Chapter 2 Compressors and auxiliary equipment

2.1 Displacement compressors

2.1.1 Displacement compressors in general

A displacement compressor is characterised by enclosing a volume of gas or air and then increasing the pressure by reducing the area of the enclosed volume.

2.1.2 Piston compressors

The piston compressor is the oldest and most common of all compressors. It is available as single or double acting, oil lubricated or oil–free with a different number of cylinders in different configurations. With the exception of really small compressors with vertical cylinders, the V configuration is the most common for small compressors.

On double acting, large compressors the L-type with vertical low pressure cylinder and horizontal high pressure cylinder, offers immense benefits and is why this is the most common design.

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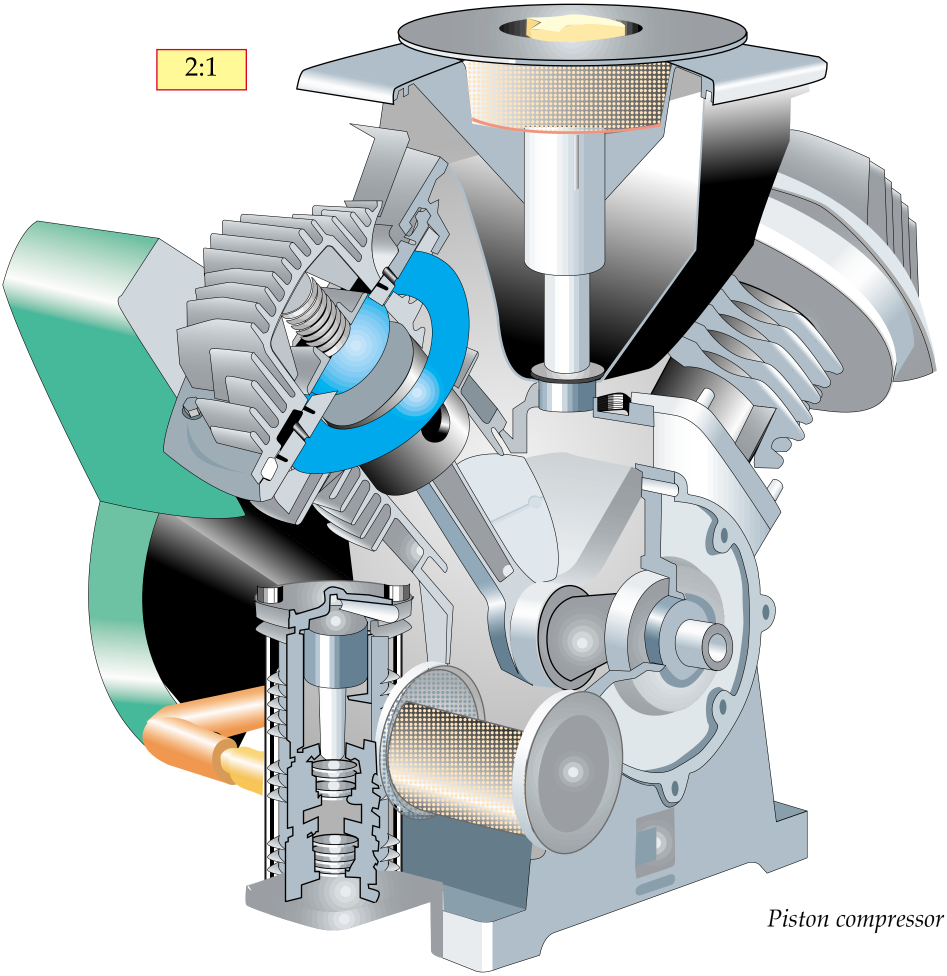

Piston compressor

Oil lubricated compressors normally work with splash lubrication or pressure lubrication. Most compressors have self-acting valves. A self-acting valve opens and closes through pressure differences on respective sides of the valve disk.

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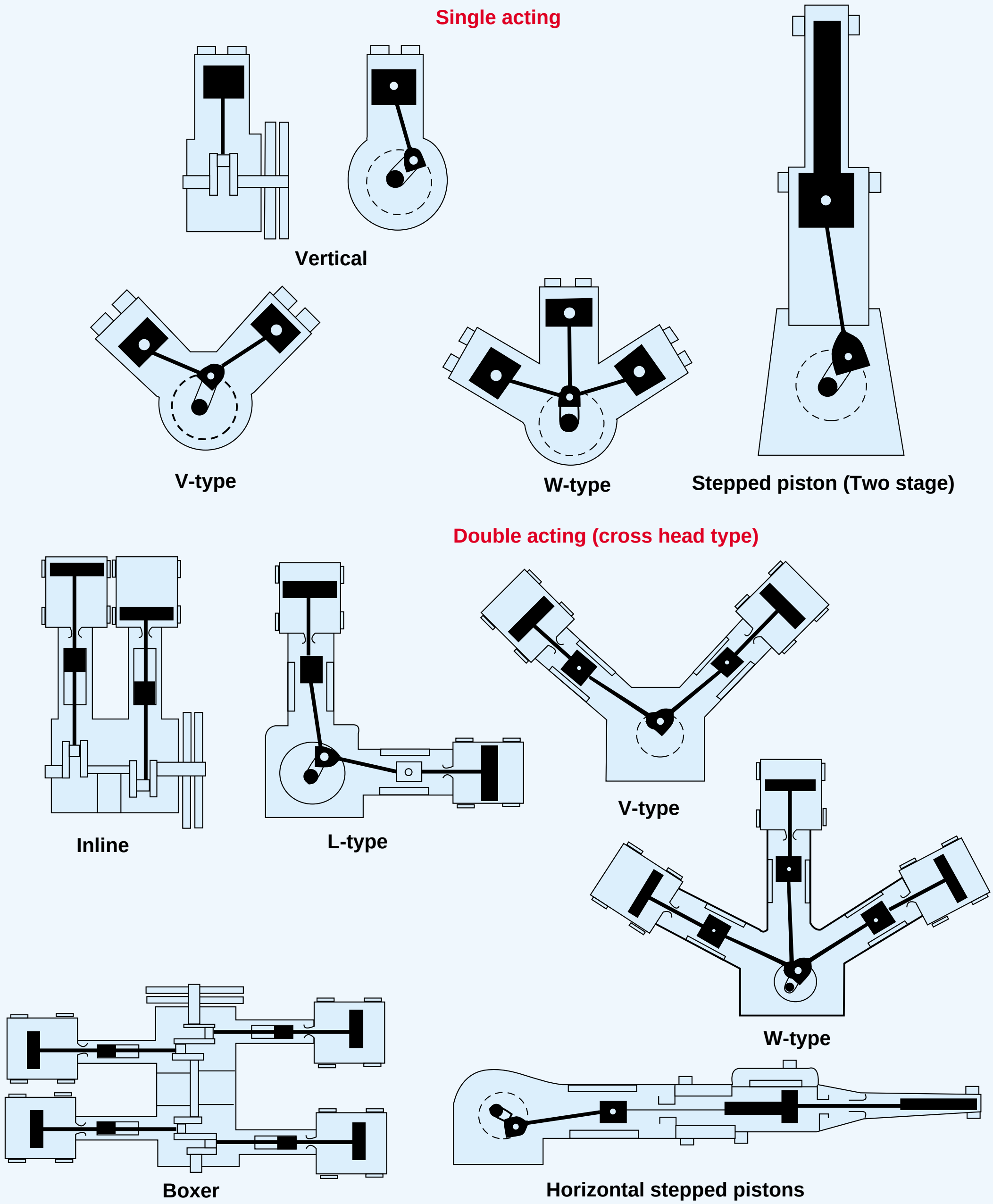

Examples of cylinder placement on piston compressors.

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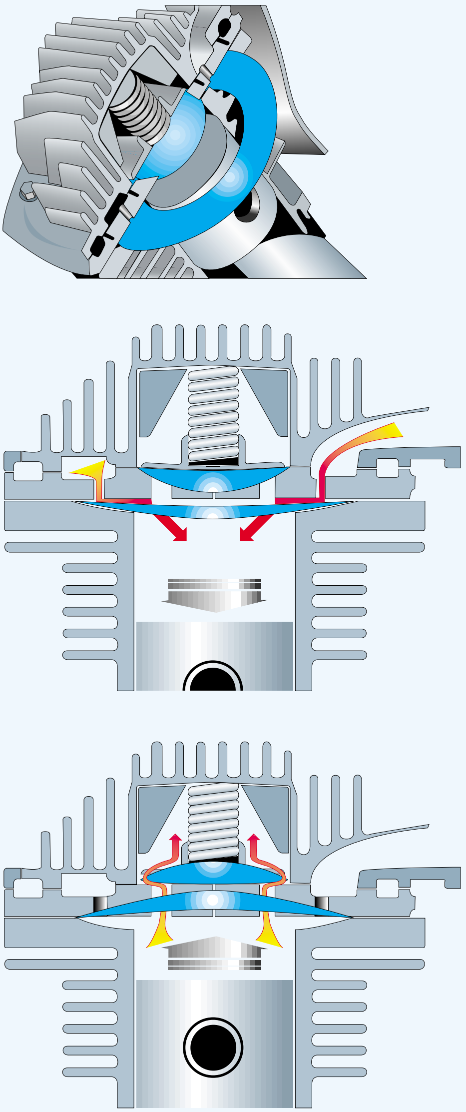

A piston compressor with a valve system consisting of two stainless steel valve discs.

When the piston moves downwards and draws in air into the cylinder the largest disc is sufficiently flexible to fold downwards to allow the air to pass.

When the piston moves upwards, the large disc folds upwards and seals against the seat. The small disc's flexi-function then allows the compressed air to be forced through the hole in the valve seat.

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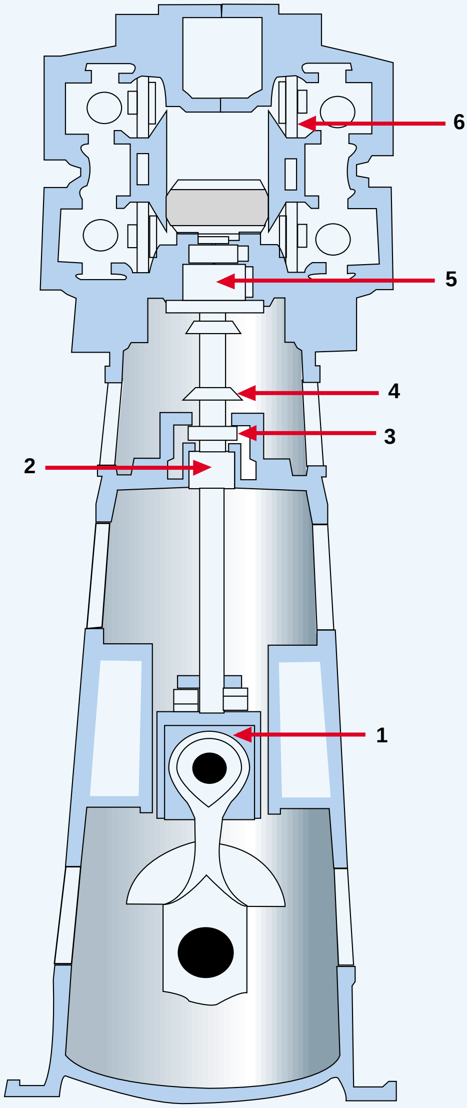

1. Crosshead
2. Guide bearing
3. Oil scraper
4. Oil thrower ring
5. Stuffing box
6. Valve disc

Labyrinth sealed, double acting oil-free piston compressor with crosshead.

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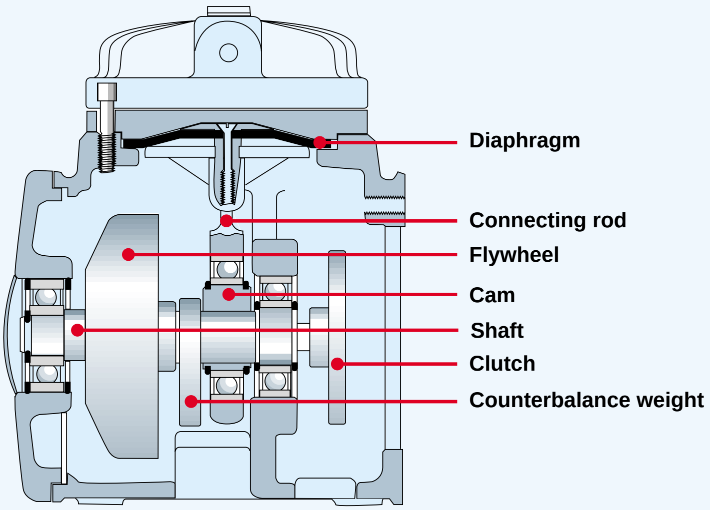

Mechanical diaphragm compressor, where the movement of the diaphragm is transferred from a conventional crankshaft with connecting rod, which is connected to the diaphragm.

2.1.3 Oil-free piston compressors

Oil-free piston compressors have piston rings of PTFE or carbon, alternatively the piston and cylinder wall can be toothed as on labyrinth compressors. Larger machines are equipped with a crosshead and seals on the gudgeon pins, ventilated intermediate piece to prevent oil from being transferred from the crankcase and into the compression chamber. Smaller compressors often have a crankcase with sealed for life bearings.

2.1.4 Diaphragm compressors

Diaphragm compressors form another group. The diaphragm is actuated mechanically or hydraulically. The mechanical diaphragm compressors are used with a small flow and low pressure or as vacuum pumps. The hydraulic diaphragm compressors are used for high pressure.

2.1.5 Screw compressors

The principle for a rotating displacement compressor with piston in a screw form was developed during the 1930s, when a rotating compressor with a high capacity and stable flow in varying conditions was required.

The screw element's main parts are the male and female rotors, which move towards each other while the volume between them and the housing decreases. Each screw element has a fixed, integrated pressure ratio that is dependent on its length, the pitch of the screw and the form of the discharge port. To attain the best efficiency the pressure ratio must be adapted to the required working pressure.

The screw compressor is not equipped with valves and has no mechanical forces that cause unbalance. This means it can work at a high shaft speed and combine a large flow rate with small exterior dimensions. An axial acting force, dependent on the pressure difference between the inlet and outlet, must be taken up by the bearings. The screw, which originally was symmetrical, has now been developed in different asymetrical helical profiles.

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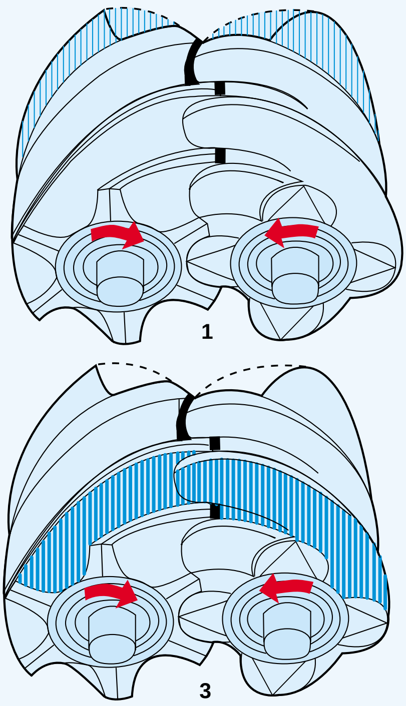

This is how air is compressed in a screw compressor. In figure 1 air fills the space between the rotors, but for each turn the space decreases more and more.

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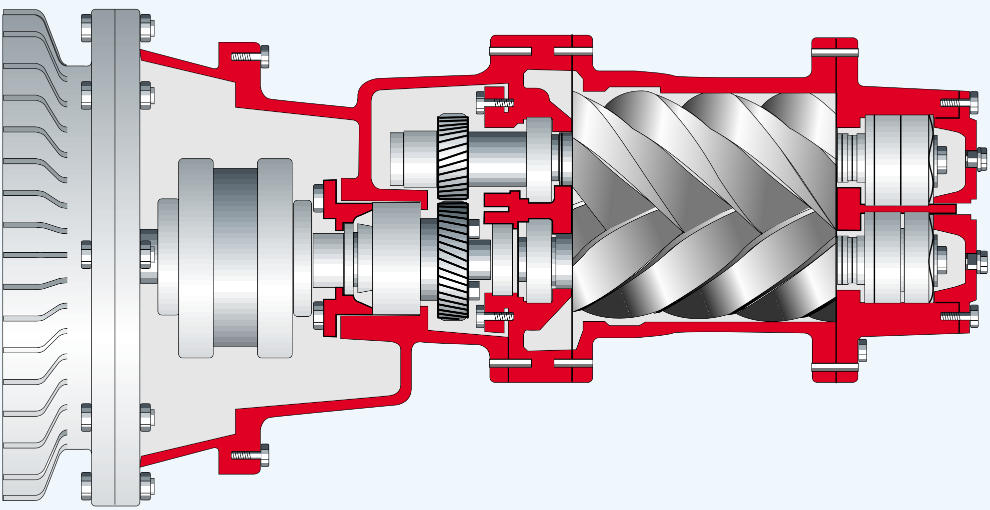
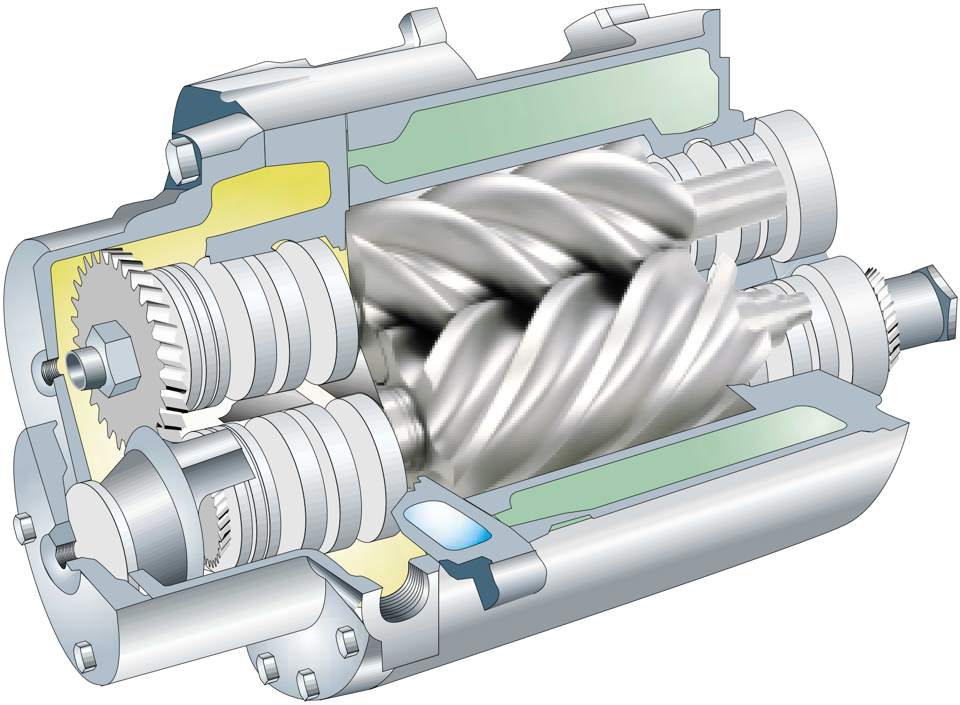


An oil lubricated screw compressor element.



A stage in an oil-free screw compressor. Male and female rotors are journalled in the rotor housing, which here is water-cooled. The front rotor, with four lobes, is the male, this is connected to the gearbox. The distant rotor, with six lobes, is the female, this is held in place by the synchronising gear to the left.

2.1.5.1 Oil-free screw compressors

The first screw compressors had a symetric profile and did not use liquid in the compression chamber, so-called oil-free or dry screw compressors. At the end of the 1960s a high speed, oil-free screw compressor was introduced with an asymetric screw profile. The new rotor profile resulted in significantly improved efficiency, due to reduced internal leakage.

An external gear is used in dry screw compressors to synchronise the counter rotating rotors. As the rotors neither come into contact with each other nor with the compressor housing, no particular lubrication is required in the compression chamber. Consequently the compressed air is completely oil-free. The rotors and housing are manufactured with great precision to minimise leakage from the pressure side to the inlet. The integrated pressure ratio is limited by the temperature difference between the intake and the discharge. This is why oil-free screw compressors are frequently built with several stages.

2.1.5.2 Liquid injected screw compressors

A liquid injected screw compressor is cooled and lubricated by liquid that is injected to the compression chamber and often to the compressor bearings. Its function is to cool and lubricate the compressor element and to reduce the return leakage to the intake.

Today oil is the most common liquid due to its good lubricating properties, however, other liquids are also used, for example, water. Liquid injected screw compressor elements can be manufactured for high pressure ratio, which why one compression stage is usually sufficient for pressure up to 13 bar. The element's low return leakage also means that relatively small screw compressors are efficient.

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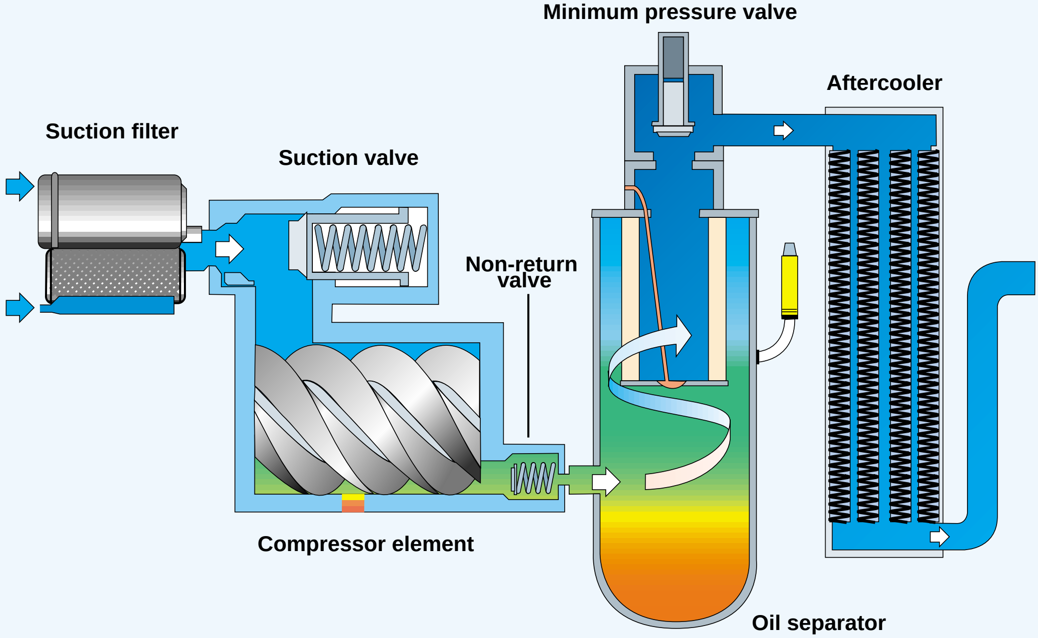

Oil injected screw compressor.

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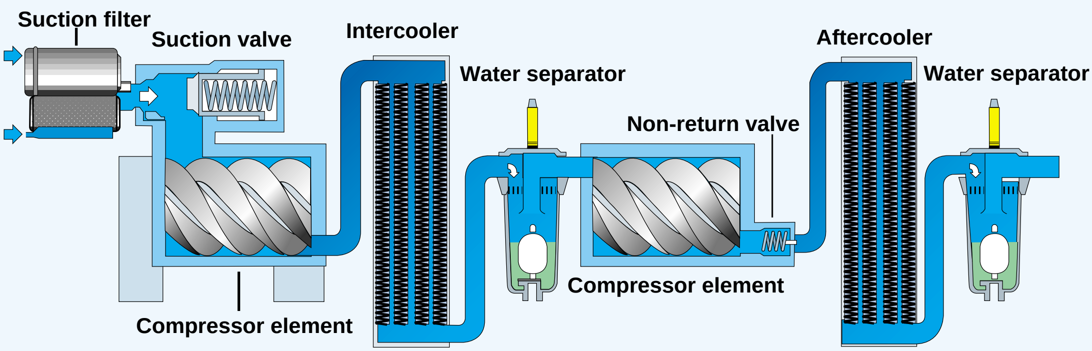

Oilfree screw compressor.

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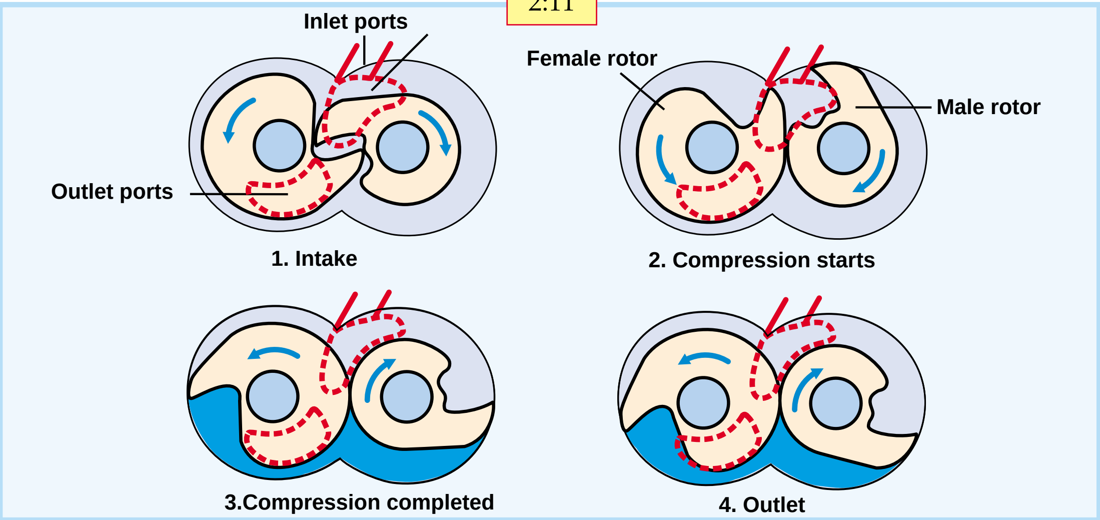

2.1.6 Tooth compressor

The compression element in a tooth compressor consists of two rotors that rotate towards each other in a compression chamber.

The compression process consists of intake, compression and outlet. During the intake phase air is drawn into the compression chamber until the rotors block the inlet. During the compression phase the drawn in air is in the compression chamber, which gets smaller and smaller as the rotors move.

The outlet is blocked during compression by one of the rotors, while the inlet is open to draw in new air into the opposite section of the compression chamber.

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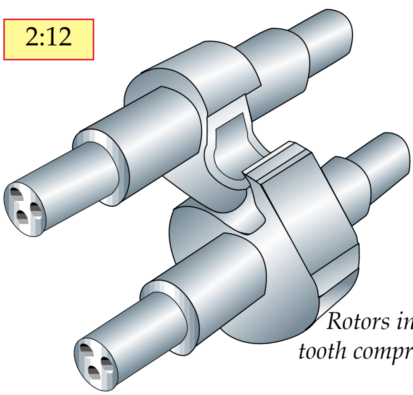

Rotors in a tooth compressor

Discharge takes place when one of the rotors opens the channel and the compressed air is forced out of the compression chamber. Intake and outlet take place radially through the compression chamber, which allows the use of simpler bearing design and improve filling properties.

Both rotors are synchronised via a gear wheel. The maximum pressure ratio obtainable with an oil-free tooth compressor is 4.5. Consequently several stages are required for higher pressures.

2.1.7 Scroll compressor

A scroll compressor is a type of oil-free rotating displacement compressor, i.e. it compresses a specific amount of air in an ever decreasing volume. The compressor element consists of a fixed spiral in an element housing and a motor powered eccentric, moveable spiral. The spirals are mounted with 180° phase displacement to form air pockets with a varying volume.

This provides the elements with radial stability. Leakage is minimised as the pressure difference in the air pockets is less that the pressure difference between the inlet and the outlet.

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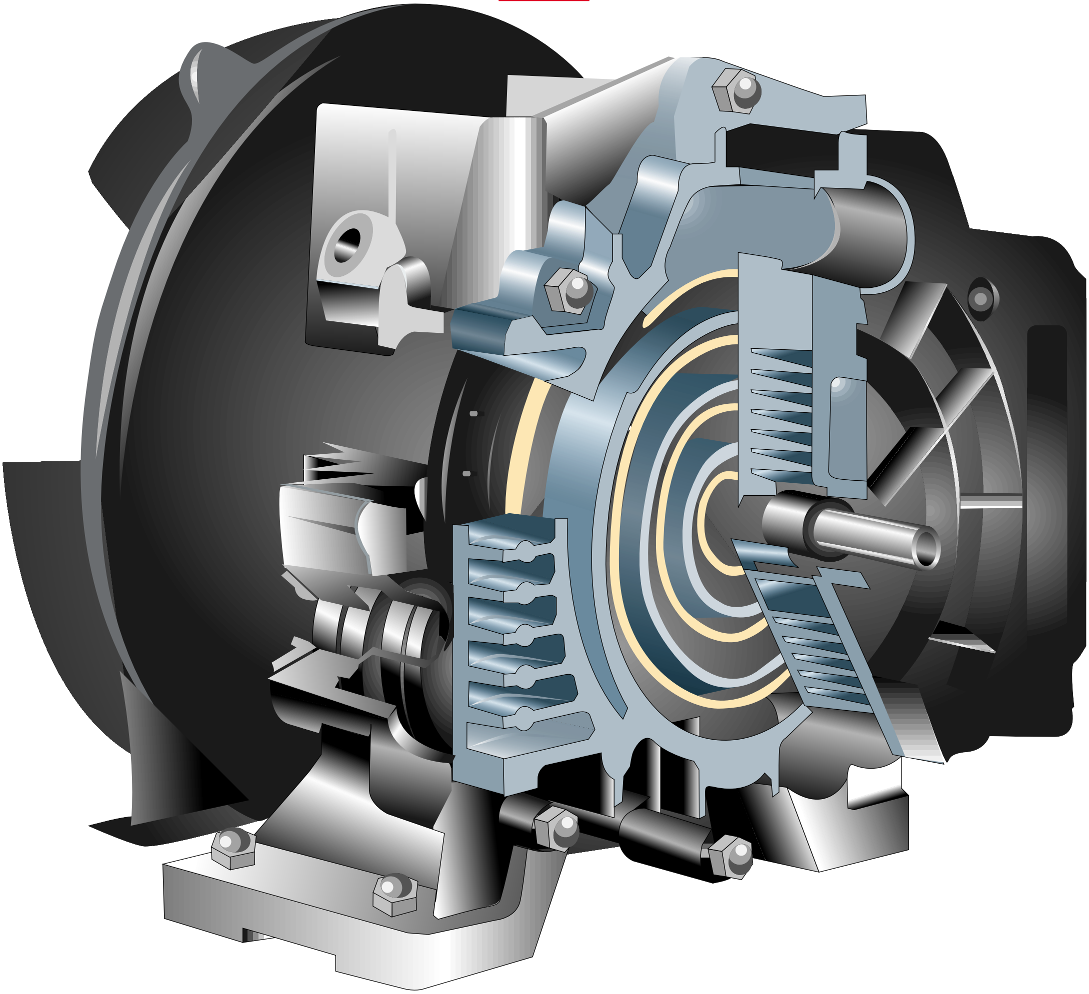

A scroll compressor in cross section.

The moving spiral is driven by a short stroke crankshaft and runs eccentrically around the centre of the fixed spiral. The intake is situated at the top of the element housing.

When the moving spiral runs anticlockwise air is drawn in, and is captured in one of the air pockets and compressed variably in towards the centre where the outlet and a non-return valve are situated. The compression cycle is in progress for 2.5 turns, which virtually gives constant and pulsating free air flow. The process is relatively silent and vibration free, as the element has hardly any torque variation compared to, e.g. a piston compressor.

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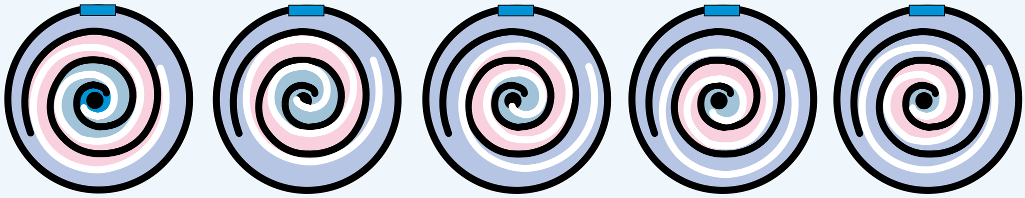

Operating principle for a scroll compressor

2.1.8 Vane compressor

The operating principle for a vane compressor is the same as for many compressed air motors. The vanes are usually manufactured of special cast alloys and most compressors are oil lubricated.

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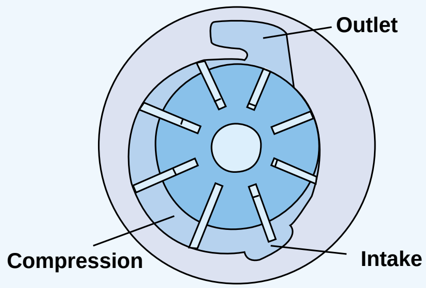

A rotor with radially movable blades is eccentrically mounted in a stator housing. When it rotates the vanes are pressed against the stator walls by centrifugal force. Air is drawn in when the distance between the rotor and stator is increasing. The air is captured in different compressor pockets, which decrease in volume with rotation. The air is discharged when the vanes pass the outlet port.

2.1.9 Liquid-ring compressor

The liquid ring compressor is a displacement compressor with built-in pressure ratio. The rotor has fixed blades and is eccentrically mounted in a housing, which is partly filled with a liquid. The blade wheel transports the liquid around in the compressor housing and a ring of liquid is formed around the compressor housing wall by means of centrifugal force. The liquid ring lies eccentrically to the rotor as the compressor housing has an oval form. The volume between the blade wheel varies cyclically. The compressor is usually designed with two symmetrical, opposite compression chambers to avoid radial thrust on the bearings.

Cooling in a liquid ring compressor is direct, due to the contact between the liquid and the air, and means the temperature increase on the compressed air is very little. However, losses through viscous friction between the housing and the blades are high. The air becomes saturated with compressor liquid, which normally is water. Other liquids can also be used, for example, to absorb a specific constituent part of the gas to be compressed or to protect the compressor against corrosion when aggressive gases are compressed.

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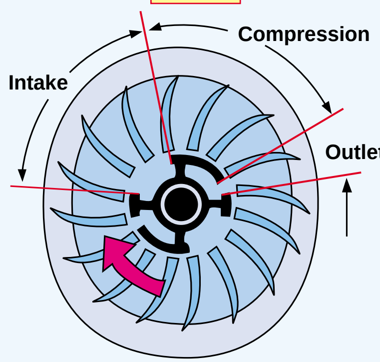

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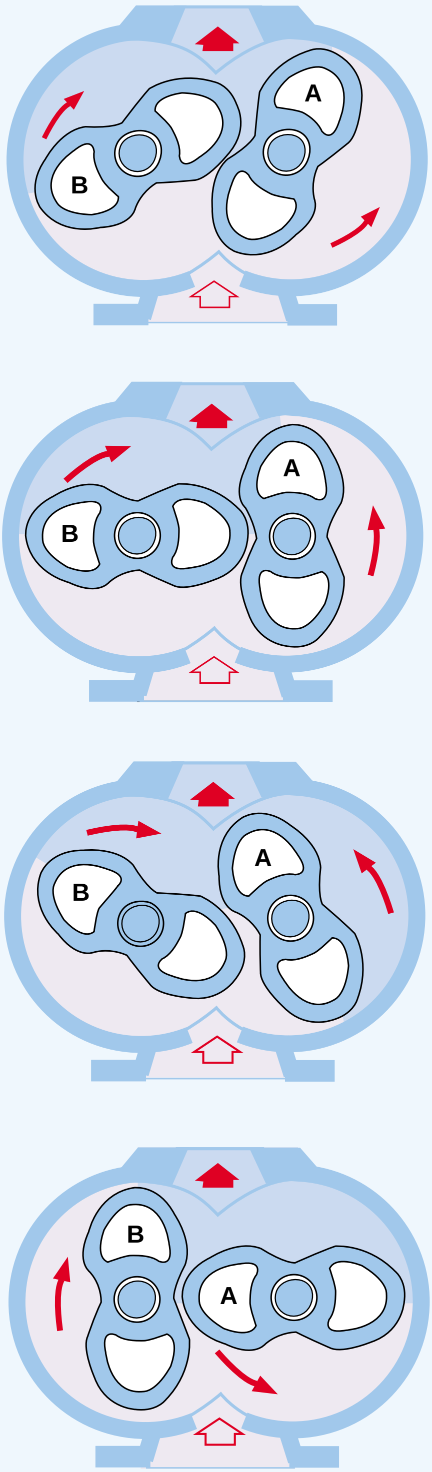

Operating principle of a blower

2.1.10 Blowers

A blower is not a displacement compressor as it works without internal compression. When the compression chamber comes into contact with the outlet, compressed air floods in from the pressure side. It is first here that compression takes place, when the volume of the compression chamber decreases with continued rotation. Accordingly, compression takes place against full counter-pressure, which results in low efficiency and a high noise level.

Two identical, normally symmetrical, counter-rotating rotors work in a housing with flat ends and a cylindrical casing. The rotors are synchronised by means of a gear wheel. Blowers are usually air cooled and oil-free. The low efficiency limits the blowers to low pressure applications and compression in a single stage, even if two and three stage versions are available. Blowers are frequently used as vacuum pumps and for pneumatic conveyance.

2.2 Dynamic compressors

2.2.1 Dynamic compressors in general

Dynamic compressors are available in axial and radial designs. The latter are frequently called turbo or radial turbo and the former are called centrifugal compressors. A dynamic compressor works with a constant pressure, unlike for example a displacement compressor, which works with a constant flow. The performance of a dynamic compressor is affected by external conditions, for example, a small change in the inlet pressure results in a large change in the capacity.

2.2.2 Centrifugal compressors

The centrifugal compressor is characterised by the radial discharge flow. Air is drawn into the centre of a rotating impeller with radial blades and is thrown out towards the periphery of the impeller by centrifugal forces. Before the air is led to the centre of the next impeller, it passes a diffuser and a volute where the kinetic energy is converted to pressure.

The pressure ratio across each stage is determined by the compressor's final pressure. This also gives a suitable velocity increase for the air after each impeller. The air temperature at the inlet of each stage has a decisive significance for the compressor's power requirement, which is why cooling between stages is needed. Centrifugal compressors with up to six stages and pressure up to 25 bar are not uncommon. The impeller can have either an open or closed design. Open is the most common with air applications. The impeller is normally made of special stainless steel alloy or aluminium. The speed is very high compared with other types of compressor, 15,000-100,000 r/min are common.

This means that journalling on the compressor shaft takes place using plain bearings instead of rolling bearings. Rolling bearings are used on single stage compressors with a low pressure ratio.

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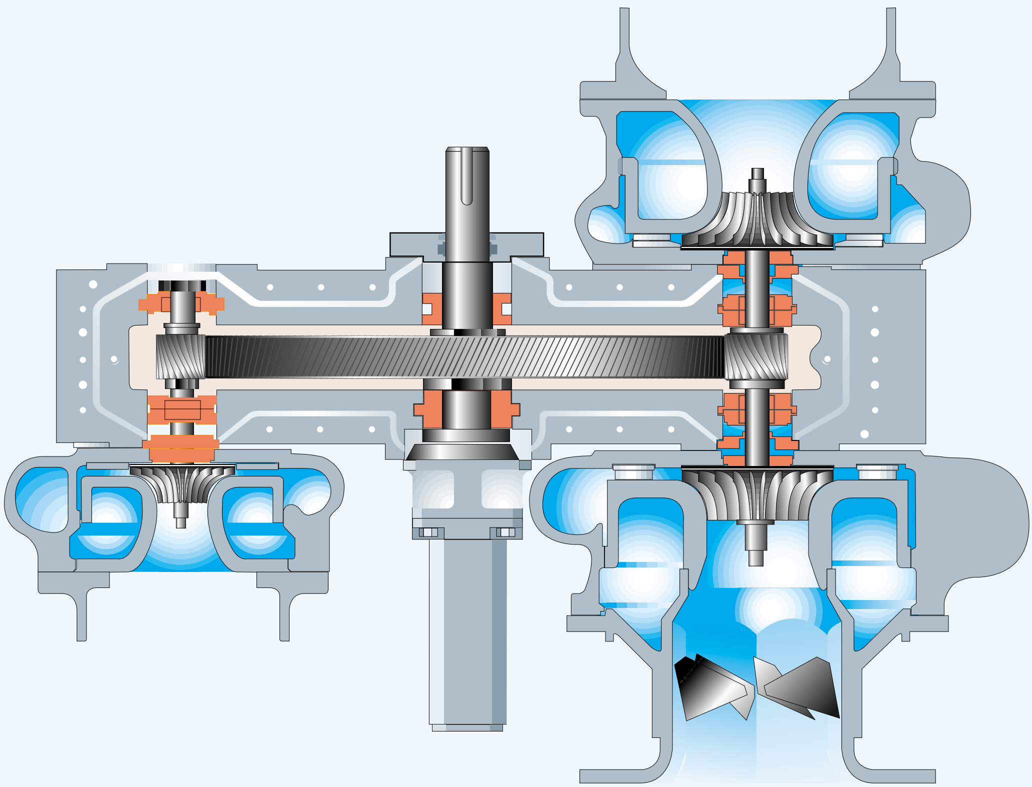

Three stage centrifugal compressor

Often multi-stage compressors have two impellers mounted on each end of the same shaft to counteract the axial loads caused by the pressure differences. The lowest volume flow rate through a centrifugal compressor is primarily determined by the flow through the last stage. A practical limit value of 160 l/s in the outlet from a horizontal split machine is often a rule-of-thumb.

Each centrifugal compressor must be sealed in a suitable manner to reduce leakage along the shaft where it passes through the compressor housing. Many types of seal are used and the most advanced can be found on compressors with a high speed intended for high pressures. The four most common types are labyrinth seals, ring seals, (usually graphic seals that work dry, but even sealing liquids are used), mechanical seals and hydrostatic seals.

2.2.3 Axial compressors

A axial compressor has axial flow, the air or gas passes along the compressor shaft through rows of rotating and stationary impellers. In this way the velocity of the air is gradually increased at the same time as the stationary blades convert the kinetic energy to pressure.

The lowest volume flow rate through such a compressor is about 15 m^3/s. A balancing drum is usually built into the compressor to counterbalance axial thrust.

Axial compressors are generally smaller than equivalent centrifugal compressors and work ordinarily with about a 25% higher speed. They are used for constant high volume rate of flow at a relatively moderate pressure. With the exception of gas turbine applications the pressure ratio is seldom higher than 6. The normal flow is approx. 65 m^3/s and effective pressure up to approx. 14 bar(e).

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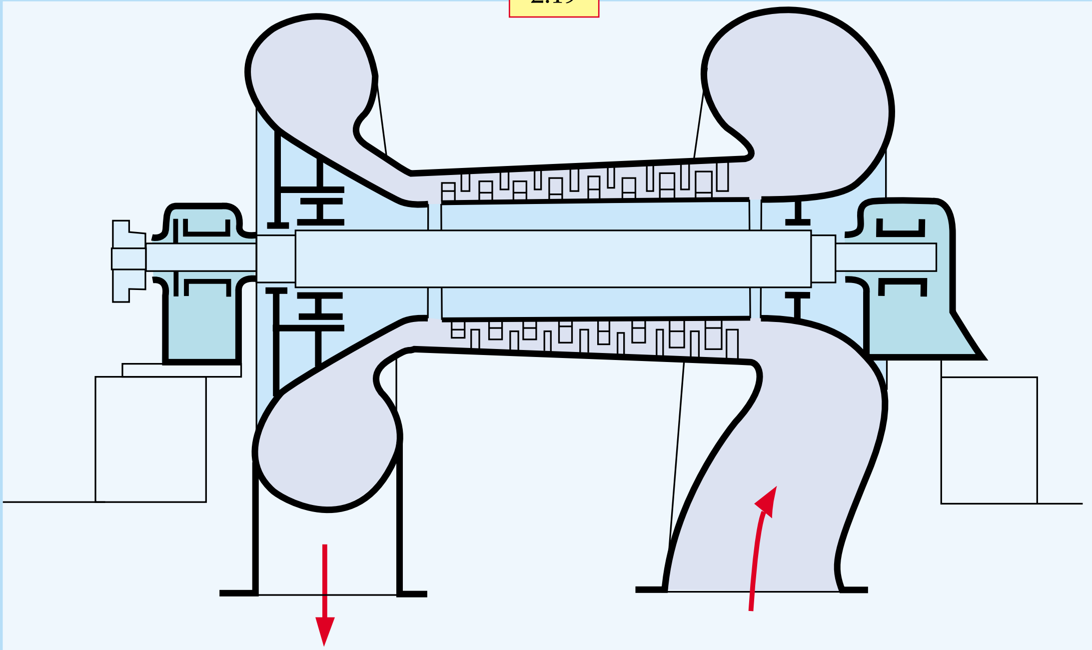

Axial compressor

2.3 Other compressors

2.3.1 Vacuum pumps

A vacuum means a lower pressure than atmospheric pressure. A vacuum pump is a compressor that works in this pressure range. A typical characteristic of a vacuum pump is that they work with a very high pressure ratio, however despite this, multi-stage machines are common. Multi-stage compressed air compressors can also be used for vacuums within the pressure range 1 bar(a) and 0.1 bar(a).

2.3.2 Booster compressors

A booster compressor is a compressor that works with air that has been compressed and compresses it to a higher pressure. It is used to compensate the pressure drop in long pipelines or in applications where a higher pressure is required for a sub-process. Compression may be single or multi-staged and the compressor can be of a dynamic or displacement type, but piston compressors are the most common. The power requirement for a booster compressor increases with a rising pressure ratio, while the mass flow drops. The curve for power requirement as a function of the intake pressure has the same general form as the curve for a vacuum pump.

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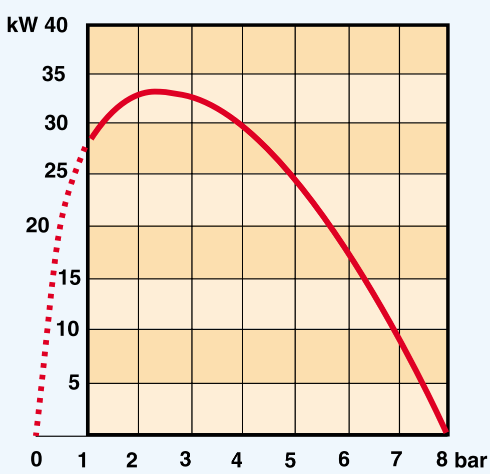

Adiabatic power requirement for a booster compressor with an absolute final pressure of 8 bar.

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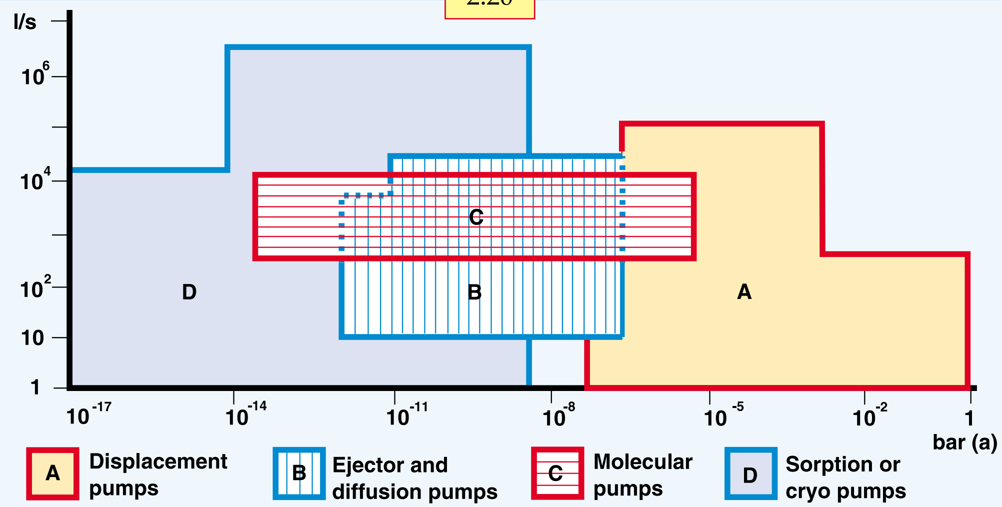

The working range for some types of vacuum pumps

2.3.3 Pressure intensifiers

Pressure intensifiers increase the pressure in a medium, for example, for laboratory tests of valve, pipes and hoses. A pressure of 7 bar can be amplified in a single stage to 200 bar or up to 1700 bar in multi-staged equipment. The pressure intensifier is only available for very small flows.

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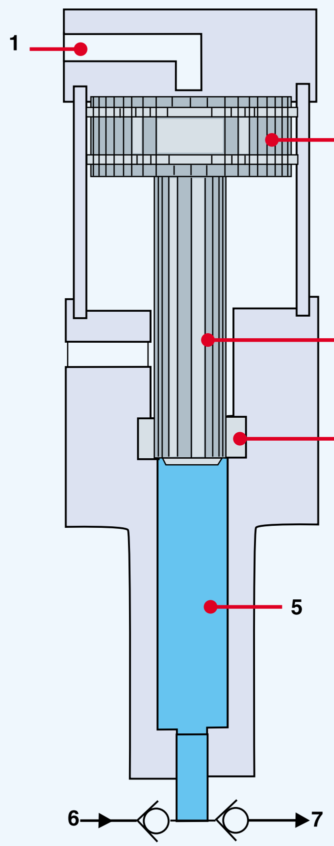

1. Propellant
2. Low pressure piston
3. High pressure piston
4. Seal
5. Compression chamber
6. Intake
7. Outlet

A cross section of a single stage pressure intensifier.

When the high pressure chamber is filled, the low pressure piston is lifted. When the propellant flows in, the piston is pressed downwards and forces the medium out under high pressure. The intensifier can work in a cycling process, up until a preset pressure level. All inert gases can be compressed in this way. Air can also be compressed in a pressure intensifier, but must be completely oil-free to avoid selfignition.

2.4 Treatment of compressed air

2.4.1 Drying compressed air

All atmospheric air contains water vapour, more at high temperatures and less at lower temperatures. When the air is compressed the water concentration increases. For example, a compressor with a working pressure of 7 bar and a capacity of 200 l/s that draws in air at 20˚C with a relative humidity of 80% will give off 80 litres of water in the compressed air line during an eight hour working day.

The term pressure dew point (PDP) is used to describe the water content in the compressed air. It is the temperature at which water vapour transforms into water at the current working pressure. Low PDP values indicate small amounts of water vapour in the compressed air.

It is important to remember that atmospheric dew point can not be compared with PDP when comparing different dryers. For example, a PDP of +2˚C at 7 bar is equivalent to –23˚C at atmospheric pressure. To use a filter to remove moisture (lower the dew point) does not work. The reason is because further cooling means

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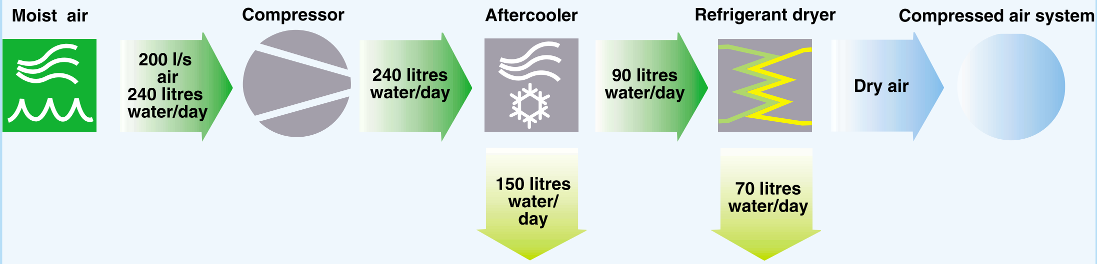

A compressor that delivers 200 litres of air per second, also supplies approx. 240 litres of water per day if working with air at 20˚C. To avoid problems and disturbances due to water precipitation in the pipes and connected equipment the compressed air must be dried. This takes place in an aftercooler and drying equipment as set out in the figure.

continued precipitation of condensation water. You can select the main type of drying equipment based on the pressure dew point. Seen from a cost point of view, the lower the dew point required the higher the acquisition and operating costs for air drying. In principle, there are four methods to remove the moisture from compressed air: Cooling, over-compression absorption and adsorption. There is equipment available, based on these methods for different types of compressed air systems.

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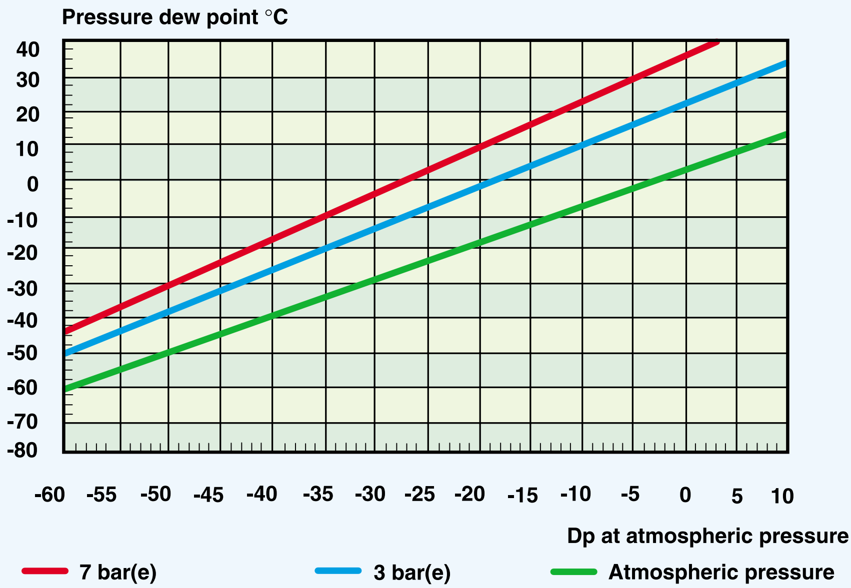

This is how the relation between dew point and compressed air looks.

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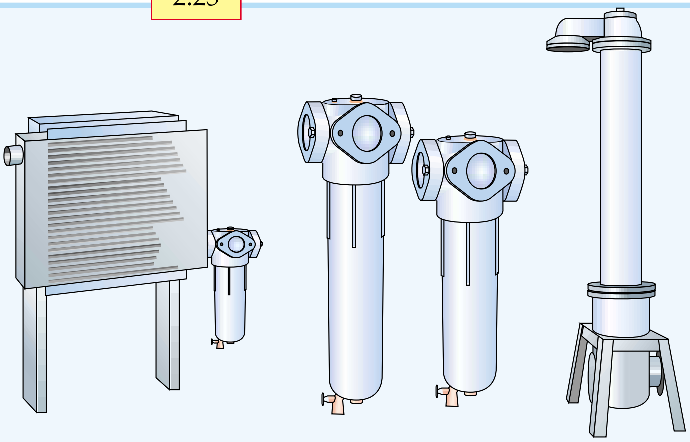

Different aftercoolers and water separators. The water separator can, for example, work with cyclone separating or separation through changes indirection and speed.

2.4.1.1 Aftercooler

An aftercooler is a heat exchanger, which cools the hot compressed air to precipitate the water that otherwise would condensate in the pipe system. It is water or air cooled, generally equipped with a water separator with automatic drainage and should be placed next to the compressor.

80–90% of the precipitated condensation water is collected in the aftercooler's water separator. A common value for the temperature of the compressed air after the aftercooler is approx. 10°C above the coolant temperature, but can vary depending on the type of cooler. An aftercooler is used in virtually all stationary installations. In most cases an aftercooler is built into modern compressors.

2.4.1.2 Refrigerant dryer

Refrigerant drying means that the compressed air is cooled, whereby a large amount of the water condenses and can be separated. After cooling and condensing the compressed air is reheated to around room temperature so that condensation does not form on the outside of the pipe system. Cooling of the compressed air takes place via a closed coolant system. By cooling the incoming compressed air with the cooled air in the heat exchanger the energy consumption of the refrigerant dryer is reduced. Refrigerant dryers are used with dew points between +2°C to +10°C and are limited downwards by the freezing point of the condensed water.

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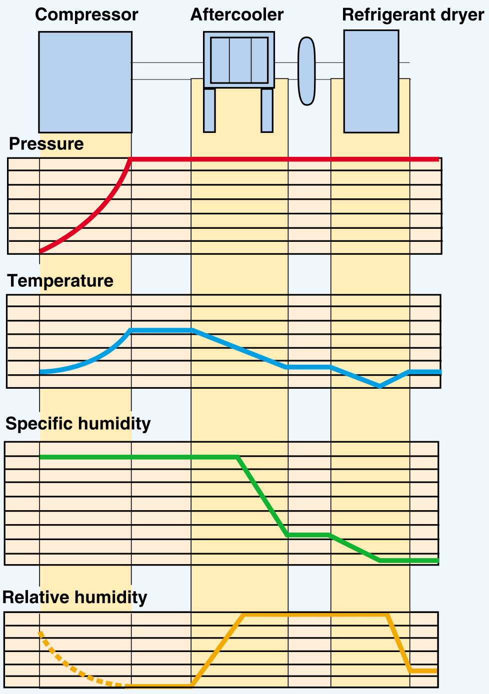

Examples of how different parameters change with compression, aftercooling and refrigerant drying.

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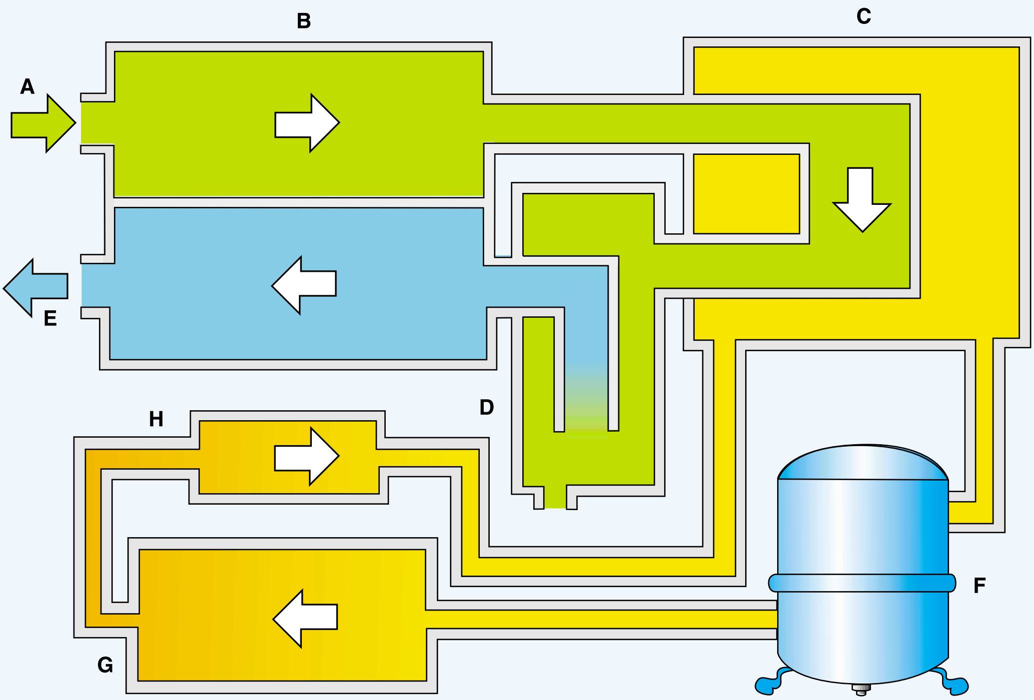

A Incoming compressed air
B Air/air heat exchanger
C Air/coolant heat exchanger
D Water separator
E Dry compressed air
F Compressor
G Condenser
H Expansion valve

This is how refrigerant cooling works in principle.

2.4.1.3 Over-compression

Over-compression is perhaps the easiest method to dry compressed air.

Air is first compressed to a higher pressure than the intended working pressure, which means the concentration of water vapour increases. Thereafter the air is cooled, whereby the water is separated. Finally the air is allowed to expand to the working pressure, whereby a lower PDP is attained. However, this method is only suitable for very small air flow rates, due to the high energy consumption.

2.4.1.4 Absorption drying

Absorption drying is a chemical process, where water vapour is bound to the absorption material. The absorption material can either be a solid or liquid. Sodium chloride and sulphuric acid are frequently used, which means the possibility of corrosion must be taken into consideration.

This method is unusual and has a high consumption of absorption material. The dew point is only lowered to a limited degree.

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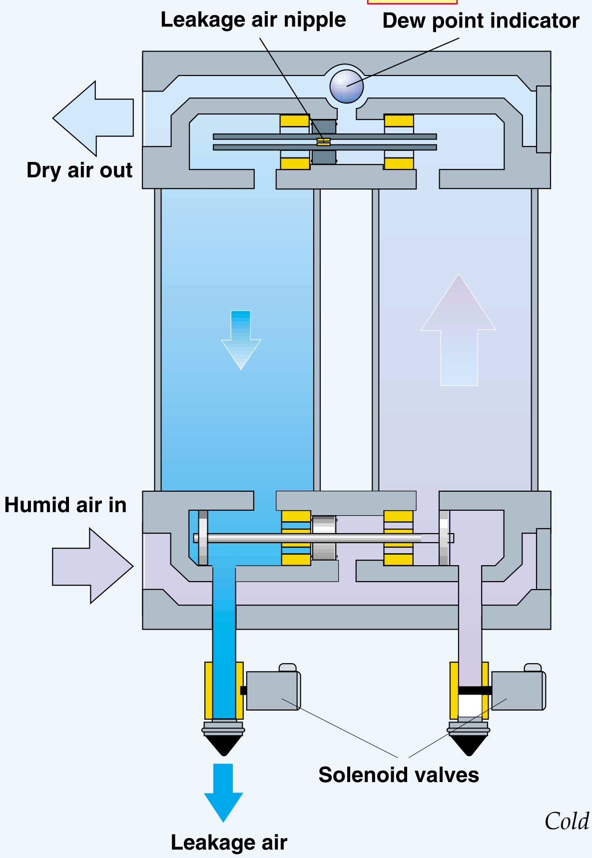

Cold regenerative adsorption drying

2.4.1.5 Adsorption drying

There are two types of adsorption dryer, cold regenerative and hot regenerative. Cold regenerative dryers are best suited to smaller air flow rates. The regeneration process takes place with the help of compressed air and requires approx. 15–20% of the dryer's nominal capacity at 7 bar(e) working pressure, PDP 20°C. Lower PDP requires a greater leakage air flow. Hot regenerative adsorption drying regenerates the desiccant by means of electrical or compressor heat, which is more economical than cold regeneration. Very low dew points (-30°C or lower) can be obtained.

Guaranteed separation and drainage of the condensation water shall always be arranged before adsorption drying. If the compressed air has been produced using oil lubricated compressors, an oil separating filter should also be fitted before the drying equipment. In most cases a particle filter is required after adsorption drying.

There are adsorption dryers for oil-free screw compressors that use the heat from the compressor to regenerate the desiccant. These types of dryers are generally fitted with a rotating drum with desiccant of which one sector (a quarter) is regenerated by means of a partial flow of hot compressed air (130–200°C) from the compressor stage. Regenerated air is then cooled, the condensation drained and the air returned via the ejector to the main air flow. The rest of the drying drum's surface (three-quarters) is used to dry the com-

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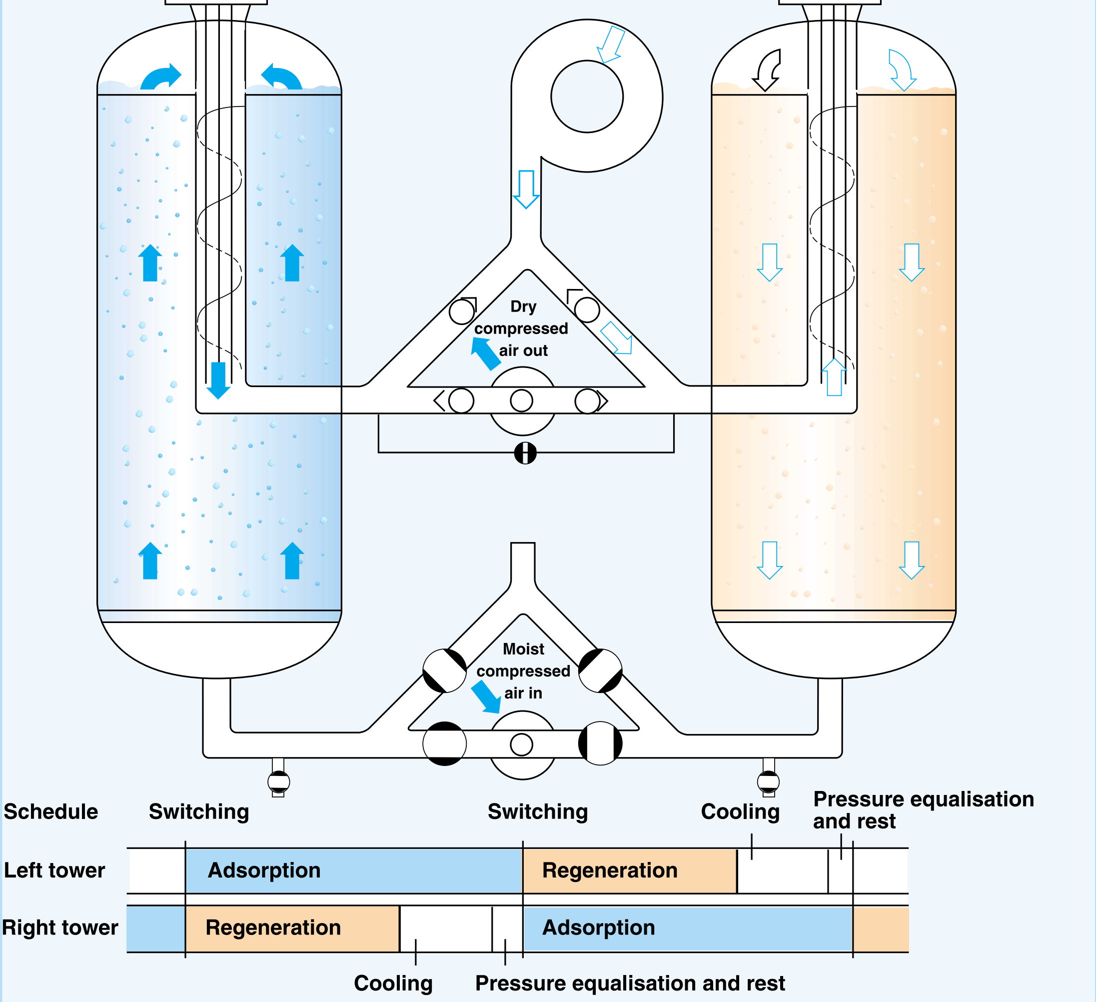
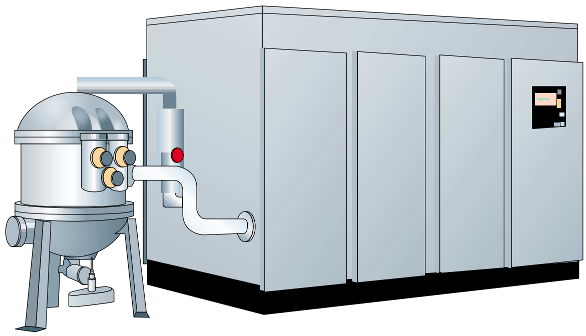


In the diagram the left tower dries the compressed air while the right tower regenerates. After cooling and pressure equalisation the towers are automatically switched.

pressed air from the compressor's aftercooler. The system gives no compressed air losses. The power requirement for such a dryer is limited to that required for powering the drum. For example, a dryer with a capacity of 1000 l/s only requires 120 W. In addition, no compressed air is lost and neither oil nor particle filters are required.

2:30



Oil-free screw compressor with a MD type adsorption dryer.

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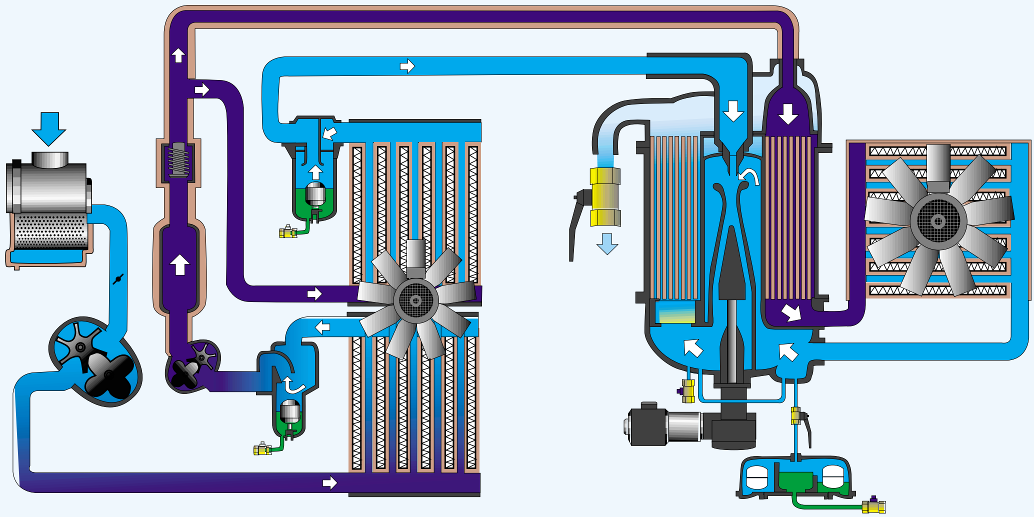

MD dryer

2.4.2 Filters

Particles in an air stream that pass a filter can be removed in several different ways. If the particles are larger than the opening in the filter material they are separated mechanically.

This usually applies for particles greater than 1 µm. The filter's efficiency in this regard increases with a tighter filter material, consisting of finer fibres. Particles between 0.1 μm and 1 μm can be separated by the air stream going around the filter material's fibres, while the particles through their inertia continue straight on. These then hit the filter material's fibres and adhere to the surface. The efficiency of the filter in this regard increases with an increased flow velocity and a tighter filter material consisting of finer fibres.

Very small particles (<0.1 μm) move randomly in the air stream influenced by collisions with air molecules. They "hover" in the air flow changing direction the whole time, which is why they easily collide with the filter material's fibres and adhere there. The efficiency of the filter in this regard increases with a reduction in the stream velocity and a tighter filter material consisting of finer fibres.

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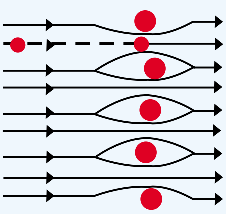

This is how filter material with mechanical separation works in theory. Particles that are > 1µm are separated.

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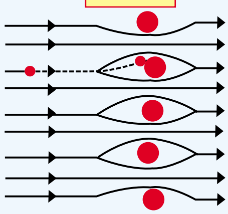

Particles between 0.1–1 µm move randomly in the air stream and are separated when they collide with the fibres in the filter material.

The separating capacity of a filter is a result of the different sub-capacities as set out above. In reality, each filter is a compromise, as no filter is efficient across the entire particle scale, even the effect of the stream velocity on the separating capacity for different particle sizes is not a decisive factor. For this reason particles between 0.2 μm and 0.4 μm are the most difficult to separate.

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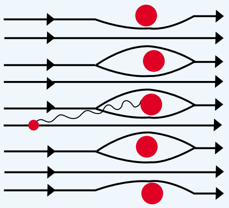

Particles (<0.1 µm) that collide with fibres in the filter are separated by adhering to the surface.

The separating efficiency for a filter is specified for a specific particle size. A separation efficiency of 90–95% is frequently stated, which means that 5–10% of all particles in the air go straight through the filter. Furthermore, a filter with a stated 95% separation efficiency for the particle size 10 μm can let through particles that are 30–100 μm in size. Oil and water in aerosol form behave as other particles and can also be separated using a filter.

Drops that form on the filter material's fibres sink to the bottom of the filter due to gravitational forces. The filter can only separate oil in aerosol form. If oil in vapour form is to be separated the filter must contain a suitable adsorption material, usually active carbon.

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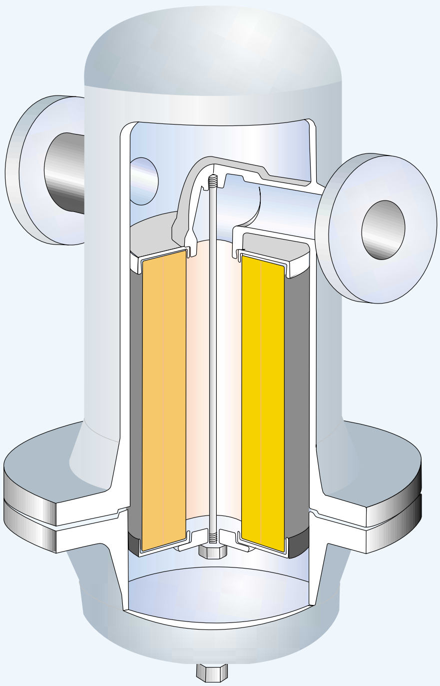
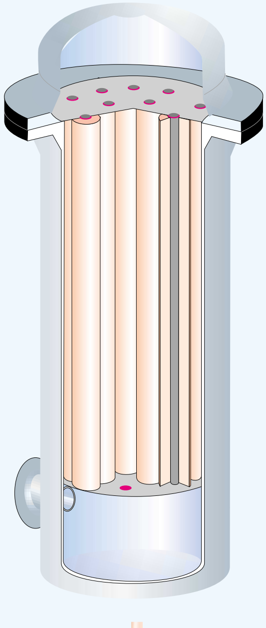


This is how a particle filter can look in reality. A large filter housing and large area mean a low air velocity, less pressure drop and a longer service life.



A filter to remove oil, water and dust particles. The filter element has a small diameter and consists of spun glass fibre

All filtering results in a pressure drop, that is to say, an energy loss in the compressed air system. Finer filters with a tighter structure cause a greater pressure drop and become blocked more quickly, which demands more frequent filter replacement resulting in higher costs.

Accordingly, filters must be dimensioned so that they not only handle the nominal flow, but also have a greater capacity threshold so they can manage a pressure drop due to a degree of blockage.

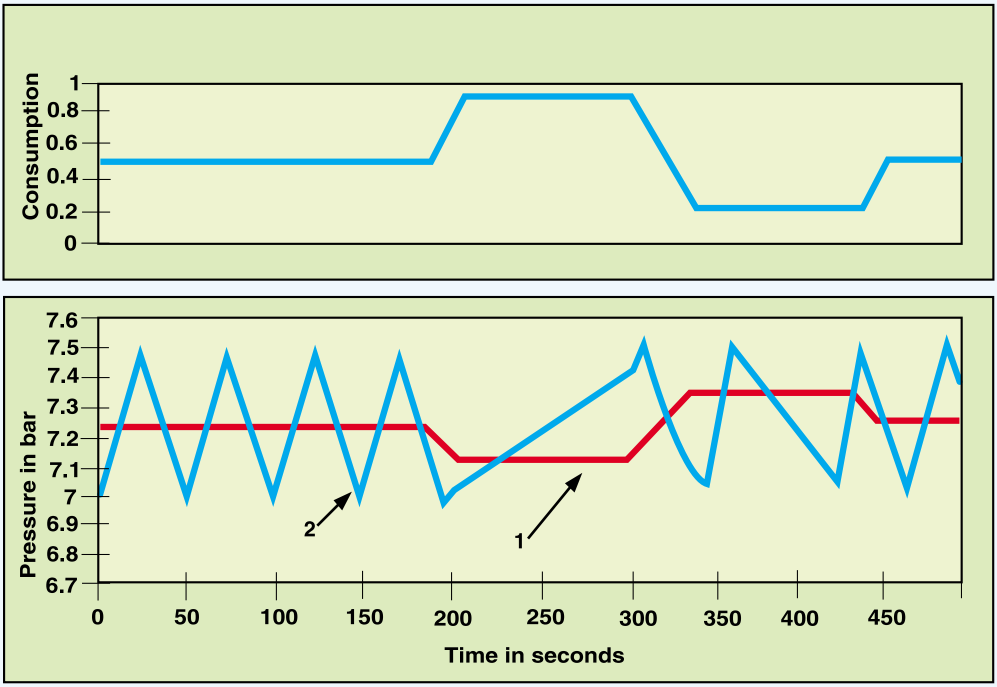
2.5 Control and regulation systems

2.5.1 Regulation, general

Frequently you require a constant pressure in the compressed air system, which makes demands on the ability to be able to control the compressed air flow from the compressor centre. There are a number of methods for this depending on, e.g. the type of compressor, permitted pressure variations, consumption variations and acceptable losses.

Energy consumption represents approx. 80% of the total cost for compressed air, which means that you should carefully consider the choice of regulation system. Primarily this is because the differences in performance broadly overshadow the differences between compressor types and manufacturers. It is ideal when the compressor's full capacity can be exactly adapted to an equal consumption, for example, through carefully choosing the gearbox's transmission ratio, something that is frequently used in process applications. A number of consumers are self-regulating, i.e. increased pressure gives an increased

2:36



1. Continuous capacity regulation 2. Load/unload regulation

flow rate, which is why they form stable systems. Examples can be pneumatic conveyors, ice prevention, chilling, etc. However, normally the flow rate must be controlled, which often takes place using equipment integrated in the compressor. There are two main groups of such regulation systems:

1. Continuous capacity regulation involves the continuous control of the drive motor or valve according to variations in pressure. The result is normally small pressure variations (0.1 to 0.5 bar), depending on the regulation system's amplification and its speed.

2. Load/unload regulation is the most common regulation system and involves the acceptance of variations in pressure between two values. This takes place by completely stopping the flow at the higher pressure (off-loading) and resume the flow rate (loading) when the pressure has dropped to the lowest value. Pressure variations depend on the permitted number of load/unload cycles per time unit, but normally lie within the range 0.3 to 1 bar.

2.5.2 Regulation principles for displacement compressors

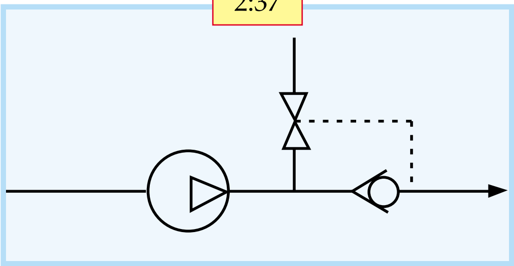
2.5.2.1 Pressure relief

The original method to regulate a compressor is a pressure relief valve, which releases excess pressure into the atmosphere. The valve in its simplest design can be spring loaded, where the spring tension determines the final pressure.

Frequently a servo-valve is used instead, which is controlled by a regulator. The pressure can then be easily controlled and the valve can also act as an off-loading valve when starting a compressor under pressure. Pressure relief makes large energy demands, as the compressor must work continuously against full counter pressure.

A variant, which is used on smaller compressors, is to unload the compressor by fully opening the valve so that the compressor works against atmospheric pressure. Power consumption is significantly more favourable using this method.

2:37



2.5.2.2 Bypass

Bypass regulation has in principle the same function as pressure relief. The difference is that the pressure relieved air is cooled and returned to the compressor's intake. The method is often used on process compressors where the gas is unsuitable or too valuable to release into the atmosphere.

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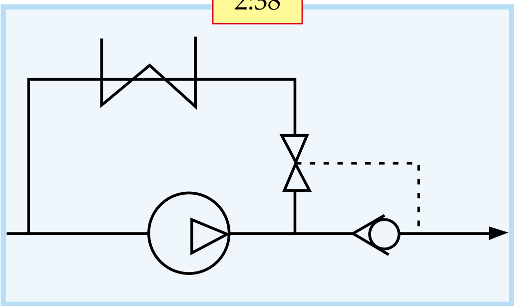

2.5.2.3 Throttling the intake

Throttling is an easy method to reduce the flow. By increasing the pressure ratio across the compressor, depending on the induced underpressure in the intake, the method is however limited to a small regulation range. Liquid injected compressors, which have a large permitted pressure ratio, can however be regulated down to 10% of the maximum capacity. This method makes relatively high energy demands, due to the high pressure ratio.

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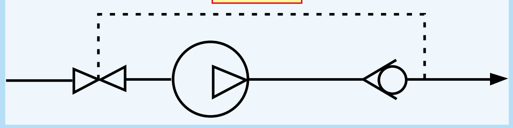

2.5.2.4 Pressure relief with throttled intake

The most common regulation method currently used that unites a maximum regulation range (0-100%) with low energy consumption, only 15–20% of full load power with an off-loaded compressor (zero flow). The intake valve is closed, but with a small opening remaining, at the same time as a blow off valve opens and relieves the outgoing air from the compressor.

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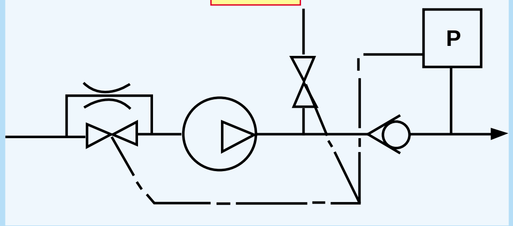
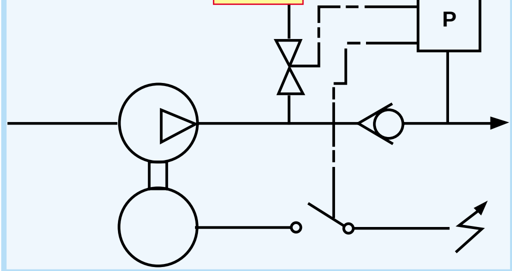


The compressor element then works with a vacuum in the intake and low counter pressure. It is important the pressure relief is carried out quickly and that the relieved volume is small to avoid unnecessary losses during the transition from loaded to unloaded. The system demands a system volume (air receiver), the size of which is determined by the acceptable difference between loading and off-loading pressure and by the permitted number of unloading cycles per hour.

2.5.2.5 Start/stop

Compressors less than 5–10 kW are often controlled by completely stopping the electric motor when the pressure reaches an upper limit value and restarting it when the pressure passes the lower limit value. The method demands a large system volume or large pressure difference between the start and stop pressure, to minimise the load on the electric motor. This is an effective regulation method under the condition that the number of starts per time unit is kept low.

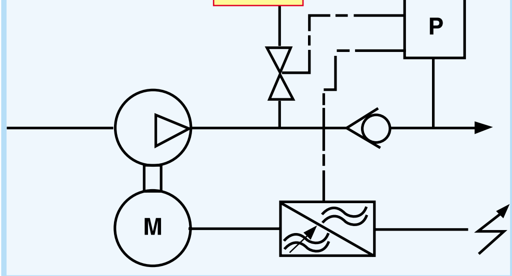
2:41



2.5.2.6 Speed regulation

A combustion engine, turbine or frequency controlled electric motor controls the compressor's speed and thereby the flow. It is an efficient method to attain an equal outgoing pressure and a low energy consumption.

2:42



The regulation range varies with the type of compressor, but is greatest for liquid injected compressors. Frequently speed regulation and pressure relief are combined, with or without a throttled intake, at low degrees of loading.

2.5.2.7 Variable discharge port

The capacity of screw compressors can be regulated by moving the position of the discharge port in the housing, in the screw's lengthways direction, towards the intake. However, the method demands high power consumption with sub-loads and is relative unusual.

2.5.2.8 Suction valve unloading

Piston compressors can be effectively relieved by mechanically forcing the intake valves to the open position. Air is then pumped out and in under the position of the piston, with minimal energy losses as a result, often lower than 10% of the loaded shaft power. On double acting compressors there is generally multi-stage off-loading, where one cylinder at a time is balanced to better adapt the capacity to the demand. An odd method used on process compressors is to allow the valve to be open during a part of the piston stroke and thereby receive a continuous flow control.

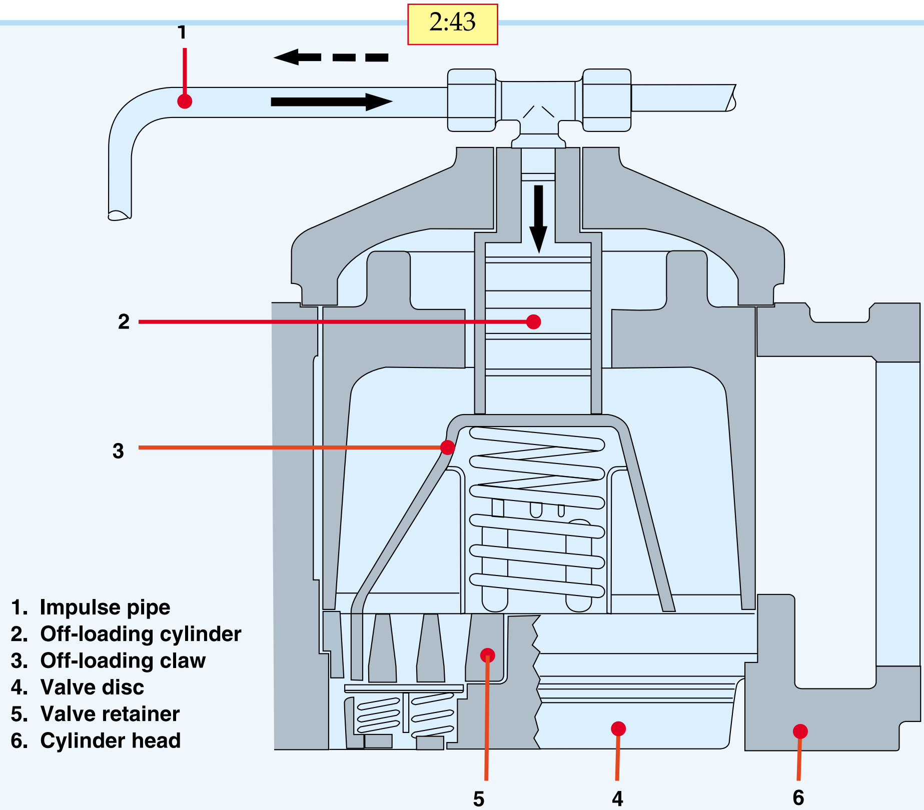
2.5.2.9 Clearance volume

By varying the clearance volume on a piston compressor the degree of filling decreases and thereby the capacity. The clearance volume is varied by means of an externally connected volumes.

2.5.2.10 Load–unload–stop

The most common regulation method used for compressors greater than 5 kW that combines a large regulation range with low losses. In practice a combination of the start/stop and different off-loading systems. See further under 2.5.4.2.

2:43



Off-loading device for a piston compressor

2.5.3 Regulation principles for dynamic compressors

2:44

2.5.3.1 Throttling the intake

The intake can be throttled on a dynamic compressor to continuously reduce the capacity of the compressor. The minimum flow is determined when the pressure ratio reaches the pump limit and the machine becomes unstable (surge).

The regulation range is determined by the design of machine, for example, the number of stages and the impeller design, but also to a large degree by external factors such as counter pressure, suction temperature, and the coolant temperature. The minimum flow often varies between 60% and 85% of the maximum flow.

2.5.3.2 Inlet guide vanes

Vanes arranged as radial blades in the intake cause the in-drawn gas to rotate, at the same time as the flow is throttled. The method acts as throttling, but with a greater regulation range and with improved energy utilisation. Regulation down to 50–60% of the design flow is a typical value. There is also the possibility of increasing the capacity and pressure of the compressor to a certain degree, by turning the vanes in the opposite direction, however, this does impair performance a little.

2.5.3.3 Outlet guide vanes (diffuser)

To further improve the regulation range you can also control the flow in the compressor stage's diffuser. Regulation down to 30% with maintained pressure is common. Normally usage is limited to single stage compressors, due to the complexity and increased costs.

2.5.3.4 Pressure relief

The original method of regulating a dynamic compressor was also to use a pressure relief valve, which releases excess compressed air into the atmosphere. The method works in principle as pressure relief on a displacement compressor.

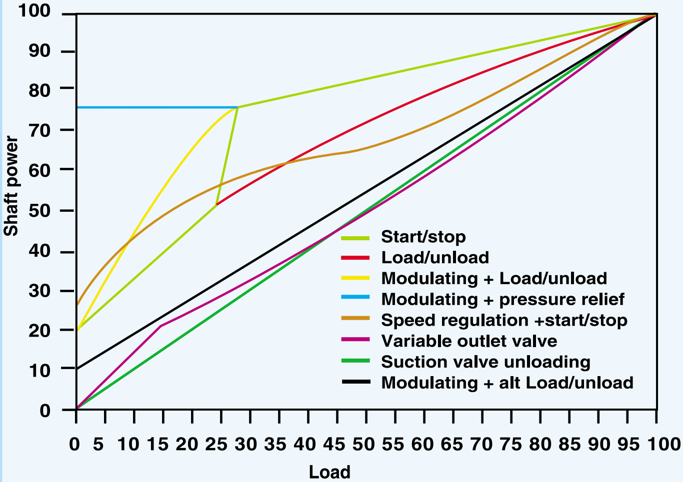
2.5.3.5 Load–unload–stop

While throttling the compressor's inlet is limited by the pump limit, this can be solved in one of two ways:

1. Modulating. The excess flow is released into the atmosphere (or intake), however, with unchanged energy consumption.
2. Auto Dual. The regulation system virtually fully closes the intake valve at the same time as the compressor's outlet is opened to the atmosphere (compare the displacement compressor). However, the off-loading power is relatively high, over 20% of the full load power, depending on the design of the impeller, etc.

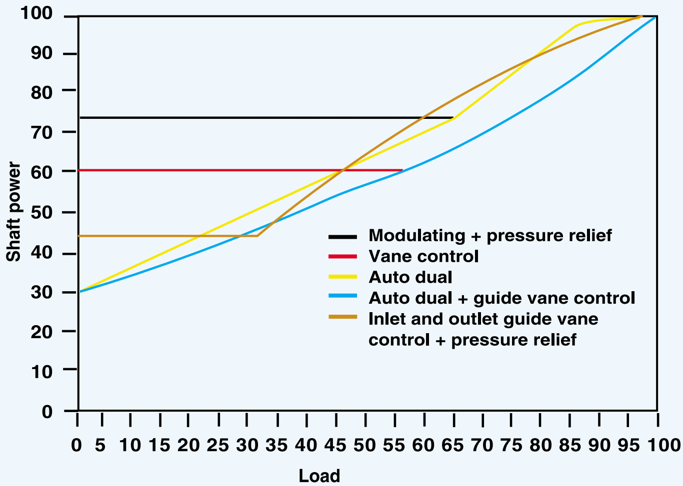
2.5.3.6 Speed regulation

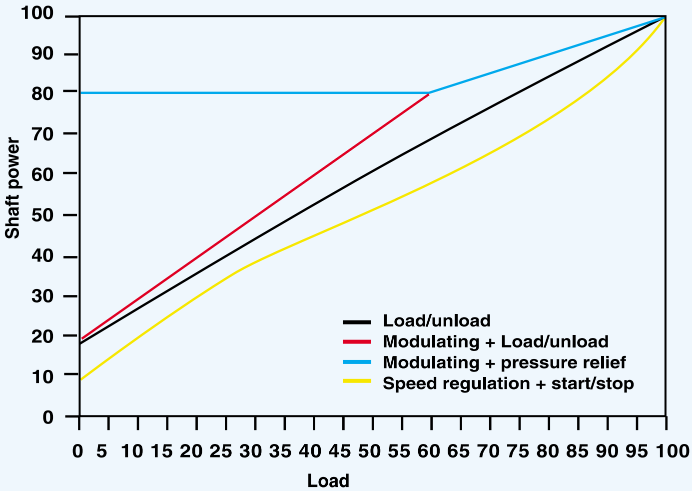
Speed regulation is commonly used on compressors where the flow shall be regulated and the pressure is permitted to vary. With constant pressure regulation, speed regulation gives no benefits when compared with other regulation systems.



The relation between the shaft power and flow for oil lubricated compressors with different regulation systems and combinations of regulation systems.

The relation between the shaft power and flow for dynamic compressors with different regulation systems and combinations of regulation systems.





The relation between the shaft power and flow for oil-free screw compressors with different regulation systems and combinations of regulation systems.

2.5.4 Control and monitoring

2.5.4.1 General

Regulation principles for different compressors are taken up in chapters 2.5.2 and 2.5.3. To control compressors according to these principles requires a regulation system that can either be intended for an individual compressor or an entire compressor installation.

Regulation systems are becoming more advanced and development goes quickly. Relay systems have been replaced by programmable equipment (PLC), which in turn are being replaced by product adapted systems based on microcomputers. The designs are often an attempt to optimise operations and cost.

This section deals with a few of the control and monitoring systems for the most common types of compressor.

2.5.4.2 Load–unload–stop

The most common regulation principles for displacement compressors are "produce air"/"don't produce air" (loaded/unloaded), see 2.5.2.4 and 2.5.2.5.

When air is required a signal is sent to a solenoid valve, which in turn guides the compressor's intake damper to the fully open position. The damper is either fully opened (loaded) or fully closed (unloaded), there is no intermediate position.

The traditional control, now common on smaller compressors, has a pressure switch placed in the compressed air system that has two settable values, one for the minimum pressure (= loaded) and one for maximum pressure (unloaded). The compressor will then work within the limits of the set values, for example, 0.5 bar. If the air requirement is small or nothing the compressor runs off-loaded (idling). The length of the idling period is limited by a timer (set e.g. to 20 minutes). When the time elapses, the compressor stops and does not start again until the pressure has dropped to the minimum value. This is the traditional tried and trusted control method. The disadvantage is that it gives slow regulation.

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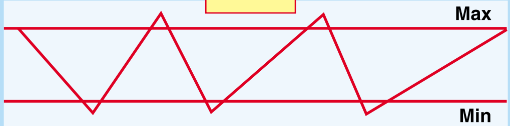

Pressure band, min–max, within which the compressor works. "Min" = load, "Max" = off-load.

A further development of this traditional system is to replace the pressure switch with an analogue pressure transducer and a fast electronic regulation system. The analogue transducer can, together with the regulation system, sense how quickly the pressure in the system changes. The system starts the motor and controls the opening and closing of the damper at the right time. This gives quick and good regulation within ± 0.2 bar.

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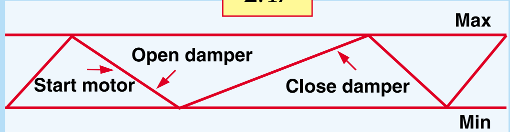

An advanced regulation system can send signals to the motor, starter and regulator at "the right time".

If no air is used the pressure will remain constant and the compressor will run off-loaded (idling). The length of the idling period is controlled by how many starts and stops the electric motor can withstand without becoming too hot and by the overall operating economy. The latter is possible as the system can analyse trends in air consumption and thereby decide whether to stop the motor or continue to idle.

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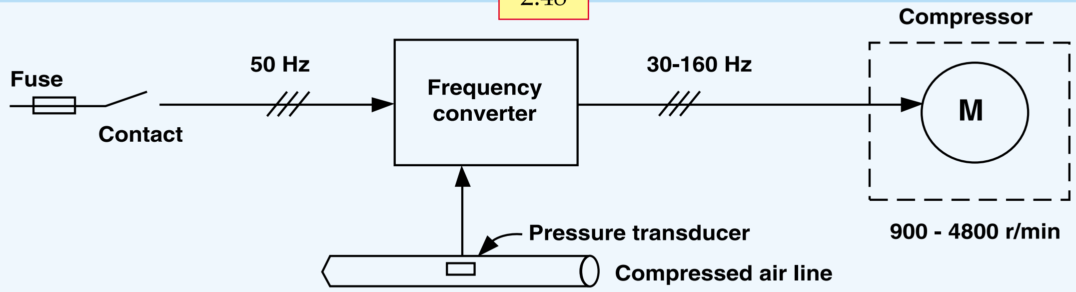

A system with a speed controlled compressor

2.5.4.3.Speed control

Compressors with a power source whose speed is controlled electronically provide a great opportunity to keep the compressed air constant within a very tight pressure range.

A frequency converter, which regulates the speed on a conventional induction motor, is an example of such a solution. The compressor's capacity can be adapted exactly to the air requirement by continuously and accurately measuring the system pressure and then allow the pressure signals to control the motor's frequency converter and thereby the motor's speed. The pressure within the system can be kept within ± 0.1 bar.

2.5.5 Control and monitoring

All compressors are equipped with some form of monitoring equipment to protect the compressor and prevent production downtime. The transducer is used to sense the current condition of the installation. Information from the transducers is processed by the monitoring system, which gives a signal to, e.g. an actuator.

A transducer for measuring the pressure or temperature often consists of a sensor and a measurement converter. The sensor senses the quantity to be measured. The measurement converter converts the sensor's output signal to an appropriate electrical signal that can be processed by the control system.

2.5.5.1 Temperature measurement

A resistance thermometer is normally used to measure the temperature. This has a metal resistor as a transducer, whose resistance increases with the temperature. The change in resistance is measured and converted to a signal of 4–20 mA. Pt 100 is the most common resistance thermometer. The nominal resistance at 0°C is 100Ω.

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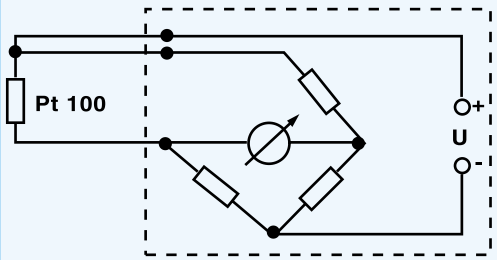

An example of a 3 wire connection using a resistance thermometer of 100Ω. The resistance thermometer and connectors are connected on a bridge.

The thermistor is a semiconductor, whose resistance changes with the temperature. It can be used as a temperature controller, for example, on an electric motor. PTC, Positive Temperature Coefficient, is the most common type. The PTC has an insignificant change in resistance with increased temperature up to a reference point, where the resistance increases with a jump. The PTC is connected to a controller, which senses the "resistance jump" and gives a signal, for example, stop the motor.

2.5.5.2 Pressure measurement

A pressure sensing body, e.g. a diaphragm is used to measure the pressure. The mechanical signal from the diaphragm is then converted to an electrical signal, 4–20 mA or 0–5 V.

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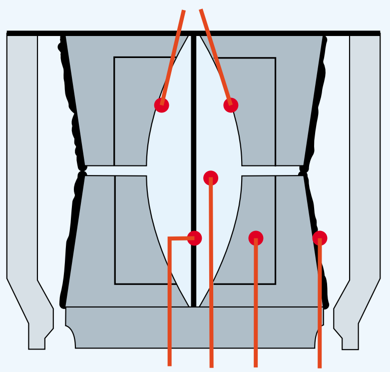

Example of a capacitive system for pressure measurement

The conversion from a mechanical to an electrical signal can take place in different measurement systems. In a capacitive system, pressure is transferred to a diaphragm. The position of the measurement diaphragm is sensed by a capacitor plate and is converted in a measurement converter to a direct voltage or direct current, proportional to the pressure.

The resistive measurement system consists of a strain gauge, connected in a bridge connection and attached to the diaphragm. When the diaphragm is exposed to

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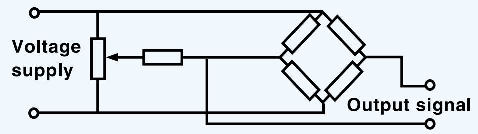

Bridge connection with strain gauge.

pressure a low voltage (mV) is received. This is then amplified to a suitable level. The piezo electric system is based on specific crystals (e.g. quartz) generating electrical charges on the surface of the crystal. The charges are proportional to the force (pressure) on the surface.

2.5.5.3 Monitoring

Monitoring equipment is adapted according to the type of compressor, which entails a large range when concerning the scope of equipment. A small piston compressor is only equipped with a conventional overload cut-out for the motor, while a large screw compressor can have a number of cut-outs/transducers for overloading, temperature and pressure, etc.

On smaller, more basic machines the control equipment switches off the compressor and the machine is blocked for restarting when a cut-out gives an alarm value. A warning lamp, can in some cases, indicate the cause of the alarm.

Compressor operations can be followed on a control panel on more advanced compressors, for example, by directly reading off the pressure, temperature and status, etc. If a transducer value approaches an alarm limit the monitoring equipment gives off a warning. Measures can then be taken before the compressor is switched off. If the compressor is stilled stopped by an alarm, the restart of the compressor is blocked until the fault has been rectified or is reset by hand.

Trouble shooting is significantly facilitated on compressors equipped with a memory where data on, e.g. temperatures, pressure and operating status are logged. The capacity of the memory covers, for example, the last 24 hours. By using this it's possible to produce trends over the last day and then, using logical trouble shooting, quickly track down the reason for the downtime.

2.5.6 Comprehensive control system

Compressors that are a part of a system of several machines should have co-ordinated compressor operations. There are many factors that speak for a comprehensive control system. The division of operating times between machines reduces the risk of unexpected stoppages. Servicing compressors is also easier to plan. Standby machines can be connected if something should occur during operations.

2.5.6.1 Starting sequence selector

The simplest and most common form of master control system is the well tried and tested start sequence selector. This has the task of equally dividing the operating times and starts between the connected compressors. The start sequence can be switched manually or automatically according to a time schedule. This basic selector utilises an on/off pressure transducer, with one transducer per compressor, which is a simple and practical solution.

The disadvantage is that there are relatively large steps between the different compressor's loading and off-loading levels, which in turn gives relatively broad pressure bands (the span between maximum and minimum levels) for the installation. Therefore this type of selector should not be used to control more than 2–3 compressors.

A more advanced type of start sequence selector has the same type of sequence control, but with only one, centrally positioned, analogue pressure transducer. This manages to keep the installation's total pressure band within a few tenths of

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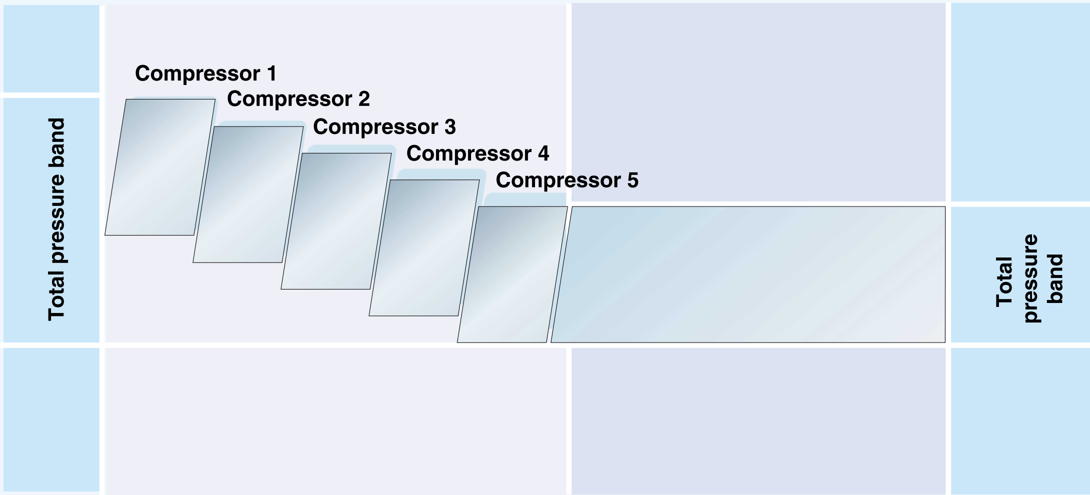
A user-friendly monitoring panel shows all the operating parameters for the compressor, for example, pressure and temperatures, with data logically grouped for direct read-off.



The difference in the pressure band for five compressors controlled by conventional pressure switches (left-hand field) and the same machines controlled by a regulation system with an analogue transducer (right-hand field).

a bar and can control 2–7 machines. A start sequence selector of this type, which selects the machines in fixed sequences, does not take the capacity of the compressors into consideration. It is therefore appropriate that the connected compressors are of approximately the same size.

2.5.7 Central control

Central control in association with compressors usually means relatively intelligent control systems. The basic demand is to be able to maintain a predetermined pressure within tight limits and that the installation's operation shall be as economic as possible. To achieve this, the system must be capable of predicting what will happen in the system and at the same time sense the load on the compressor.

The system senses how quickly the pressure changes, upwards or downwards (i.e. the time derived pressure). Using these values the system can perform calculations that make it possible to predict the air requirement and, for example, off load/load or start/stop the machines. In a correctly dimensioned installation the pressure will be within ± 0.2 bar.

It is extremely important for the operating economy that the central control system selects a compressor or compressor combinations, if compressors of different capacity are included in the system.

The compressors shall run virtually continuously loaded and thereby minimise idling to give the best economy.

An another advantage of a comprehensive control system is that it is generally possible to connect older machines to these systems and thereby, in a relatively easy manner, modernise the entire compressor installation. Operations become more economic and availability increases.

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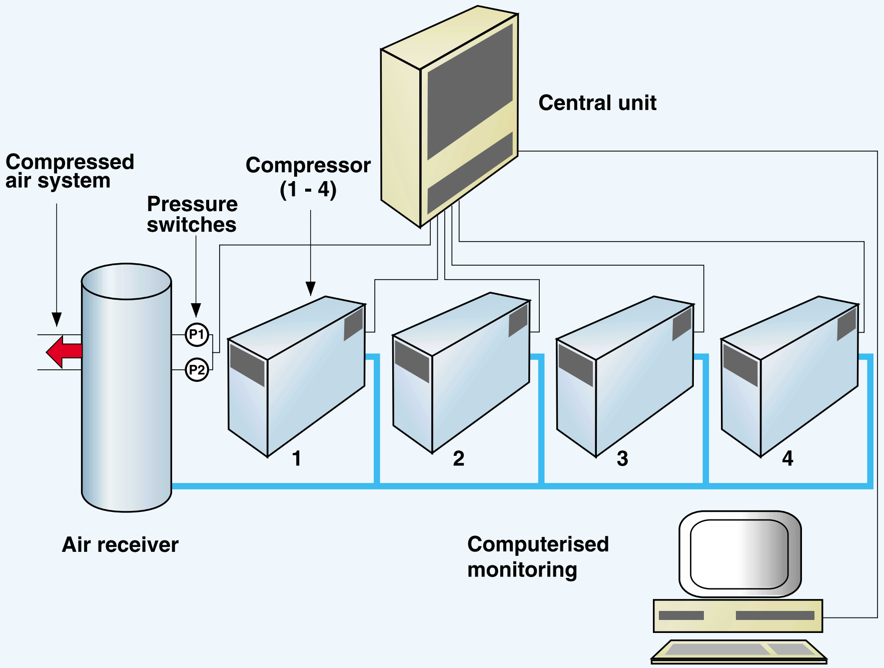


A centrally controlled compressor installation

2.5.8 Remote monitoring

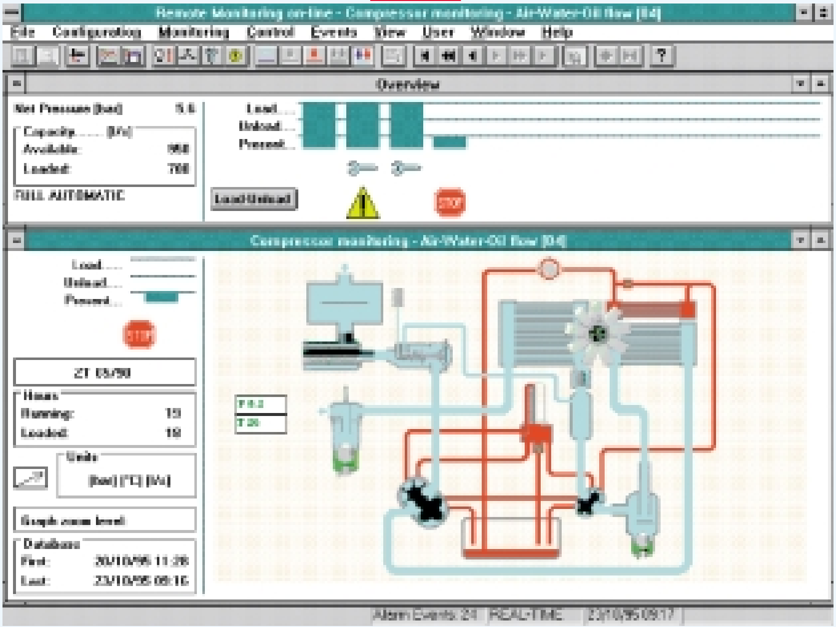
In a number of compressor installations there may be a need of monitoring and controlling compressor operations from a remote location. On smaller installations it is fairly easy to connect an alarm, operating indicator, etc. from the compressor. Normally it is also possible for remote starting and stopping.

On larger installations, where immense value is at stake, central monitoring can be motivated. It should consist of equipment that gives a continuous overview of the system, but where it is also possible to access individual machines to control details such as the intercooler pressure, oil temperature/ etc.

The monitoring system should also have a memory, so that it is possible to produce a log of what has happened during the past 24 hours. The log makes up the basis for trend curves, where it is possible to read off whether any values have a tendency of deviating from the default. The curves can form the basis for continued operations or a planned stop.

The system frequently presents compressor installation status reports in the form of different levels, from a total overview to detail status for individual machines.

2:55



An overview display with remote monitoring. The upper section shows the installation status. Three machines in operation, one stopped. In the lower section details for compressor 4 are shown, among others, flow chart for the compressed air, cooling water and oil as well as prevailing compressor data.