motors are used. These cover a range from 380 to 415 V at 50 Hz and 440 to 480 V at 60 Hz. Special voltages such as 690 V or 230 V do not as a rule cause any problems, but the compressor manufacturer should be informed.

Alternative diesel engine

If no adequate electricity supply can be obtained for the operation of a high-pressure compressor, it is possible to use an internal combustion engine, usually a diesel engine as the drive unit. If an internal combustion engine is being considered, the compressor manufacturer should always be consulted as early as possible in order to guarantee choice of the correct engine. In this context, compliance with the emission class prescribed in each respective country has to be ensured. This can lead to different designs of internal combustion engines.

What cooling medium is preferred?

Forced draft air, freshwater and, in rare cases seawater, can be used for cooling. An important parameter in selecting the cooling me-

dium is the difference between compressed air intake and final outlet temperature [ΔT], usually expressed in degrees Celsius [°C]. Depending on the cooling method chosen, different values arise here.
The importance of proper cooling is not only to reduce compression temperatures, but also to reduce the final outlet air temperature. Lower outlet temperatures aid downstream drying and reduce the risk of oil carryover.

Air cooling
The most frequently employed compressors are air-cooled high-pressure compressors, which are usually operated between 5°C to 55°C. Simple installation and lower maintenance costs can be achieved with air-cooled high-pressure compressors, since there is no need to incorporate major additional peripheral components such as circulating pumps or a cooling tower.

Compressor-dedicated fan

Air-cooled compressors are equipped with a cooling fan, usually driven by the compressor crankshaft, which generates the necessary cooling-air flow. It is necessary on-site to ensure an adequate supply of cooling air and to allow this cooling air to exhaust freely (see chapter “Heat dissipation”, pp. 33-37). For air-cooled compressors, the ambient temperature has a direct influence on the temperature difference between the compressed air intake and final outlet temperature. With some applications the temperature difference can be ignored, however, if, for example, the high-pressure compressor is followed by a dryer, attention must be paid to the maximum inlet temperature permitted for the dryer to work efficiently.

Water cooling

After air cooling, freshwater cooling is the next most frequently used cooling method. This is necessary within a closed operating environment or when a poorly ventilated installation does not allow reliable operation with an air-cooled compressor. The criterion for use of this system is again the temperature difference between the compressed air intake and outlet temperature. With high ambient temperatures, for example, air cooling cannot always guarantee reliable function of a downstream dryer. When this is the case, it is possible to use compressors with direct water cooling. A prerequisite for this, however, is the availability of a water circulation system.

For poorly ventilated rooms

The following formula can be used to calculate the required quantity of cooling water Q_{cw} [in l/min]:

Calculation of the cooling water flow

$$Q_{cw} = \frac{13 \cdot P_{comp}}{(50 - T_{in})}$$

P_{comp} Installed compressor performance, kW
T_{in} Upstream cooling water temperature, °C

The formula assumes an increase in cooling water temperature of approximately 15°C when it flows through the compressor. The increase in cooling water temperature is directly proportional to the quantity of cooling water flowing.

In connection with the water supply, it is necessary to determine if it involves 'open-' or 'closed-loop' water circulation. In the case of an 'open' water system the quality of the water must be guaranteed and the compressor manufacturer should be provided with an

Open- or closed-loop water circulation

analysis. Differing water contents can impair safe operation of the compressor. An example of damage caused by the water supply can be clogging the cooling system resulting from scale build-up or calcification. When using closed-loop water circulation, the compressor manufacturer should be contacted in advance to ensure the proper design for an air/water or a water/water heat exchanger.

Special cooling with seawater

Seawater cooling is a 'special' method of cooling. With certain applications such as provisioning ships in a 'dry' dock, this type of cooling can be used.

Water cooling from 110 kW

As a general guide, high-pressure compressors should be designed for water cooling if the kW threshold is more than 110 kW. The background behind this is that for larger, more powerful high-pressure compressors, the available cooling surface increases to the power of four, while the heat-retaining mass, i.e. installed material, increases to the cubic power.

What accessories are required?

In addition to the generation of compressed air discussed until now, compressed air storage, compressed air treatment and compressed air distribution also play important roles in the field of high-pressure air compression.

As already mentioned, the storage of compressed air is necessary to make the required compressed air available for the process. Compressed air is stored in standard-size vessels, or where higher pressures are used, in 'standard' horizontal or upright cylinders. What the vessel dimensions should be were mentioned at the beginning of this chapter.

The treatment of compressed air has a special significance in compressed air technology. It

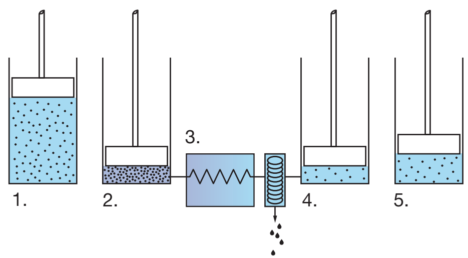
is governed by ISO 8573, wherein the moisture content or measured pressure dew-point, the number and size of solid particles and the amount of oil are specified as criteria. As this book focuses on high-pressure compressors, discussing the basic principles of air treatment would go beyond the scope of this publication.
For high-pressure drying, which falls under the topic of compressed air treatment, four variants exist:

- Drying by means of super-compression
- Drying with cartridges
- Drying using membrane technology
- Drying by means of adsorption dryers

Super-compression and ...

With super-compression air drying, the required air is compressed at a higher pressure level than is necessary for the application. This compressed air is allowed to expand back again to the desired lower operating pressure level (Fig. 14). In this way, the com-

... subsequent expansion



1. Humid intake air
2. Compression with volume reduction and air heating; absolute water content same as at 1.
3. Cooling of air at constant volume and separation of the condensed water
4. Compressed, cooled and moisture-saturated air; absolute water content now less than at 1.
5. Expansion to final pressure at constant water content resulting in a reduction in relative humidity

Fig. 14: Principle of super-compression

pressed air reaches a defined pressure dew-point at the required pressure adequate for some applications. While this approach may eliminate the need for a downstream drying unit, the energy consumption must be evaluated for each specific application.

Use with small air-flow rates

Regarding other drying options, a decision is made based on volume throughput. Cartridges and membranes are normally used for relatively small air flow rates, while adsorption dryers are used for medium to high-volume throughput. Cartridges are typically designed to last for 50 to 100 operating hours, after which the cartridge must be replaced as the desiccant in the cartridge is absorbent. Pressure dew points of –70°C can be reached.

Maintenance-free membrane dryer

Unlike cartridge or adsorption dryers, membrane dryers have no moving parts and are therefore considered maintenance-free. However, no solid particles or oil should ever enter the dryer as this can block the membrane fibres and reduce drying efficiency. Purge air is needed to help the drying process and for this, about 10% of the compressed air flow is used. Membrane dryers can reach pressure dew points of about –55°C.

Two adsorption vessels

Adsorption dryers are primarily used in industry applications. Although investment costs for this kind of dryer are high, life-cycle costs remain quite low by comparison. A typical adsorption dryer has two vessels filled with a desiccant material (Fig. 15). For high-pressure applications this usually involves heatless ‘pressure swing’ operation, which uses part of the dry compressed air coming from one vessel to dry the desiccant in the vessel being regenerated at a lower pressure. This results in 8 to 15% of the compressed air

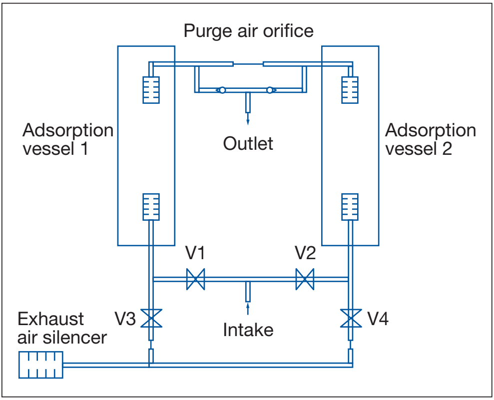


Fig. 15: Functional view of an adsorption dryer

flow being required as regeneration air. Pressure dew points of down to –70°C can be reached with adsorption dryers.

Pressure maintaining valve required

In practice, all dryer types require a pressure maintaining valve. This prevents the dryer from being overloaded with too high a flow volume during the start-up phase of the compressor. The pressure maintaining valve does not open until a correspondingly selected working pressure for the dryer has been reached for optimal drying of the compressed air.

Design for maximum compressor pressure

As a great deal of 'free water' is formed in high-pressure installations and the compressed volume becomes even smaller with increasing compression due to the very high compression of the compressed air, it is beneficial to design the high-pressure dryer to match the maximum final pressure of the compressor. As a result, in a high-pressure dryer lower flow velocities are reached (stationary flow continuity equation) and the period spent in the dryer is increased. This improves the quality of the compressed air. The increased compression pressure has almost no effect on investment costs. The cost differential between a dryer designed for 100 bar and one for 350 bar is marginal. The size of the machine is reduced and the quality of the compressed air is improved.

Important accessories

Compressed air filters and accessories required for condensation management are important elements in the area of compressed air treatment. The same filter types are used for both high-pressure and low-pressure applications. Filter design includes the same considerations which are valid for high-pressure dryers. During the high-pressure compressor selection process, attention must be paid to equipment which captures and disposes of the oil/water mixture often referred to as condensate. Stable emulsions of oil and condensed water which cannot be separated through the effects of gravity always form with high-pressure. Various possibilities exist from simple pressure-free collection to chemical separation. Given the ecological aspects, which are becoming increasingly important, close attention should be given to the composition of the condensate. This topic will be discussed in greater detail in chapter “Condensate removal” (see pp. 37-43).

Efficient compressed air distribution requires specialist know-how and planning to decide the dimensions of piping diameters and airflow velocities.

What energy recovery is to be employed?

Just as with low-pressure applications, energy recovery plays an increasingly important role in high-pressure installations. However, the size and the far fewer operating hours commonly associated with high-pressure engineering restrict the opportunity for energy recovery. High-pressure applications cannot be compared with those in low-pressure applications. For air-cooled compressors as well as for water-cooled compressors, the opportunity for energy recovery is limited to using heat dissipation from the cooling air. What layout is necessary is discussed more fully in chapter “Installation and commissioning” (see p. 34 ff.)

Utilisation of cooling air …

A further possibility for water-cooled compressors to recover energy is the use of the cooling water under application of a plate-type heat exchanger, wherein the dissipated heat from the cooling water can be transferred to the end-user process water system for any use desired.

… or cooling-water waste heat

Installation and commissioning

Proper assembly of an installation contributes substantially to the reliable and efficient operation of a compressor system. Apart from the selection of an appropriate installation site and making sure the necessary operating conditions at the site are met, as well as the connection to a power source complying with local regulations, essential points are in particular heat dissipation by means of adequate ventilation and air extraction in addition to condensate removal.

Installation of the compressor

Ideally, the compressor system should be installed in an operating environment planned especially for it in order to guarantee proper functioning under unchanging conditions. In selecting and equipping the operating area the following criteria should be observed:

Criteria for installation site

- The environment should be as cool, clean, dry and dust-free as possible.
- Room temperature should be targeted between +5 and +45°C and not subject to any major changes (when temperatures are too low condensation can occur).
- Additionally, enough space between compressors or pipelines should be provided to allow heat to radiate or insulation should be provided.
- Direct exposure to sunshine should be avoided.
- The area should be adequately ventilated or additional forced-ventilation installed for an air extraction system.

The space needed for a compressor system is primarily determined by the construction and type of the components used and should always be based on a machine-specific installation drawing prepared in advance. Basically, a certain minimum distance which permits unhindered operation and maintenance of all components should be kept on all sides between the compressor and the walls of the operating area. During assembly and installation, specific legal requirements regarding machine safety and pressure vessels, but also environmental protection, must be strictly observed and conformed to, as well as national and international standards and regulations.

Minimum clearance on all sides

Special mountings or specially designed foundation blocks are no longer typically required for modern high-speed compressors. Today's compressors are mostly isolated from vibration via their own dedicated elastic mounts. A solid, level floor with adequate load-bearing strength (found in the specific data for the compressor) is sufficient in selecting the set-up location.

No special mountings required

If installation under special operating conditions, e.g. extreme heat or cold, mobile applications, etc., is needed, consultation with the manufacturer is recommended. Most compressors can be adapted for special conditions through appropriate modifications.

Heat dissipation

Close to 100% of the total energy supplied to a compressor are converted into heat which has to be reliably dissipated by means of a cooling medium such as air or water in order to maintain operating and ambient temperatures at a permissible level. For air-cooled compressors, it is necessary to ensure that an adequately strong flow of cooling air is provided to reliably dissipate the amount of heat generated. The required flow of cooling air is significantly influenced by the installed motor power and can be calculated, assuming a temperature rise of cooling air of $\Delta T = 15°C$, using the following rule of thumb:

Rule of thumb for required flow of cooling air

$$Q_{ca} = P_{drive} \cdot 250$$

Q_{ca} Cooling air flow, m^3/h
P_{drive} Power input, kW

For a more accurate calculation of the required cooling air flow, the room size and temperature, the allowable increase in temperature and the material from which walls are constructed have to be taken into account in addition to the drive power.
Dependent on the local conditions in the operating area, heat dissipation can be carried out by means of three different forms of ventilation: natural ventilation, forced ventilation using an exhaust air fan or again forced ventilation by means of supply air and exhaust air ducts.

Natural ventilation

Natural ventilation can be used up to a maximum drive performance of about 20 kW and is based on the natural circulation of the air mass at different temperatures. The required air flow therefore takes place automatically through the increase in the supply air which is heated by the compressor (Fig. 16). To ensure effective ventilation, the air supply opening must be placed close to the floor and the exhaust air opening as high as possible. The compressor should be placed as close as possible to the air supply opening so that the cooling air, as well as the fresh air to be compressed, is drawn directly from the air supply

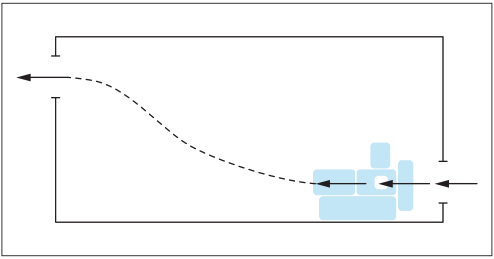


Fig. 16: Principle of natural ventilation

opening. Drawing in or re-circulating exhaust air that has already been heated must be avoided. The air supply opening should also be equipped with an air 'flap' in order to be able to regulate the temperature of the air supplied when external temperatures are below +5°C. The required flow of cooling air, area and height of the space determine the dimensions of the air supply and exhaust air openings. For guidance, the air supply opening should be 20% larger than the exhaust air opening, so that an unhindered stream of cooling air is guaranteed even when there are additional attachments such as controlled air 'flaps' or protective grilles. With a room size of 100 m^3 and a height of 3 m, the air supply opening at a drive power of more than 20 kW would need to be more than 3 m^2, which could lead in many cases to restrictions in construction.

Forced ventilation with exhaust air fan

If the necessary stream of cooling air cannot be achieved through natural ventilation, heat must be dissipated using an additional thermostatically controlled exhaust air fan. This form of ventilation is more likely to be needed when the drive power is over 20 kW, in the case of construction limitations such as small room size or through limitations in the size of the air supply and exhaust air openings. By means of a supplementary air fan at

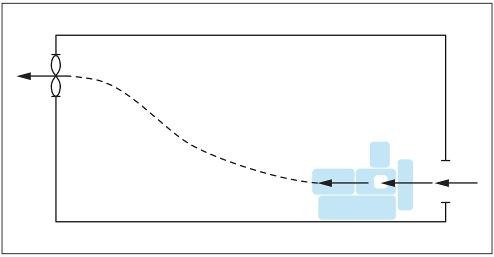


Fig. 17: Principle of forced ventilation with an exhaust air fan

the exhaust air openings (Fig. 17), the flow velocity of the cooling air can be increased and the required flow of cooling air achieved. Forced ventilation can also be appropriate for compressors with a drive performance under 20 kW as, for example, smaller supply and exhaust air opening sizes can be selected and the ambient temperature can be better regulated by a thermostatically controlled exhaust air fan. The dimensions of the air supply and exhaust air openings are dependent upon air fan performance and the desired flow velocity. It must be kept in mind that the flow speed should not exceed 5 m/s.

Forced ventilation via supply or exhaust air ducts

Under certain circumstances such as high ambient temperatures, multiple installations, or very high drive power levels, cooling air feed with the help of supply and exhaust air ducts is recommended (Fig. 18). In this case, the cooling air flow is conveyed directly through

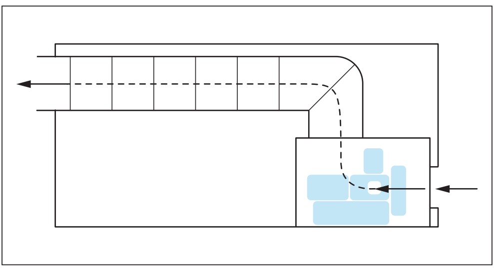


Fig. 18: Principle of forced ventilation with supply and exhaust air ducts

the compressor and then discharged, and is then the most efficient form of ventilation. With this approach, the exhaust air duct conveys the waste heat directly into the open air while an additional thermostatically controlled circulating air flap or louvre can be used for temperature regulation/heating within the operating area. With this variant, particular attention must be paid to the supply air and exhaust air duct cross-sections in order to achieve the lowest possible dynamic pressure. With longer exhaust air ducts, it may be necessary to install an additional exhaust air fan in the exhaust duct. Where several compressors are installed, each should have its own supply air and exhaust air duct. The VDMA-Einheitsblatt (Technical Rule) 4363 “Guideline on the ventilation of operating areas of air-cooled compressors” can be referred to when designing the ventilation of air-cooled compressors.
When water-cooled compressors are used, ventilation of the operating environment involves significantly less effort, as the cooling water conveys away the heat generated in the compressor during the compression process away. It is then only necessary to dissipate the remaining heat from radiation and to conduct away the additional heat generated at the motor with cooling air. On the other hand, the installation costs increase because a freshwater supply line and water cooling circuit is needed.

Condensate removal

Increase in relative humidity

During compression the relative humidity of the aspirated air is increased. The reason for this is a reduction in the volume of the air while the quantity of water remains constant.

When the compressed air is cooled at constant pressure, any water-oil emulsion (condensate) entrained in the compressed air will drop out at a separator fitted after each compression stage. To guarantee trouble-free operation over a long period of time, the condensate must be reliably removed with the help of a ‘condensate separator’. Inadequate condensate removal can lead to substantial damage both to the compressor and to downstream equipment such as adsorption dryers or filters.

Reliable condensate removal required

With a small number of exceptions, high-pressure reciprocating piston compressors are lubricated with mineral or synthetic VDL oils (in compliance with DIN 51506). Because of the oil content, condensate is considered hazardous. The treatment and disposal of condensate is described and regulated whereby the operator’s responsibility is to employ specialist waste disposal. Considering that one litre of oil pollutes approximately one million litres of water, the operator must prevent condensate from entering the environment, in his own and above all in the general interest.

Condensate hazardous to water

The amount of condensate that forms depends on many factors such as air flow rate, final pressure and operating hours of the compressor, as well as humidity, season, outside temperature, weather conditions and geographic location. Table 1 shows how much condensate is formed in the generation of compressed air (final pressure 40 bar and 250 bar) in a period of 24 hours at different ambient temperatures with varying humidity.

Influencing factors

Generally, there are various possibilities for disposing of accumulated condensate. A simple variant is to link the condensate drain pipes of the individual compression stages

Pressure 40 bar			
Ambient temperature in °C	Humidity		
	50 %	70 %	90 %
10	10	15	20
20	20	30	38
30	35	50	70
40	65	95	120
Pressure 250 bar			
Ambient temperature in °C	Humidity		
	50 %	70 %	90 %
10	12	16	21
20	22	32	40
30	40	55	72
40	70	98	125

Table 1: The quantity of condensate resulting from compressed air (in litres) within a period of 24 hours at the final pressure of 40 bar and 250 bar and different ambient temperature and relative humidity

Common drain pipe

to a common discharge for the entire compressor station (Fig. 19). This drain must be sufficiently sized, as the condensate/air mixture discharged is under pressure and directly upon being discharged, the mixture rapidly expands to ambient pressure and increases in volume several times. An incorrectly dimensioned drain can lead to blowback and, in extreme cases, to the condensate pipe bursting.
The common discharge should lead into a central collector for hazardous water which is

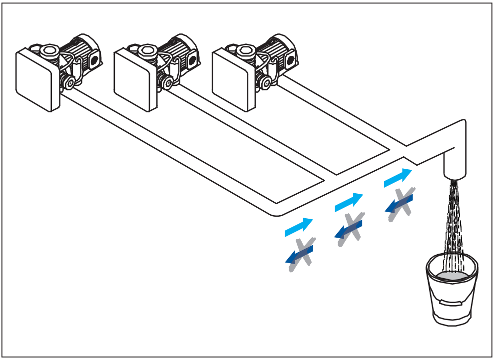


Fig. 19: Connecting condensate drains

emptied at routine intervals by specialists and disposed of in an environmentally responsible manner. If the location of the high-pressure compressor does not permit direct connection to a central collector, the operator can use a local vessel to collect the condensate. For this solution the condensate/air mixture must be delivered free of pressure. To achieve this, there are simple collection separators (Fig. 20) which function according to the vortex principle (cyclone) to allow the liquid removed to drain and the air to vent to atmosphere. The oil and water droplets as well as any solid particles in the condensate are thrown to the outer wall of the separator vessel. From the outer wall, the oil-water mixture and the particles naturally gravitate down and collect in the base. The air that has been separated from the condensate is conveyed upwards to freely vent to atmosphere. It is recommended that a co-

Separation based on vortex principle

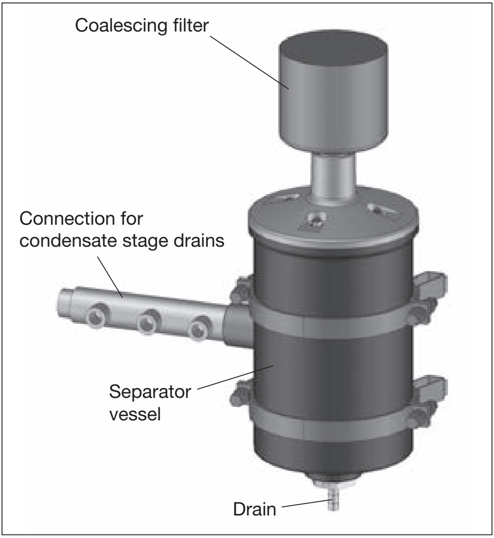


Fig. 20: Collection separator (demister)

alescing filter, which helps to remove any remaining oil from the air, is installed above this collection separator.

Installation options

The collection separator can be mounted directly on the compressor or on a wall at some distance from the compressor. The condensate pipe of the compressor is connected directly to the collection separator. The size of this collection separator must be adjusted to suit the anticipated volume of the expanded condensate/air mixture and not in relation to the compressor final pressure. As a result, the collection vessel is not subject to pressure equipment regulations, as the internal pressure in the container is usually less than 0.5 bar and can only climb above 0.5 bar for a fraction of a second under certain circumstances.

Regular cleaning

After a certain period of time in service and compounded by the use of different lubricants, oil sludge can form in the collection separator and internal cleaning of the separator is essential. Additionally, any coalescing filter should be replaced in accordance with supplier specifications. If this is neglected, the filter can clog and any blockage will impair the collection separator's performance or may cause it to burst.

Condensate discharge

For efficient use, the collection separator should be mounted vertically and also at an elevated position relative to the compressor discharge connection. This ensures that the condensate can drain freely downwards. The discharge of the condensate occurs either through the use of a drain valve or simply through the opening in the floor. Care should be exercised that the drain connections have the same diameter as the inlet connection, as different diameters can affect the efficiency of the separator.

Drain valve improves efficiency

It can be helpful to install a solenoid-operated drain valve at the collection separator base to help improve efficiency. This solenoid valve should be connected in parallel with any solenoid valves mounted in the individual stage separator drains on the compressor. At the moment when the individual compressor separator condensate drain valves are opened, the collection separator valve is closed. In this way the condensate is discharged silently into a closed collection separator, expanded, and after the compressor separator drains are closed again, the collection separator drain is open to drain the condensate collected by gravity.

Operators of high-pressure compressors must understand clearly, however, that the collection separator cannot be used for collecting or storing condensate. The collection separator's exclusive function is to collect condensate created in the individual stages of the multistage compressor and expand it safely to normal atmospheric pressure. For collecting the condensate which runs out under no pressure, a plastic container or metal drum should be placed under the collection separator. This container can then be used to dispose of the accumulated condensate in an environmentally compatible manner.

Condensate collection

Separation of oil and water

The drained condensate can also be separated into oil and water. Whereas in low-pressure applications, separation gravity can be employed, for medium- and high-pressure applications, a chemical breakdown process has to be used since the oil from the compressor forms a stable emulsion. In the case of oil-free or non-lubricated service compressors, condensate which as a rule has a very low pH value (pH 4-6) is also formed.

Commissioning

After installation and connection of the compressor, attention should be paid to the following during commissioning:

Commissioning guidance

- As a first step, the cooling system (either air or water) for the compressor should be started up insofar as cooling is not linked direct to compressor operation, e.g. natural ventilation.
- The temperature of the cooling air should be more than +5°C, if less, then there is a risk that the machine runs without lubrication.
- Before start-up there should be no pressure in the compressor.
- If larger compressors have to be started up against pressure, a reduction in pressure can be achieved by holding 'open' the suction valves to relieve pressure and reduce start-up torque.
- If compressor and drive are connected by a flexible coupling, it is recommended to first start the drive unit (e.g. a diesel motor) on its own and then to slowly engage the compressor coupling.

Operation and control

Safe operation

The legal principles for operating high-pressure compressors cannot be stated in detail here as the regulations in Germany alone are very extensive. They can be found among others in the following texts (with no claim to completeness):

- Occupational Health and Safety Law
- Regulations for Safety and Health at Work
- Accident Prevention Regulations
- Employers' Association Rules/Information

Systems requiring authorisation

Since installed compressors are systems which require official authorisation and must be checked regularly, the operator should first contact the institution responsible, such as TÜV or Dekra in Germany or the corresponding regulatory bodies outside of Germany, to review the local requirements.

Ensuring safety

Common to all regulations is that over and above the safety aspects of construction – the responsibility for which lies with the manufacturer of the pressure device, safe operation of the system by the operator must be guaranteed. To ensure safe construction, manufacturers give the highest priority to preventing excessively high pressure. In addition to the mechanical loading of pressurised parts and the compressor's drive, elevated pressure also leads to elevated temperatures. The simultaneous presence of compressed air under high pressure, high temperature and flammable hydrocarbon (in the form of the lubricating oil) can lead to uncontrolled combustion. In fact, fires caused by compressors have led to serious accidents in the past. For this reason, high-pressure compressors are safeguarded by the following measures:

Safety measures

- Safety valves at every compression stage
- Temperature monitoring of the compressed air (or rather monitoring of the cooling system)
- Oil pressure monitoring to ensure adequate lubrication
- Monitoring the electric motor current

Use of safety valves

The compressor is equipped with safety valves at each compression stage. The safety valve of the final stage protects the compressor from exceeding the maximum pressure for which it has been technically designed, but does not simultaneously serve to safeguard the compressed air system behind the compressor. It is mandatory that as a minimum safety measure the downstream system has its own safety valve.

Temperature …

Temperature monitoring can take place in any compression stage; however, it is advisable to have it in the next-to-last or last stage. If there is insufficient cooling, the compressed air temperature increases sharply so that a temperature sensor or a thermometer with a switching contact can rapidly transmit a signal to the compressor control.

… and oil pressure monitoring

Oil pressure monitoring measures the oil pressure behind the oil pump. A pressure sensor or switch sends a signal to the compressor controller if the oil pressure is too low. If the oil pressure is too high, a certain amount of oil is released into the crankcase via a safety valve.

The current consumption of the drive is directly dependent upon the input power of the compressor. For a given speed and the maximum possible pressure, the current consumption will always be the same on the same compressor. If the current consumption increases sharply, the compressor must be switched off immediately.

Compressed air generation

In compressors, air is compressed from intake pressure to final pressure in multiple stages. With a compressor which intakes air at atmospheric pressure, the intake pressure then relates to the ambient air pressure. If the intake pressure decays, for example, because of a clogged air filter, the compressor can no longer generate the required amount of compressed air. At the same, time the operating temperature of the compressor increases.

Final pressure equals counter-pressure of the system

The final pressure of the compressor, in other words the pressure at the highest compression stage, always equals the counter-pressure of the system into which the compressed air is pumped. For example, if the compressed air chamber is emptied at the beginning of compressor operation, then initially there is only atmospheric pressure at the highest compression stage. As operation continues, the chamber is filled and the pressure rises. Under certain circumstances, the pressure in the highest compression stage is slightly higher than in the downstream compressed air system when additional dynamic pressure is needed to overcome pipeline and valves losses within the compressed air system. This can, however, be kept to a minimum by using pipes, valves, etc. of sufficiently large diameter.

The stage pressures at the lower compression stages are only influenced by the final pressure to a small degree. As every compression stage pumps the air into a smaller compression chamber of the following stage, stage pressures are determined by the geometric

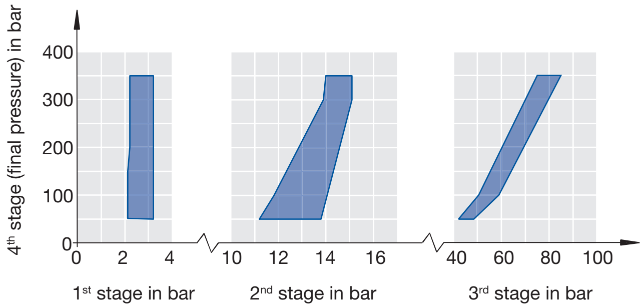


Fig. 21: Stage pressure diagram

cylinder volumes (Fig. 21). For this reason, the input power of a high-pressure compressor – unlike low-pressure compressors – only depends on the final pressure to a limited extent. The lower compression stages have almost constant power requirements; only the input power of the highest compression stage depends on the final pressure.

Insufficient final pressure causes damage

If a multi-stage high-pressure compressor is operated for a longer time at a final pressure that is too low, the highest compression stage also runs, but does so “empty”. However, because the cooling for the compressor is adjusted for the maximum final pressure, permanent under-cooling of the compressor occurs. This can lead to increased condensation in the crankcase, and as a result, to corrosion and accumulation of water in the oil. Furthermore, the oil consumption increases because typical high-pressure final stage pistons without oil scraper rings and thus without sufficient counter-acting pressure literally pump oil out of the stage.

Too low a final pressure for only a short time, however, is of no consequence. When the compressor is taken into service after an overhaul, then in doing so it typically works below its minimum pressure for a time to ‘run-in’. In normal operation, by contrast, the compressor only compensates for pressure losses caused by consumption of air without going below the minimum pressure. The ‘rule of thumb’ for the minimum pressure for a multi-stage compressor is that the final pressure should be at least 15% higher than the stage pressure of the next lower stage. In the case of a four-stage compressor with an average pressure of 90 bar in the 3rd stage, the final pressure in continuous operation should not fall below 105 bar. If operating processes make this impossible, a pressure maintaining valve should be installed at the outlet from the compressor. The compressor then runs ‘internally’ against its minimum pressure set by this valve. The air behind the pressure maintaining valve expands to system pressure. At the time of installation with a pressure maintaining valve, the compressor final pressure safety valve may under some circumstances be set higher than the system’s allowable pressure. This is permissible as the compressed air system must have its own safety mechanism to safeguard against exceeding the allowable pressure.

Minimum pressure 15% below final pressure

Among other things, this principle is used in practice to dry compressed air through “super-compression”. More highly compressed air contains less moisture than air at a lower pressure level. Thus, if air is compressed more than necessary, more moisture in the air is separated out as condensate and after expansion to a lower pressure it is “drier”, i.e. its moisture content is lower. In comparing the efficiency of drying air by super-compression or by using a dryer, the higher energy consumption in the case of super-compression must be weighed against the cost of buy-

Air drying or super-compression

ing and maintaining a dryer. It should also be borne in mind thereby that it is only possible to achieve a relatively low level of air drying by using the super-compression method.

The air becomes warmer in each stage as a result of compression. To avoid exceeding permissible temperatures and to save energy, the compressed air is cooled after each stage. This involves a continuous process, i.e. the air is expelled from a lower stage and flows through a cooler before entry to the next stage. The inter-stage cooling temperatures that can be achieved depend on the coolant, the size of the cooling surfaces and the efficiency of the inter-stage cooler. As a rule, ambient-air-cooled high-pressure compressors achieve about 10°C to 25°C above ambient temperature, while water-cooled compressors, independent of the ambient air, about 10°C to 30°C above the cold water inlet temperature. With this inter-stage cooling process, practically the entire power input of the compressor must be dissipated as heat by the cooler. The proportion of heat remaining in the cylinder and various compressor surfaces is small and amounts to only about 10% to 20%.

Interstage-cooling temperatures

The air drawn in from the surroundings contains humidity. The absolute water content of the air in grams depends on the temperature of the air and its volume. When the volume of the air is reduced while the temperature remains constant, its ability to hold water vapour is also reduced. The water vapour condenses into droplets of water. This physical process described here in greatly simplified form occurs at every compression stage. During compression the volume of the air is reduced and at the same time its temperature rises sharply. In subsequent cooling, the com-

Formation of water droplets

Fig. 22:
Valve spring failures

pressed air is cooled almost to ambient temperature and during this process, condensation forms in the cooler. Any water droplets in the air flow to the next compression stage could have a strong eroding effect, similar to 'sandblasting', on the cylinder head valves. Should that happen, the valve plates show a characteristic pattern of damage referred to as "mouse gnawing" (Fig. 22). Additionally, water droplets have an adverse effect on the lubricating film between the piston and cylinder, and can also cause corrosion.

To prevent the negative effects of water droplets described, condensate is separated after each compression stage. For the first compression stage in which very little or no condensate is formed, compressor manufacturers provide no or only very simple condensate collectors. Most condensate is produced in the next compression stages, in particular the 2nd and 3rd. Here, the preference is for very effective cyclone mechanical separators at the inter-stage coolers exit to remove condensation droplets from the air flow. The working principle of cyclone separators is based on

Use of cyclone separators

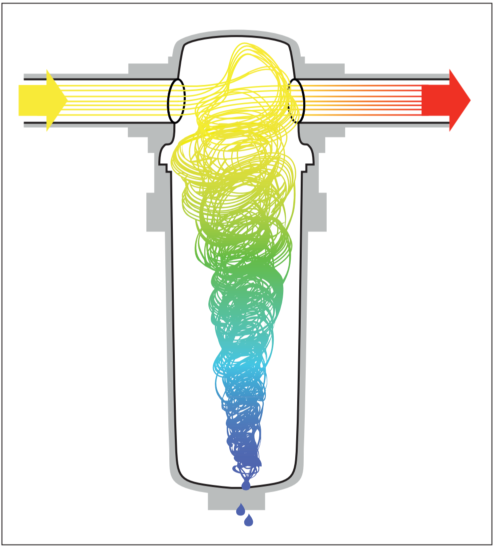


Fig. 23: The operating principle of cyclone separators is to separate condensate droplets by centrifugal force.

Operating principle

centrifugal force (Fig. 23). The air is set into rapid rotation by a swirl vane. This spins the heavy condensate droplets against the wall from where they run down into a reservoir at the base. In the centre of the vortex (hence the term "cyclone"), the air that has been mostly freed of liquid droplets flows out of the separator to the suction side of the next stage.

Periodic condensate drain intervals

The condensate collected in the reservoir of the separator must be drained regularly. This is mostly done using solenoid-operated valves which open at pre-determined intervals. The valves are frequently set to open for 15 seconds every 15 minutes. In individual cases, the required intervals can be significantly shortened (compressor located in the tropics) or lengthened (desert), according to the average moisture content of the intake air, i.e. water vapour content.

The compressed air leaves the compressor saturated. As the air temperature falls in the compressed air downstream pipework, condensation and the formation of liquid water droplets occurs. The air flow itself contains 'free water' in the form of miniscule drops, and as experience has shown, the effectiveness of the separator after the last compression stage is only 60 to 85%, so that all the condensate cannot be removed. These tiny water droplets and the additional condensate formed through the reduction in temperature are removed from the compressed air by means of condensate drains. If further drying of the compressed air is required between compressor and compressed air system, the manufacturer of any compressed air dryer must allow for this at the time of its configuration through the use of appropriate filtration. In addition to the particle filter, a coalescing filter should be installed as a droplet separator, or else the dryer becomes overloaded with too much moisture or 'free water' and is not able to guarantee the necessary drying or dew-point of the compressed air.

Compressed air drying

Monitoring and control

During operation, the high-pressure reciprocating piston compressor must be controlled and monitored just as with other compressor types. The purpose of the controller is to optimise availability and to monitor the important parameters discussed in the previous chapter for safe operation.

Final compression pressure as control variable

It is customary to use the final compression pressure as the control variable in industrial high-pressure applications. For modern compressors, the pressure can be read either by means of sensors (4 to 20 mA) or switches in the system. Sensors or switches may be installed behind a steady flow section on the compressed air vessel or for modern compressors directly behind the non-return valve.

Operating modes

During operation, a high-pressure compressor passes through various operating conditions. A distinction is made between 'standstill', 'idle' and, importantly, 'load' cycle. With high-pressure compressors, a part-load cycle, such as is typical with low-pressure compressors, is uncommon and is not reviewed for the applications described in this book.

At standstill, the compressor is not in operation and consumes no power, but is ready for operation and switches automatically to its load cycle when activated. In an idling cycle or 'unloaded cycle', the compressor is not compressing air but still uses approximately 20% to 25% of its installed power. The compressor stage drain valves usually remain 'open', not in order to compress the air but rather to return it to the suction side. This process is similar to that used to assist a start-

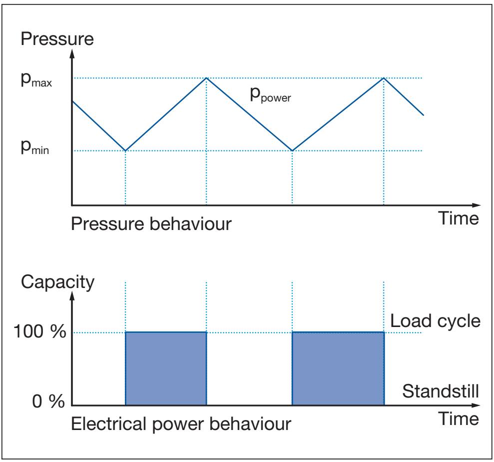


Fig. 24: Intermittent operation

p_{min} Switch-on pressure

p_{max} Switch-off pressure

$p_{network}$ Existing pressure in (system) network

up. When required, the compressor switches immediately into its load cycle to compress air until the switch-off pressure is reached. During the load cycle, the compressor delivers maximum volume flow and consumes the most power.

Intermittent operation

The most commonly used operational duty for high-pressure compressors is the 'intermittent' operation (Fig. 24) which offers the best energy balance. With this duty cycle, the high-pressure compressor switches between 'load' and 'standstill' and uses energy only when on 'load'. The high-pressure compressor starts at a pre-set switch-on pressure and fills the high-pressure system storage vessel until a pre-determined switch-off pressure is reached. After this it goes directly to 'standstill'. When the system pressure falls as the compressed air is being used, the compressor starts again at switch-on pressure. A prerequisite for this operating mode is a switch-on time lasting between 10 and 15 minutes, so that the compressor can reach the required operating temperature and an electric drive motor does not have to start too frequently. Intermittent duty is a discontinuous operation. For continuous operation applications, it is also customary to the extent that the switch-on period does not fall short of the time already mentioned.

Delayed load/ unload cycle

An alternative intermittent cycle is a delayed 'load/unload' (Fig. 25). This can be used with many medium-pressure compressors in 'continuous' operation in the event that the switch-on time falls short of 10 to 15 minutes. With this setting option, the medium-pressure compressor starts at a pre-set switch-on pressure and once the switch-off pressure is reached, the compressor is switched to de-

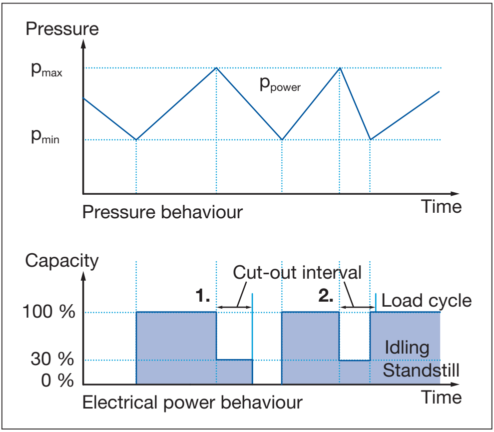


Fig. 25: Delayed load/unload cycle

layed idle or 'unload' for a predetermined time interval. In the event that the switch-on point is not reached within this 'unloaded' time interval, the compressor saves energy and switches off to 'standstill'. If, on the other hand switch-on pressure is reached, the compressor immediately switches to 'load' until the switch-off pressure is reached again. Though the compressor requires about 20% to 25% of its installed power for delayed 'load/unload', this setting can also optimise continuous operation and help reduce wear. The time setting starts either directly when the compressor starts up or when idling commences.

In modern compressors, both intermittent operation and delayed load/unload cycle can be implemented using sensor-regulated controllers. As a rule, controllers with alphanumeric or plain text indicators are used. The controllers support additional functions such as preventive maintenance. These additional functions can be found in the respective operator manuals.

Touch screens are also used for easier and clearer operation of compressor controllers. A disadvantage of touch screens can be the higher cost and the inferior robustness. For this reason, current strategies in the compressed air sector involve making individual compressor controllers simpler while making network controllers or their graphic presentation more complex and flexible.

Network controller

Network controllers can be used when several high-pressure compressors are installed in a high-pressure network. With these controllers, it is possible to link different compressor models and various accessories and to even out operating hours for all networked compressors. This possibility simplifies the planning of maintenance work as this can be carried out at the same time.

Integration in a combined pressure band

An additional controller strategy involves linking high-pressure compressors to a combined pressure band (Fig. 26). The interacting compressors are then controlled via a pressure sensor within a common switch-on and switch-off point. The compressors are switched on and off according to priorities or other requirements. Exchange of data be-

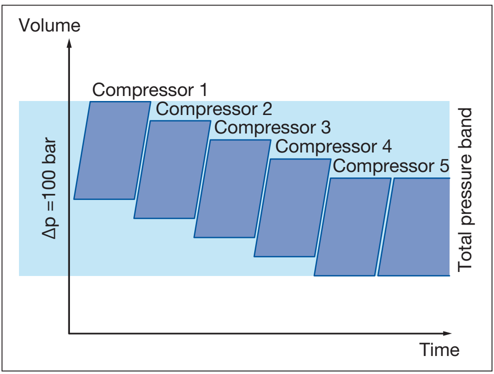


Fig. 26: Combined pressure band

tween the compressors linked in a row frequently takes place through a modern bus system such as an RS485 bus. In addition, the network controller checks the gradient that develops from rises or falls in pressure per unit of time. On the basis of the magnitude of this gradient, it decides which compressors are switched on or off. At the same time, the network controller optimises energy consumption because different compressors having different volume flows can be put to work. In this way, compressors with large volume flows can be used to guarantee the basic load and compressors with smaller volumes utilised during peak load phases only. The use of network controllers in larger compressor installations offers numerous possibilities for optimal utilisation and optimal monitoring for individual compressors in a high-pressure network.

Exchange via databus

Requirements-based setting

An additional control option for high-pressure compressors is cascade control (Fig. 27). With this method of control, compressors are operated within their individual pressure bands with their respective switch-on and switch-off points.

Cascade control

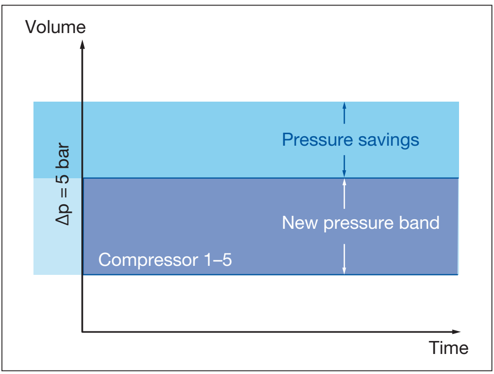


Fig. 27: Cascade control

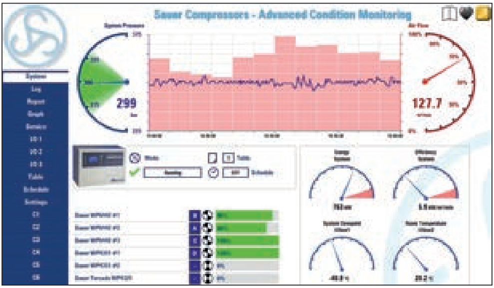


Fig. 28: Visualisation with Web browsers

A systematic extension of optimal control and monitoring is the transfer of data from the network controller described above to a local computer located in a central monitoring station. To do this, data from the network controller is either transferred from the RS485 bus to an RS232 interface or – adopting a more modern approach – by means of the company's LAN network. This enables their display in a normal Internet browser and opens up the possibility of accessing the data anywhere in the world via this browser (Fig. 28). This makes it possible to employ optimal maintenance strategies and to significantly improve preventive maintenance as the availability of the compressor/compressors is maximised. Additionally, users are placed in a position to monitor compressor operations through remote monitoring and to then operate high-pressure stations more efficiently.

Data access via Internet

However, it should be borne in mind that not all possible high-pressure network functions are sensible. Which controls and which form of regulation are the most appropriate for a particular compressor installation should be clarified with the manufacturer.

Maintenance and fault diagnosis

During operation, reciprocating piston compressors, like all machines, will suffer a degree of wear. Measures have to be adopted against this in order to ensure the safe operation and availability of the compressor. In contrast to emergency repairs, regular maintenance is a normal and necessary procedure. The goal is to replace worn parts in such a timely manner before any unexpected major repair work becomes necessary.

Maintenance effects

Through carefully planned maintenance carried out according to manufacturer's instructions, a situation can be reached where:

- operational availability of the compressor is increased
- operating life of the compressor is extended
- performance and electricity consumption remain constant
- unplanned downtimes are minimised
- risks to operating personnel and equipment are reduced
- unwanted costs for replacement, exchange and commissioning, and unnecessary operator training is avoided.

The maintenance of high-pressure compressors is of particular significance because of the enormous energy density of the compressed air. The potential energy in a 50-kW high-pressure compressor at 350 bar corresponds to about the kinetic energy of a 100-t locomotive travelling at a speed of 50 km/h.

Genuine spare parts

To limit the risk of injury and machine damage, a critical requirement is to obtain genuine spare parts from the original manufacturer and not to use lower-cost, unproven parts from other sources. It is just as important that only authorised personnel carry out work on high-pressure compressors. Incorrect procedures such as working on parts that are under pressure or work carried out improperly can have dangerous consequences.

Maintenance fundamentals

The significant factors that influence wear are:

- Temperature
- Lubrication
- Start and stop intervals
- Working pressure

The components subject to the most impact in a high-pressure compressor are the compression valves. For each revolution of the crankshaft, the intake and discharge valves must each complete one full load cycle, and this can result in up to 30 changes in load per second for a modern high-speed compressor.

High-load valves and bearings

Valve failure (Fig. 29) not only leads to the compressor no longer functioning properly, but sharp-edged broken pieces of a valve plate can fall into the compression chamber and cause further damage. Other highly loaded parts include both crankshafts and piston-pin bearings, the latter being mostly needle-roller bearings because of space limitations. Lubrication for all bearing types is essential. A bearing that is worn or damaged by inadequate lubrication leads to piston wear and the risk of catastrophic failure of the entire compressor.
The correct choice of lubricating oil is important. The lubricant for the compressor

Fig. 29: Carbon build-up on a valve from oil residue and overheating

not only prevents surfaces from rubbing against each other but also and importantly removes heat, washes away particulate and helps prevent possible corrosion. Oil life will be reduced with high temperatures and is also affected by any particles in the air that are highly reactive under pressure. Regular lubricating oil changes are essential and the operator must ensure that only lubricating oils approved by the manufacturer are used.

Regular lubricating oil changes

Any maintenance work required is usually detailed in the manufacturer's maintenance and repair handbook for the individual compressor model. Included within each handbook are typical maintenance schedules which specify the parts needed and necessary maintenance steps dependent upon the operating hours (Fig. 30). In everyday practice, maintenance service intervals are determined from the manufacturer's experience.

Maintenance schedules

In general, lower operating pressures and temperature levels together with regular lubricating oil changes with a premium-quality compressor oil and fewer start/stop cycles

Maintenance plan no.:	
Maintenance schedule beginning:	
☐ After commissioning ☐ After last maintenance	
Date:	
Operating hours:	

Compressor type:	WP45L
Type series	Mistral
Compressor number:	
Factory no.:	
Year of construction:	
Date of commissioning:	

Interval (operating hours) **Maintenance work**	50 h after commissioning	50 h after last maintenance or repair	At least annually if < 1000 h	1 000 h	2 000 h	3 000 h	4 000 h
Maintenance kit part number				069 146	069 147	069 146	069 148
Check screw connections, *see 8.5*	☐	☐					
Change air filter insert, *see 8.6*			☐	☐	☐	☐	☐
Change oil, *see 8.7*	☐	☐	☐	☐	☐	☐	☐
Check 1st stage valve, *see 8.8.*				☐		☐	
Check 2nd stage valve, *see 8.8.*				☐		☐	
Replace 1st stage valve, *see 8.9.*					☐		☐
Replace 2nd stage valve, *see 8.9.*					☐		☐
Replace piston rings, gudgeon pins and 1st stage small-end bearings, *see 8.10*							☐
Replace piston rings, gudgeon pins and 2nd stage small-end bearings, *see 8.10*							☐
Replace coupling flexible insert, *see 8.11*							☐
Check condensate separators, *see 8.12*							☐
Overhaul drain valves (order-related), *see 8.13*							☐
Verify safety valves, *see 8.14*	(according to the owner's instructions)						

Operating hours							
Date							
Signature (initials)							

Fig. 30: Maintenance schedule

reduce wear in a compressor. A compressor which is "oversized" does not necessarily mean "greater safety". Oversizing can result in an increased frequency of the number of starts and stops, and in the final analysis increase wear.

Maintenance dependent on operation and preventive maintenance

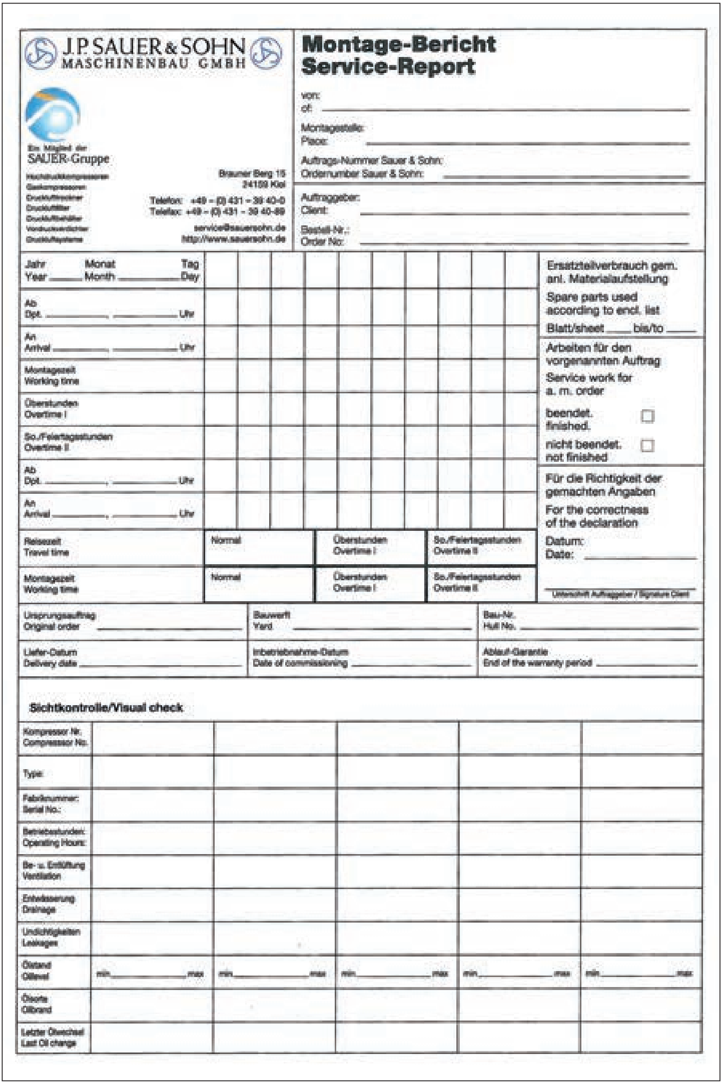
Compressors are critical consumers in plant operations. In a functioning business or process, work processes cannot be maintained without a trouble-free compressor. In practice, there are three basic approaches for servicing and maintaining a compressor:

- No maintenance but repair work only when damage occurs
- Condition-based maintenance
- Preventive planned maintenance

It is self-evident that the first variant is not a viable option. What operator would be prepared to accept unpredictable machine shutdown and the operational consequences?

Goal: reducing maintenance costs

The concept behind condition-based maintenance is to reduce maintenance work by extending maintenance intervals to the maximum possible. Parts are only replaced just before they fail. For this strategy, it is necessary to continuously record the operating data and determine any component wear from its deviation over time. For this purpose, pressure and temperature levels are measured in the machine. Vibrations on the other hand can only be used to a very limited extent for evaluating the operating condition because of the irregular vibration behaviour of reciprocating piston compressors. Temperatures and pressures can be measured for the air, lubricating oil and, if required, cooling water. The best predictor of the condition of a compressor can be obtained by reading stage pressures, because pressure indicators respond far faster to changes in operating



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Montage-Bericht
Service-Report

von: / of:

Montagestelle: / Place:

Auftrags-Nummer Sauer & Sohn: / Ordernumber Sauer & Sohn:

Auftraggeber: / Client:

Bestell-Nr.: / Order No:

Jahr / Year ____ Monat / Month ____ Tag / Day

Ab / Dpt. ____ , ____ Uhr

An / Arrival ____ , ____ Uhr

Montagezeit / Working time

Überstunden / Overtime I

So./Feiertagsstunden / Overtime II

Ab / Dpt. ____ , ____ Uhr

An / Arrival ____ , ____ Uhr

Reisezeit / Travel time	Normal	Überstunden / Overtime I	So./Feiertagsstunden / Overtime II
Montagezeit / Working time	Normal	Überstunden / Overtime I	So./Feiertagsstunden / Overtime II

Ersatzteilverbrauch gem. anl. Materialaufstellung
Spare parts used according to encl. list
Blatt/sheet ____ bis/to ____

Arbeiten für den vorgenannten Auftrag
Service work for a. m. order
beendet. / finished. ☐
nicht beendet. / not finished ☐

Für die Richtigkeit der gemachten Angaben
For the correctness of the declaration
Datum: / Date:
Unterschrift Auftraggeber / Signature Client

Ursprungsauftrag / Original order	Bauwerft / Yard	Bau-Nr. / Hull No.
Liefer-Datum / Delivery date	Inbetriebnahme-Datum / Date of commissioning	Ablauf-Garantie / End of the warranty period

Sichtkontrolle/Visual check

Kompressor Nr. / Compressor No.					
Type:					
Fabriknummer: / Serial No.:					
Betriebsstunden: / Operating Hours:					
Be- u. Entlüftung / Ventilation					
Entwässerung / Drainage					
Undichtigkeiten / Leakages					
Ölstand / Oillevel	min ____ max	min ____ max	min ____ max	min ____ max	min ____ max
Ölsorte / Oilbrand					
Letzter Ölwechsel / Last Oil change					

Fig. 31:
Maintenance logbook

condition than do temperatures, which take time to respond to the inertia of the compressor's thermal mass.

Data control using maintenance log

The simplest – although perhaps least reliable – method is for the operator to maintain a regular record of essential compressor data by means of a maintenance logbook (Fig. 31). Performance trending then has to be extrapolated from these entries over a certain period of time. For this, a substantial degree of specialist knowledge and experience is required. It is also possible to divide values digitally into "good" or "not good (any more)"; in this case, using switches or sensors, the compressor controller is sent a threshold value which, when reached, is linked to the need for maintenance. This system is admittedly simple, but is also inflexible as it does not allow any extrapolation of operating data into the future. More important for the decision to carry out a maintenance procedure is always a change in a value over time and not just a value at a particular moment.

Monitoring with sensors

A more exact estimate of the machine's condition and prediction for the next maintenance date are only possible through permanent monitoring by means of analogue sensors and their evaluation in a microprocessor controller. For this, the compressor must be equipped with a number of feedback devices and a controller which should include the possibility for remote monitoring. Because this equipment requires comparatively high investment costs, it is only feasible for very high-grade installations. Even in such cases, careful consideration must be given to each case as to whether the potential savings in reduced maintenance costs are worth the additional costs for monitoring.

Difficult interpretation of measured values

Basically, the necessary interpretation of the measured values is made more difficult by intermittent operation typically encountered with reciprocating piston compressors. The compressor is started under low pressure and fills a compressed air reservoir. On reaching the set final pressure it is switched off. This intermittent operation results in the measurements of pressure and temperature constantly changing. As a general rule, therefore, only values deviating sharply from normal operations are recognised.

Component-specific maintenance intervals

In practice, preventive planned maintenance has proven itself. It is based on the experience of the increasing frequency of failure of components as a function of the total hours of operation. Thus, an economically sensible maintenance interval can be specified with a high level of accuracy for every component. As shutdown periods and production losses are always linked with any maintenance, the work required should be distributed over the fewest possible maintenance blocks. Modern maintenance concepts take this into account and as a result deliver, among other things, the following benefits to the operator:

Advantages

- Predictable shutdown times
- Reduced expenditure of effort for procurement, storage and operating personnel
- Predictable, constant and therefore manageable fixed costs in the budget
- Parts for a unit to be serviced that are obtainable as a package and can be ordered by part number (Fig. 32)
- Guaranteed quality of original parts

In the past, it was still common to inspect parts requiring servicing and – if possible – to overhaul them. For example, valve seats

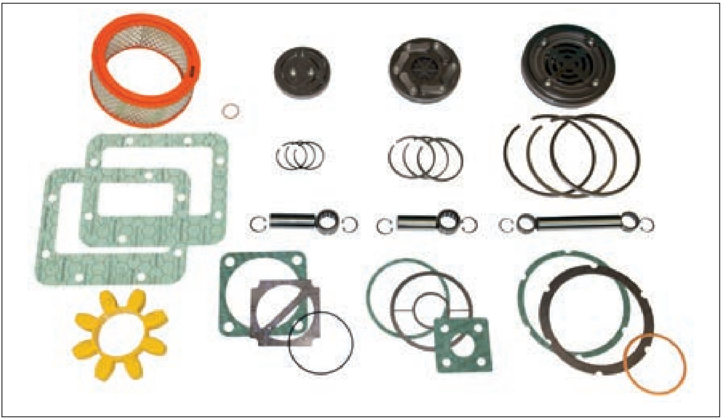

Fig. 32: Maintenance package

and guards were re-ground and then used again. These days, this is no longer an accepted practice. A high level of specialist knowledge is required to assess what needs to be done and performed properly; otherwise there is a real risk of reduced efficiency through leakage or parts failing prematurely. As a rule, this leads to even more expensive repairs which turn the initial savings effect into the opposite through the high costs incurred.

Fault diagnosis

Fault diagnosis can be carried out for a compressor based on an assessment of the following parameters:

- Stage pressure and final pressure
- Stage temperatures and final temperatures
- Oil pressure
- Current consumption of the drive motor (if driven by an electric motor)
- Vibrations
- Operating noise

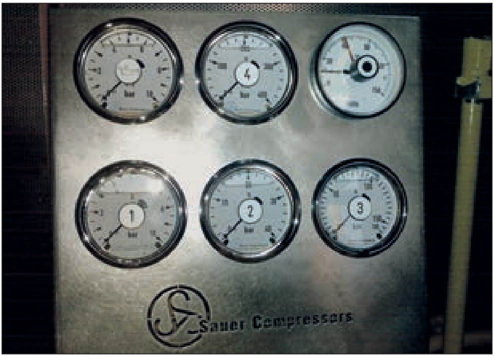

Fig. 33: Compressor monitoring via pressure gauge panel

- Oil sample
- Compressed air quality

As already explained above, absolute values do not tell you very much. Only changes in values over time permit statements about the quality of the compressor. For this reason, multi-stage high-pressure compressors usually have pressure gauge panels displaying the most important values at a central location (Fig. 33).

Leakage indicator

In the case of multi-stage high-pressure compressors, pressures in the individual compression stages are the easiest operating data to monitor and at the same time the most informative. Since the stage pressures are determined by the geometry of the compressor and only depend to a small degree on the final pressure of the machine, major changes in stage pressures indicate leaks within the compressor. In such cases it is frequently a matter of leaks in the valve seals or the valves themselves. These internal leaks can lead to the activation of protective safety valves.

Keeping a log of temperatures can provide information on the condition of the cooling system; for example, coolers can become contaminated and thus lose efficiency. However, rapid rises in temperature for a brief period are seen only when there are significant cooling problems.

Cooling problem indicator

Oil pressure rises with the viscosity of the oil and the final pressure of the compressor, and is then somewhat higher at low temperatures and with new oil. When the compressor runs without pressure, the oil pressure often falls slightly as the piston bearings have more play.

Observing oil level

When the oil level is too low, the oil pump can no longer take in the proper amount of oil, and the oil pressure falls sharply.

Signs of increased friction

If the current consumption of the electric motor climbs sharply, this is a sign that there is increased friction among the moving parts of the compressor. The cause is most likely a seizure, or partial seizure, between the piston and the cylinder or liner; it rarely involves damage to bearings. When there is a significant increase in current, the compressor is often just about to fail catastrophically.

Indication of bearing stress

A significant change in compressor vibrations with otherwise unaltered operating conditions such as pressure and number of revolutions indicates tension of the resilient mounts and in the worst case serious problems with the drive. Changes in normal operating noise are often caused by external air leaks. Escaping compressed air expands noisily and the sound this causes affects the operating noise.

Indication of compressor and condensate quantity

An oil sample can provide information on wear of the compressor and the formation of condensate (Fig. 34). The oil in a sample should be clear and should not contain any large particles. Milky discolouration comes from condensate in the lubricating oil; in this case, the function of the drainage system and the ventilation for the compressor should be

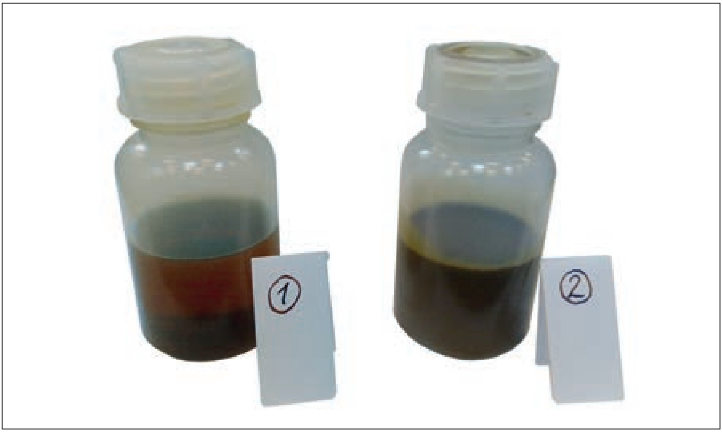

Fig. 34:
Oil samples
1 Oil after minimal use
2 'Old' compressor oil; the milky clouding comes from condensate

checked. If the moisture content of the intake air is very high, it is possible that the drainage intervals have to be more frequent; in addition, the compressor must not be cooled when at a standstill with the help of air or water flow. A chemical analysis of the metals contained in used lubricating oil is also possible, but must be interpreted. Elements detected in oil and where they come from include, for example:

- Silicon: sand from the surroundings (air filter!), occasionally casting residue
- Iron: wear from piston rings and cylinder liners
- Copper, tin, lead: friction bearings
- Aluminium: piston(s) of the low-pressure stage(s)

Threshold values for the quantity of metal particulates in oil are difficult to specify. Here, as with servicing based on operation, an analysis of trends is more informative.

Measurement of the air quality is the least informative for assessing the condition of the compressor. Very high levels of particulate and oil in the compressed air can indicate poor intake filtration, worn piston rings or again poor lubricating oil. High water content can be caused by inadequate removal of condensate. Critical values here are not specified by the compressor manufacturer but in terms of the particular compressed air application. Measurement and specification of threshold values are carried out according to ISO 8573 or ISO 12021.

Switch-off in case of danger

Under potentially dangerous operating conditions, the compressor control and monitoring system should in every case shut down the compressor to prevent damage to the machine or personal injury. Dangerous operating conditions include:

- Excess temperature
- Insufficient oil pressure or low oil level
- Electric motor overcurrent

The information in this chapter for diagnosing faults is not meant to be exhaustive. In every operating and maintenance handbook for compressors, there is a table to help diagnose faults which is aimed at that particular compressor.

Maintaining an operating data log

In cases of doubt, the manufacturer should be consulted. To assist faster and more decisive remote diagnosis, it is wise to provide the manufacturer's service department with not only the compressor serial number, but also the operating data for the compressor such as pressures, operating times, oil type and maintenance that has been carried out. An operating data log should be kept by every operator. Templates for this can be obtained from the compressor manufacturer.

Applications

Most industry sectors and processes would be unthinkable today without compressed air. Its application as a working medium and energy carrier in industrial applications is both varied and extensive. The applications described in this chapter are limited to medium-pressure and high-pressure compressors, i.e. to applications where pressures of 30 bar or more are used.
In general it can be said that the greater the pressure of air, the less space and the more energy is needed to store a given amount of air. Two basic approaches arise from this which justifies the use of medium- and high-pressure compressors rather than low-pressure compressors.

Requirements

- A large amount of air must be made available in a very short time. In doing this, however, it is perfectly normal that the actual process may only require low pressure. As a rule, this application is not continuous.
- The application really does need the energy which is stored in the compressed air. Use of the air in this application tends to be continuous.

Power generation

In hydroelectric power plants (Fig. 35), the kinetic energy of the water is converted into electrical energy by means of turbines and connected generators. Depending on the various levels of output, the following text reviews low-, medium- and high-pressure power plants and, based on how the water is used, they are referred to as “hydropower” and “storage

Fig. 35: Hydroelectric power plant

power" plants, which include pumped-storage hydroelectric power plants.

Supplying compressed air

The turbine blades and large valves of hydroelectric power plants are usually operated by a hydraulic system. To maintain the pressure in these hydraulic systems, a chamber (air chamber) is filled to two-thirds with oil and one-third with compressed air. Since oil and air are consumed at every turn of the turbine blades, the air chamber must constantly be refilled. The pressure required is usually in the region of 30 to 80 bar, while the amount of air required depends on the number and capacity of the turbines in use and ranges from 10 to 300 m³/h per turbine.

An additional application is with pumped-storage hydroelectric power plants which, because of the high demand for high-performance energy storage, are experiencing a renaissance. With such power plants, a large column of water from the storage reservoir or storage cavern rests on the turbines. However,

Fig. 36: Typical high-pressure compressor for pumped-storage hydroelectric power plants

these have to be started up in a ‘load-free’ condition, i.e. the water column must be blown out of the turbines to enable a start. To achieve this, a very large supply of compressed air at between 30 and 80 bar is required, and this is generated by high-pressure compressors (Fig. 36). The required pressure is determined by, among other things, the height and the inflow differential.

Energy distribution

A substation (Fig. 37) is part of the electric power supply grid network of every country. Operated by energy supply companies, these substations function as the interface between differing voltage levels within the supply network. The optimal voltage level is selected according to the power to be transmitted and the distance it is to be transmitted. Sub-

Fig. 37: Substation

stations are divided into supra-regional and regional transmission networks (mostly open-air plants), as well as into local and area distribution networks (mostly enclosed plants). Transformer stations are the last link in the chain for supplying the final customer with low-voltage power.

Expelling compressed air impulses

When in such substations using open-air switching, the individual networks are separated from each other, the "leftover current" looks for its "old" contact and as it cannot find this, the current flows freely in the atmosphere. This "free dancing" current causes a spark to jump, which subjects isolators and contacts to extreme wear. To help prevent this from occurring a compressed air impulse, or blast of air, is used. This compressed air impulse requires only low or medium pressure but in an appropriately large quantity, as the impulses are often needed in different places at the same time. Usually, compressed air between 70 and 350 bar is used for this. The advantages of super-compression are employed in this application to achieve a pressure dew point of about –10°C. The pressure dew point value is necessary because of the long cross-country transmission lines and is intended to avoid a failure due to moisture.

Use of super-compression

Processing industry

Any gas process that is operated under pressure has to be pressure-tested well above its maximum working pressure and, if necessary, the sealing, too, has to be proven with highly volatile gases. Pressure tests (Fig. 38) historically have been carried out with water, nowadays however, the preference is to use optimised air or nitrogen. The advantages in comparison with water testing are fewer process steps with reduced testing time. For example, there is no cleaning or drying necessary as is the case when testing with water.

Fig. 38: Valve pressure test

Fig. 39: Composite materials

Pressure tests

Pressure tests with air or gases are now conducted across all industries. Within the automobile industry for example, brake systems, airbags and the high-pressure fuel injection systems of modern motors are tested. In addition, coolant circulation in nuclear power plants or gas cylinders, fire extinguishers or even compressed-air cylinders are tested. In the same way, pressure tests are carried out to prove safety valves. The pressure bands range from 20 to 500 bar with volume flows from 50 to 2000 m³/h.

Applications in manufacturing materials

The manufacture of composite materials both in the plastics industry and wood materials industries is also a part of the process industry (Fig. 39). In both areas, various materials are pressed together under pressure with heat to produce materials with special characteristics. In the synthetics field, special gas-tight sealable pressure chambers, so-called autoclaves, are used. High-pressure compressors are used efficiently here to ensure the necessary pressure for the manufacturing process.

The pressures required lie between 40 and 150 bar and the required volume flows are from 200 to 600 m^3/h.

Research and development

Universities, state and private research institutes need high-pressure compressors for a number of applications such as supersonic tests in wind tunnels, motor vehicle crash tests or nano-coating. For these applications, among other things, the provision of very high air volumes in a short time is required.

More especially for wind tunnel testing at supersonic and hypersonic speeds (from Mach 5), a great deal of very 'dry' air must be stored. The final compressed air is then rapidly expanded until the required speed is reached. The very high speeds achieved allow flow-related project testing to be completed with scaled models, for example, for aircraft wing profiles.

Expansion of compressed air

There are also new applications in the field of nano-coating. Here, tiny particles are shot against prepared basic surfaces at high speed. The required speed is also reached here through the rapid expansion of compressed air. For this application, work is carried out with pressures between 100 and 300 bar and air volume flow rates of 500 to 2000 m^3/h.

Metallurgy

A fertile field of application for medium- and high-pressure compressors is metallurgy, which encompasses all procedures for obtaining and using metals, metalloids and nonmetals.

For a long time, steel was the pillar of heavy industry alongside coal, and is still the world's most important metallic material. Both in the manufacture of steel (changes to the carbon content in a blast furnace) and in the milling and treatment of strands, the application of medium- and high-pressure compressors to generate compressed air and gases is indispensable (Fig. 40).

Application for surface scale removal

High-pressure compressors are usually used to assist descalers. These involve jets which separate the scale from the cooling steel strips using a water jet at a specified angle. To generate the required pressure, water pumps or high-pressure compressors are used. A high-pressure buffer is connected to the water reservoir to balance the pressure loss during scale removal quickly and flexibly. The pressures required are between 250 and 350 bar with volume flows required between 50 and 200 m³/h.

Fig. 40: Steel plant

Miscellaneous applications

Further applications of high-pressure compressors include ‘pigging’ in the oil and gas pipeline sector. Large pipelines are tested for leaks with water. To remove this water from a pipe, inspection gauges referred to as “pigs” are slid into the pipe opening under pressure.

High pressure is also used with modern air force jets. For example, compressed air is needed to eject the cockpit cover in an emergency or to control and manage weapons’ systems. Because space is limited in such jets, the air that is required must be stored in a confined area under high pressure.

The future of high-pressure compressors

It is recognized that today's reciprocating piston compressors are far more advanced and efficient than their predecessors. Even over the past 20 years, compressor makers have significantly improved reliability, reduced maintenance and made efficiency improvements with more changes to come. While the fundamental operating principle of reciprocating piston compressors has not changed for 100 years, progressive development has meant the piston still offers the best choice in the foreseeable future for high-pressure engineered products.

To remain competitive, however, it is necessary not only to continue improving the performance with high-pressure compressors but also to develop more individual and more economical concepts. Future possibilities exist, for example, with drive technology and new materials. Through the use of modern linear drives and a combination of different compression methods, significantly more energy-efficient compressor designs could be realised. A compressor with linear drive can, for example, be modulated more easily simply by varying the compressor stroke with a variable power device, and prove to be less expensive than the variable-frequency drives needed until now. If traditional reciprocating piston compressors were combined with other compression concepts such as screw-type and diaphragm compressors, additional efficiency gains may be achieved in certain pressure bands through the optimal use of these differing compressor concepts.

Energy-efficient concepts

Use of new materials

The use of novel materials with an ability to assimilate different functions would improve reliability and safety as well as efficiency. Intelligent materials such as those already in use in both the automobile industry and in medical technology can react to changing environmental conditions such as pressure, temperature, humidity, pH-levels or voltage without having to be actively controlled. Their integration into new machine designs offers numerous opportunities for making compressors even more powerful.

Thermo-responsive materials such as shape-memory alloys or polymers are materials which change their shape with a change in temperature. This would make new light-weight piston designs which display less thermal distortion conceivable. Such materials open up completely new possibilities for piston motion, power transfer and, above all, extended speed ranges. The drive for improvement in efficiency and cost reduction for compressors is a must, and the way forward with high-pressure technology places increasing demands on engineers regarding the use of materials and fewer parts. In summary, this drive for improvement is to reduce the conflicting goals within the high-pressure field between compressor design and construction which, because of the combination of high pressures, high temperatures, higher running speeds and smaller dimensions, cannot be avoided and place high demands on both materials used and the quality of manufacture.

The company behind this book

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Sauer Compressors

Sauer Compressors is a mid-sized German company group with headquarters in Kiel. Now being managed in its third generation by the Murmann family, Sauer Compressors can look back on a more than 125-years-old history and more than 80 years of experience in compressed air technology.

The focus today is on the development, assembly and sale of medium- and high-pressure compressors for use in the marine, shipping, offshore and industrial sectors. Modern reciprocating piston compressors for compressing air as well as neutral and inert gases reach pressures of 20 bar to 500 bar. For every field of application, individual solutions are offered for individual customers, OEMs and internationally operating companies. With a worldwide network of representatives and retailers, Sauer is always in close touch with its customers.

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