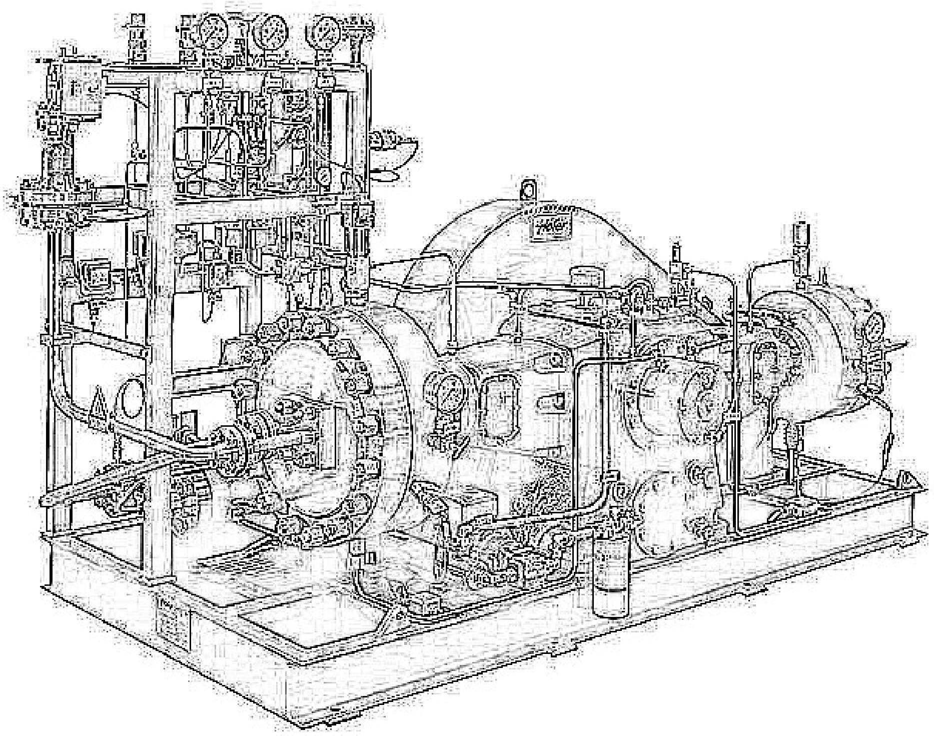
Diaphragm Compressors



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Introduction

Nearly all chemical processes as well as process engineering involve the requirement of compressing gas from a lower to a higher pressure level.

Selection of the type of compressor is done depending on the parameter of the process (type of gas, capacity, pressure difference to be overcome). For higher pressure differences (approx. 40 bar upward) only reciprocating compressors can be used (Fig. 1) [1].

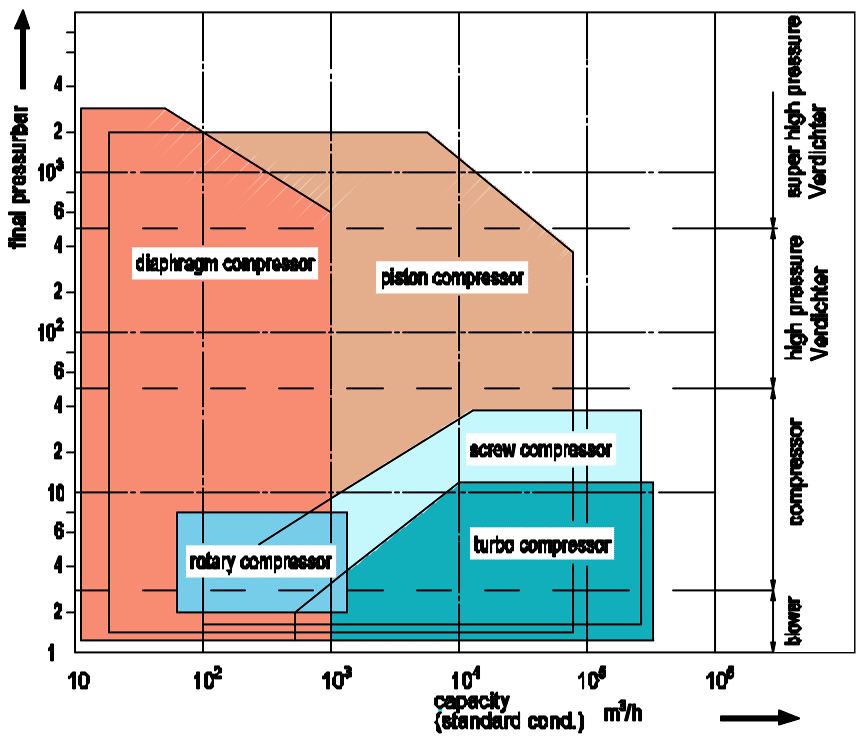


Fig. 1: Present applications of different compressor types [1]

The classic piston compressor has been and will be oil-lubricated, and thus will have the inherent disadvantage of this type of compressor design, which is that lube oil enters and appears in the different compression stages. This lube oil has to be drained again from the gas, separated and suitably removed downstream the last compressor stage. These washed-out lube oil may admittedly not be too great a problem for compressors for air, nitrogen or hydrogen, but positively these residual oils are difficult to be handled from e.g. sour-gas compressors and require a considerable extent of treatment and cleaning.

The availability of new modern synthetics, being sufficiently heat- and chemical resistant and having perfect sliding properties made it possible to design a non-lubricated type of piston compressor. This type of compressor needs no lubrication of the cylinder space, but, sure, has other disadvantages. The quantity of leak gas which escapes to the atmosphere via the (non-lubricated) piston rod seal is by far larger than it is at oil-lubricated machines. Furthermore, even with only low requirements to maintain purity of the gas, filter systems have to be installed downstream the compressor, because abrasive particles originating from the piston rings and rod seal will penetrate into the gas. Finally, the efficiency of non-lubricated compressors is considerably lower, because the oil-film, which helps with the sealing, is missing and consequently the inner leakage increases [2].

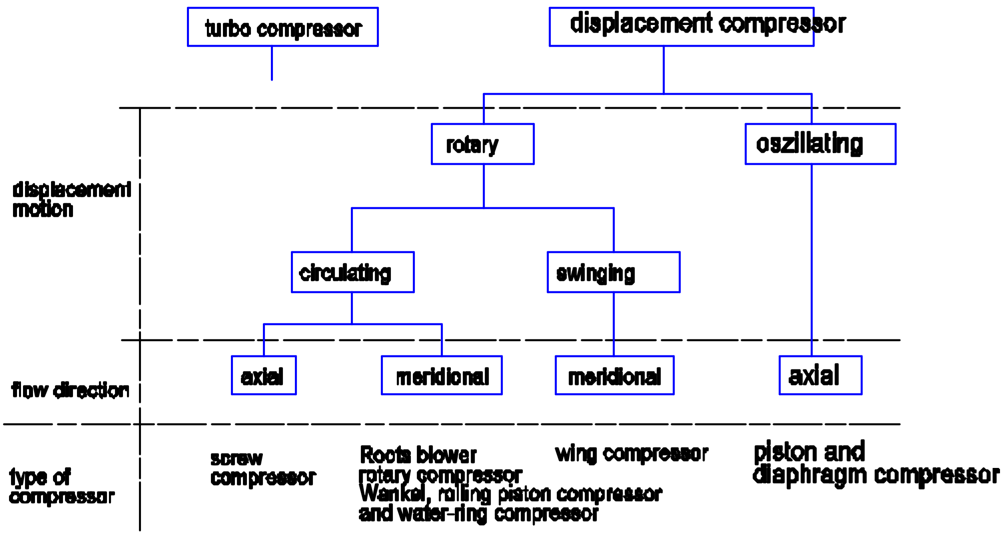


Fig. 2: Classification of compressors as per their displacement motion and flow of medium [1]

The intensive efforts to avoid all above disadvantages and to meet steadily increasing environmental and accident prevention requirements resulted in the further development of the piston compressor to a diaphragm compressor (Fig. 2). This compressor design has no sliding components in the gas chambers which need to be lubricated. Only static sealings are used which guarantee, that absolutely no leakage appears. Due to this special design,

- diaphragm compressors are hermetically sealed towards the outside. The whole compression chamber of the compressor is sealed by metallic, static sealings. Leakage rates of 10^{-4} mbar l/sec. are quite usual and are achieved without any special action; higher tightness of 10^{-8} mbar l/sec. can be obtained with special modifications in the design. These small leakage rates allow the diaphragm compressor to be used also for the "hot areas" in nuclear power plants or for the compression of highly toxic gases.

- diaphragm compressors are operating absolutely lubricant-free in their compression chamber, i.e. the process gas will not come into contact with any lubricants, and the removal of used and contaminated oils and grease is deleted. Critical gases, such as oxygen and chlorine can be compressed to higher pressures without any problem.

- contrary to other types of compressors, no abrasion occurs from piston rings and stuffing boxes. No need to provide purging or buffer gas devices at the stuffing box sealings. The process gas leaves the compressor with exactly the same purity level, as prevails at the compressor inlet. If the gas enters the machine already in a certain high quality level, it can be used directly after the process as breathing air, doting gas for semi-conductors, or as hydrogen for the fuel cell technology.

- the process gas will come into contact only with metallic materials. Depending on the type of gas and on process duties, different material qualities are at choice. When selecting the correct material, a high corrosion resistance and a long lifelength of the gas-contacted components can be achieved. The wide range of materials reaches from simple structural steel via stainless steel qualities up to high alloy special materials, such as Hastelloy.

An exception hereof is the diaphragm plate itself, which, in view of the high mechanical requirements, can only be produced from a spring-hard material of high strength and elasticity [4]:

- stainless chrome nickel steel (1.4310). This material withstands most of the chemical substances and offers very good mechanical properties. This quality meets most of the requirements and thus is most frequently used.
- special material Hastelloy and Inconell, having the highest chemical resistance.
- alloys from copper-beryllium with the best mechanical properties.
- duplex steels with the best resistance against intercrystalline corrosion.

Also for the highly loaded compressor valves, many combinations of various materials can be chosen. For the production of these valves the optimal material can be chosen depending on the operating conditions. In long years of practical experience these materials have proved their suitability (not only in diaphragm compressors). For quick-running diaphragm compressors (n > 400 1/min), often valve plates in creep-resistant synthetic material will be used, if the chemical resistance and the compression temperature will allow.

1. Design and operational characteristics

1.1 Function

The gas is compressed in a double concave chamber by an oscillating sandwich diaphragm (Fig. 3), which is hydraulically set into motion from one side. This diaphragm seals the gas chamber hermetically against the drive unit. At the periphery, it is clamped between diaphragm cover and flange with perforated plate and is set into oscillating motion by the hydraulic pressure.

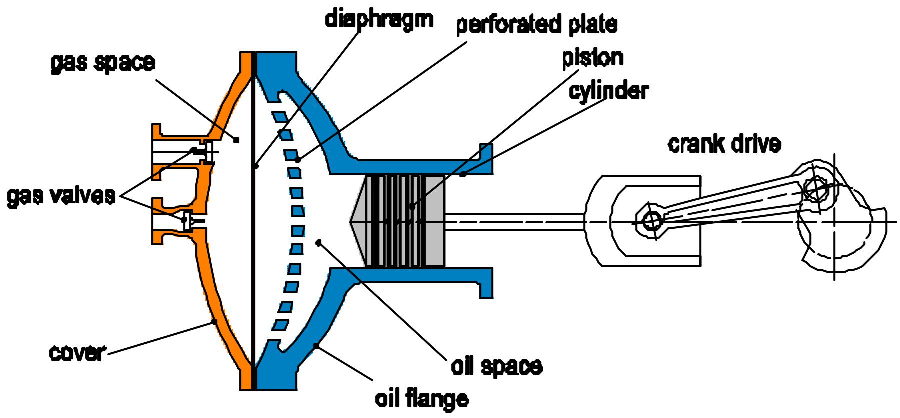


Fig. 3: Scheme of a 1 stage diaphragm compressor

The displacement of the plates causes the gas chamber between the diaphragm plate and the diaphragm cover to be enlarged resp. reduced with every cycle. With the beginning of enlarging the gas space, the gas is sucked in from the suction tube via the suction valve, which is installed in the cover and with reducing the gas space, the gas is compressed through the discharge valve - also installed in the cover - into the discharge tube.

The oil pressure, which is required for this bending movement of the diaphragm plates, is generated from the crankcase by the piston moving to and fro. This piston displacement nearly equals to the displacement inside the diaphragm head. The possibility to use the crosshead of the crank drive as piston reduces the manufacturing charges of the diaphragm compressor, however, due to the lateral forces out of thecrannk movement, it drastically shortens the lifelength of the sealing elements. For production plants wiht high availability requirements, this design should not be used.

With the compression stroke, the piston presses the hydraulic oil into the diaphragm head and there through the perforated plate to the rear side of the diaphragm plate. Hereby the diaphragm plate is bent against the concave surface of the cover. In its return movement, the piston draws the diaphragm back against the also concave surface of the perforated plate.

With one rotation of the crankshaft, the piston runs one complete stroke, so the frequency of oscillation of the diaphragms corresponds to the speed of the compressor. Medium- and large sized machines have a speed between 450 and 250 rpm ; smaller compressors with crankshafts being directly coupled to the electric motor, operate at approx. 720 rpm [4]. Due to the nearly complete compensation of the dynamic forces and moments of 1. and 2. order, all more-stage HOFER diaphragm compressors do not require an expensive foundation. Only a good bearing bottom plate is required for the installation. Upon request, 1-stage compressors can also be equipped with this mass compensation.

1.2 Design of the diaphragm head

Main components of the diaphragm head are: the diaphragm cover, the triple sandwich diaphragm, the perforated plate and the flange (Fig. 4).

The compressor valves (Fig. 5) are installed in the diaphragm cover, arranged one aside the other. They are sealed by metal sealing rings and are held by thrust pieces.

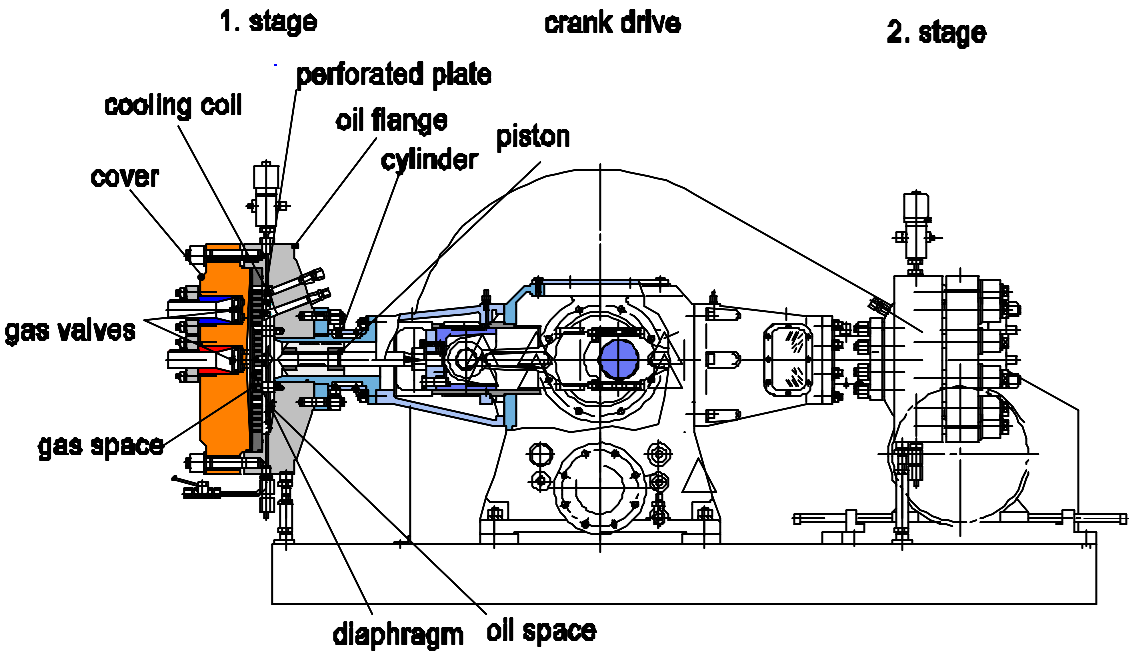


Fig. 4: Sectional drawing of a 2 stage diaphragm compressor

The diaphragm set consists of 3 separate, non-profiled plates, which are clamped-in gas-tight at the periphery between the cover and the perforated plate. Tightness towards outside is achieved by a metal 0-ring.

In this arrangement only following components of the diaphragm head are gas-contacted parts:

- the diaphragm cover,
- the gas-side plate of the sandwich diaphragm set,
- the compressor valves with thrust pieces and sealing rings,
- the metal 0-ring for sealing the diaphragms,

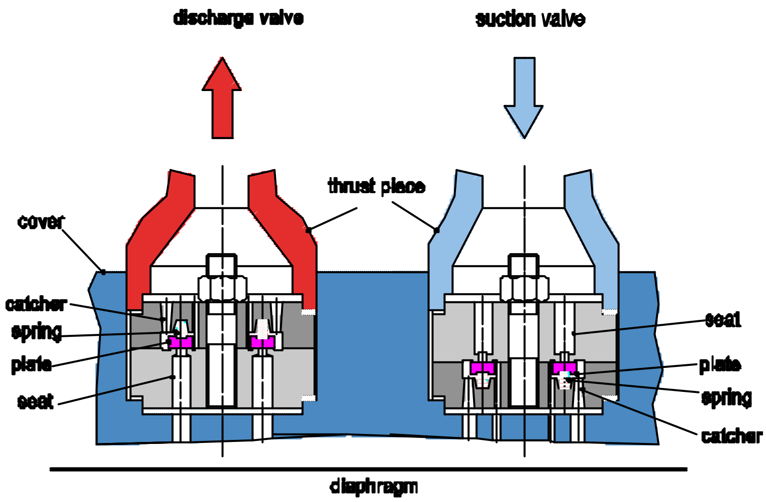


Fig. 5: Compressor valves in plate/ring design

and therefore, the exemption of leakage is easily achievable with only little expenditure. The static sealings, in particular their geometry and installation rooms, have proved best in long decades of practical experience [4]. Only the set of diaphragms, undergoing the load cycles, needs to be controlled. Such control will allow to determine the failure of one of the individual diaphragm plates early enough and to shut the compressor down in time.

1.3 Design of the hydraulic drive

The diaphragm head is screw-connected to the cylinder via the flange part. During the compression stroke, the piston, which moves to and fro inside the cylinder presses the hydraulic oil from the cylinder into the flange. There the oil flows through the perforated plate to the reverse side of the diaphragm. The perforated plate acts as distributor in order to achieve a uniform pressure load by the oil on the diaphragm plate.

With every compression stroke of the piston, a small quantity of oil creeps back at the piston sealings into the crankcase. In order to avoid that this reduction of the oil volume steadily decreases the efficiency, the leakage has to be compensated permanently.

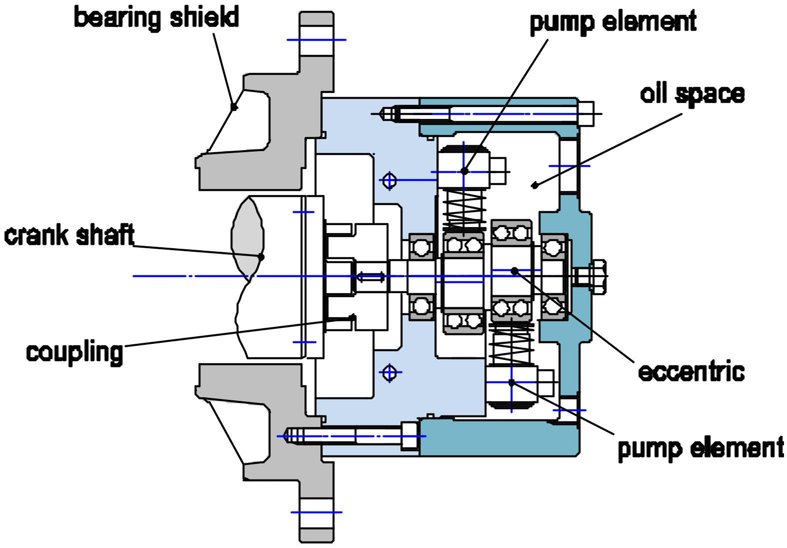


Fig. 6: Compensating pump

This is ensured by a compensation pump. This oil pump is directly driven by the crankshaft, and at every suction stroke of the piston, it is feeding a small quantity of oil into the chamber behind the diaphragm. In every case, the so injected oil quantity has to exceed the oil loss of the leakage, which means, that before the compression stroke, the diaphragm head is slightly overfilled.

The excess oil has to be removed from the system now. For this purpose, an oil overflow valve is provided at the highest point of the oil chamber on top of the flange. This overflow valve feeds back the excess oil, pumped in by the compensation pump.

When the compressor is operating with a constant or nearly constant discharge pressure, the opening pressure of this overflow valve is firmly adjusted by a pre-tightened spring (Fig. 7). In this case, the oil pressure has to be always approx. 10 % higher than the maximum allowable gas discharge pressure.

If the application of the compressor foresees a variable discharge pressure, e.g. when filling pressure vessels, an overflow valve is being used, which is controlled by the gas pressure (Fig. 8). As a function of the varying discharge pressure, the valve spring is pre-tightened by a stem and thus the oil pressure is limited to approx. 10 % above the momentary gas pressure. This ensures, that the oil pressure is steadily adapted to the slowly increasing gas pressure; a measure which contributes to increase the life length of all components, since it avoids to overload the compressor by operating it over a longer period with a an unnecessarily high oil pressure.

With the forward movement of the piston - already before reaching the front dead point - the diaphragm is pressed against the diaphragm cover; the oil quantity which is compressed with the remaining stroke of a few millimeters flows back through the oil overflow valve into the oil tank. Simultaneously, all air will be entrained, which has gathered at the highest point from de-gasing of the hydraulic oil, and thus is reducing the efficiency of the compressor.

The excess oil quantity flows into the surge oil tank, where it degases and from where also the compensation pump sucks in oil. This particular arrangement ensures, that the hydraulic system is always filled up to the optimum oil quantity and that the oil chamber is totally air-bleeded.

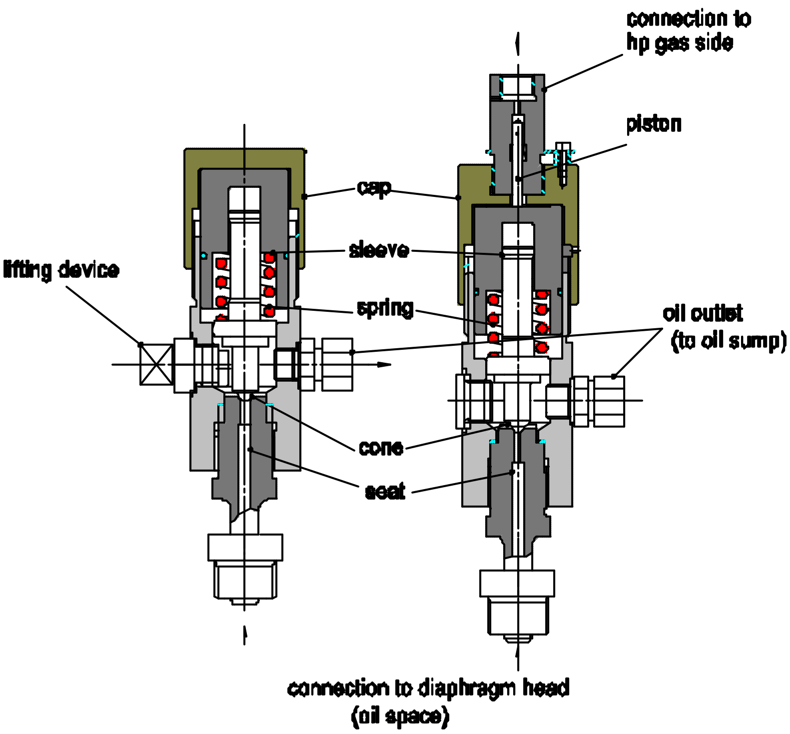


Fig. 7: Spring loaded overflow valve *Fig. 8: gas loaded overflow valve*

In middle and larger sized diaphragm heads, the hydraulic oil needs to be cooled. By means of a cooling water coil, already a part of the compression- and friction heat is emitted.

Special types of mineral oils are used as hydraulic medium; at the same time, these oils serve for lubrication of the crankcase. These oils have to meet following requirements:

- high lubricating properties
- compressibility
- reduced tendency to foaming
- highest possible viscosity

For special applications and duties, different hydraulic media have to be used, such as e.g. special synthetic oils or water with rust inhibitor (the latter requires a separate loop of crankcase lubrication) e.g. for high pressure oxygen compressors.

The use of these special hydraulic media is just a precautionary measure. Even in case - which is extremely unlikely - that the complete diaphragm set fails at the same time and thus hydraulic medium comes into contact with the process gas, the burning-out is avoided.

1.4 Multistage design

Should a one-stage compression not be sufficient, 2 diaphragm heads are connected in serie with an interstage gas cooling. In this case, a 2-crank duplex or boxer crankcase with single-acting cylinder (Fig. 9).

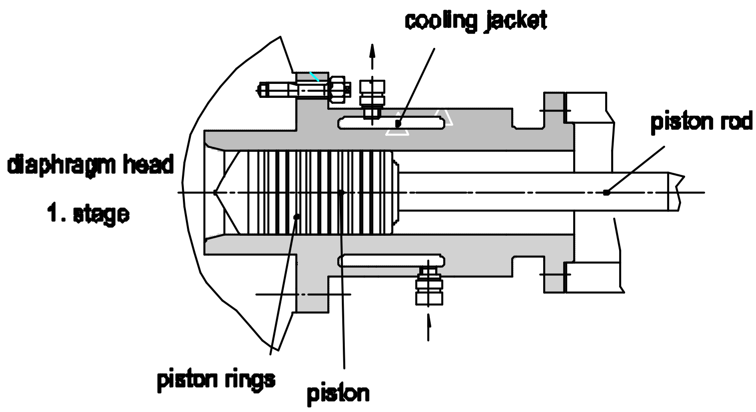


Fig. 9: Single action cylinder for 1 & 2 stage compressors

For 3-stage (and 4-stage) compressors, a boxer crankcase is provided. Here, the piston of one crankcase side (or of both sides at 4-stage compressors) will be designed as stage pistons (Fig. 10). The differential surface, which is originated from this, the hydraulic pressure for the diaphragm head of the next higher stage will be generated. E. g. thus, at the pressure stroke of the 2. stage the 3. stage carries out a suction stroke.

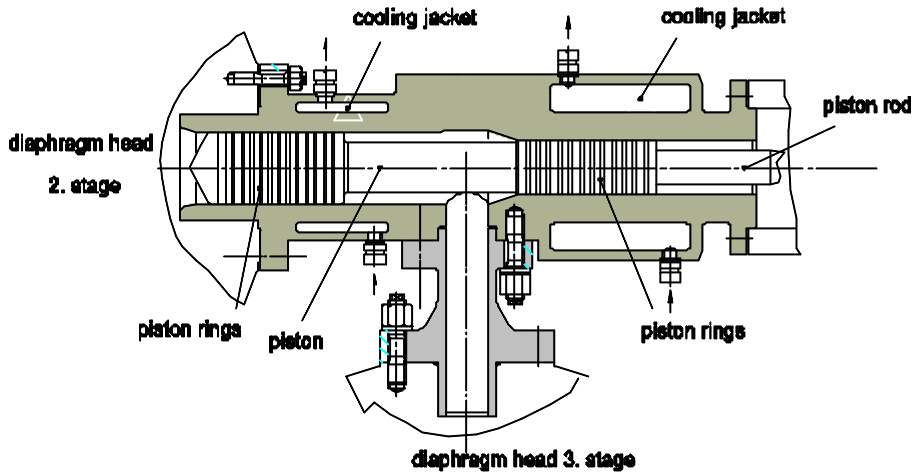


Fig. 10: Double action cylinder for 3 & 4 stage compressors

2. Thermodynamic and design

The exact design of the compressor guarantees a high efficiency, long service life of the individual components and consequently a high reliability and availability of the machines.

In order to meet the intended duty, the compressor has to be designed exactly in accordance with the technical parameter pre-determined by the end-user. Only this will ensure, that the compressor complies to the technical requirements and also meets economical expectations.

Following parameter must be known for designing a diaphragm compressor

- type of gas (also specific gas data)
- requested, resp. desired suction volume
- suction- resp. inlet pressure

- discharge pressure
- gas temperature at suction socket

Based on these gas data, the effective suction volume (related to suction pressure and - temperature) is calculated by means of the equation of state.

The total pressure ratio of discharge pressure versus suction pressure determines the necessary number of stages and herewith the interstage pressure ratio of the individual compression stages of the compressor. Depending on the type and quantity of gas, diaphragm compressors allow a stage pressure ratio of up to 1 : 20 (compared hereto for piston compressors, the max. ratio is 1: 6). The stage pressure ratio is limited by the allowable gas temperature at the end of the compression (max. however 250 ^{0}C) and by the clearance. Since, at the end of the compression stroke, the diaphragm is pressed to the cover, no dead space will result here and only the clearance in the compressor valves and in the valve pockets has to be taken into account for designing. The gas compression is very close to the ideal isothermic curve, because of the good thermodynamic conditions caused by the excellent emission of the compression heat to the atmosphere via the large diaphragm cover and by the gas cooling, which is already effected during the compression by the cooled hydraulic oil (very good heat flow via the thin diaphragm plate).

Fig. 11 shows the pV-diagram of a compressor.

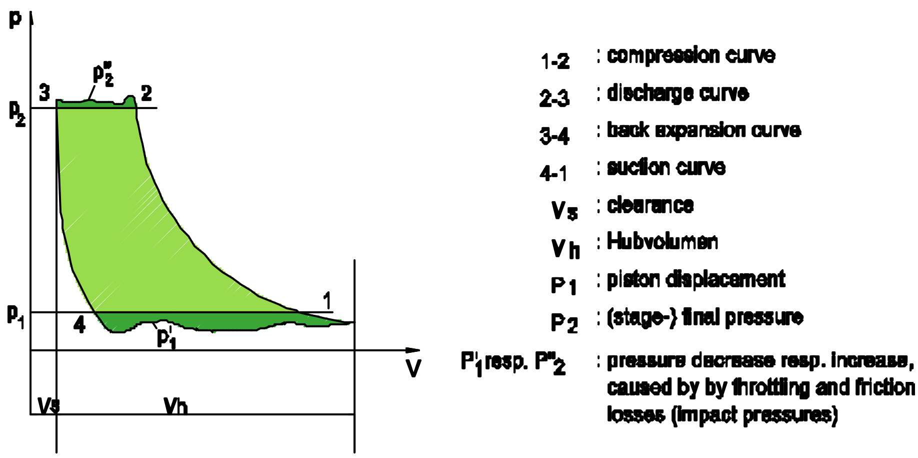


Fig. 11: p, v diagram

2.1 Determination of the main dimensions

The necessary piston displacement of the first stage is dependent on:

- the pre-determined suction pressure
- the pre-determined requested suction volume
- the pre-determined suction temperature
- the deviation from the perfect gas law, applicable to the type resp. mixture of gas to be compressed
- the isothermic efficiency

Should a further compression stage be necessary for the total gas pressure ratio, an interstage cooling is provided behind the 1. stage. If the gas contains condensing particles, the condensate has to be drained by interstage separators.

The piston displacement of the second stage is determinated in the same way, however, under consideration of the discharge pressure 1. stage and the calculated gas temperature prevailing at the outlet of the interstage cooler.

2.2 Efficiency

The efficiency determines the efficient operation of a compressor and thus also its economical rentability [3]. Due to the above mode of operation, which is dose to the ideal compression curve, a diaphragm compressor has a high efficiency. Depending on the suction pressure and on the medium to be compressed, efficiencies between 80 and 85 % are achieved (compared hereto, 65 to 75 % at non-lubricated piston compressors) [1].

2.2.1 Volumetric efficiency (feeding)

The volumetric efficiency is defined as effective suction volume / piston displacement. It is dependent on:

- the back-expansion of the gas, compressed in the clearances
- the sub-expansion of the gas during suction
- increase of discharge pressure, resp. decrease of suction pressure, caused by impact pressures in the discharge and suction socket
- heating-up of the gas, when entering the warm diaphragm head

2.2.2 Indicated, isothermic efficiency

The isothermic efficiency takes into account the flow- and heat losses, as well as the volumetric losses, mentioned in 2.2.1, however, the heat losses are having the higher influence on the isothermic efficiency. lt. is defined as:

$$h_{isi} = \mathbf{P}_{isothermic} / \mathbf{P}_{indicated}$$

where h_{isi} = indicated isothermic efficiency

$\mathbf{P}_{isothermic}$ = required power to achieve the (ideal) isothermic efficiency

$\mathbf{P}_{indicated}$ = required power to achieve the real compression

2.2.3 Mechanical and hydraulic efficiency

All mechanical and hydraulic losses are taken into account by these efficiencies. The hydraulic efficiency specifically applies to diaphragm compressors and considers the losses of oscillating oil quantities as well as the leakages which are lost via the piston rings.

2.2.4 Actual isothermic efficiency

The actual isothermic efficiency comprises all losses of the compressor and thus indicates the total losses as:

$$h_{ise} = h_{isi} * h_{mechanical} * h_{hydraulic}$$

The quality of the compressor is determined by this efficiency.

3. Supervision of the diaphragms

The metal diaphragms, depending on the operating conditions and when working with dean gas, uncontaminated by foreign partides, will reach a service life of approx. 3000 to 5000 hours. The larger lifelenghts are reached at continuous operation (24 h), the lower ones at intermittant service.

In order to guarantee, that the diaphragm compressor remains free from any leakage, even if one of the diaphragm plates fails, these wear parts have to be supervised.

The system of using triple sandwich diaphragms and to connect a failure indicator avoids, that gas will penetrate into the hydraulic part, or oil into the gas part respectively, in case of a failure of one of the individual diaphragms.

The sandwich diaphragm consists of 3 superposed diaphragm plates, of which the middle plate is slotted. (Fig. 12). In case, one of the diaphragms, either on oil side or gas side,

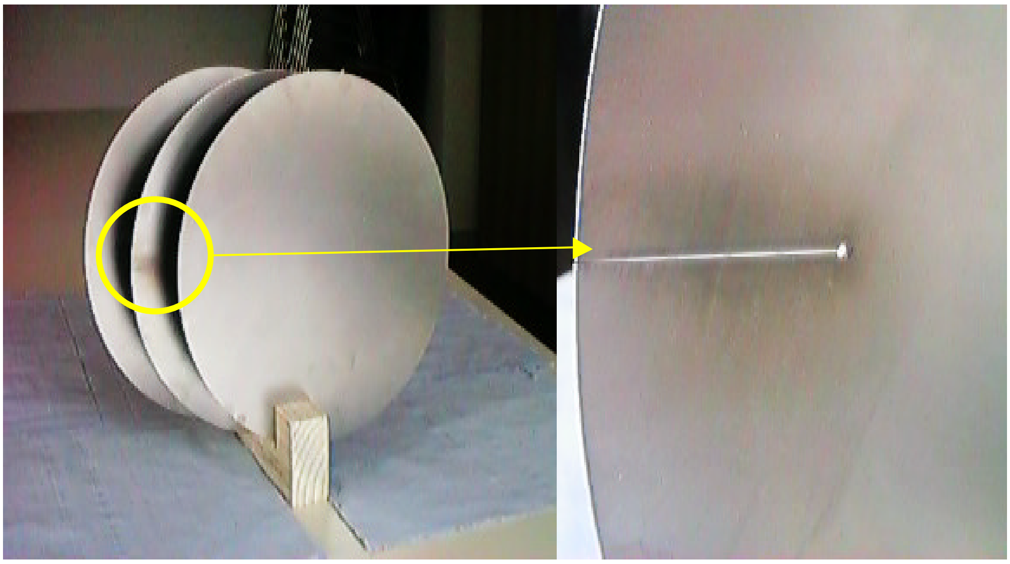


Fig. 12: Sandwich diaphragm with slotted centre plate

fails, the corresponding medium penetrates between the gas-side and oil-side diaphragm, which will pressurize the chamber between the plates.

A pressure switch (Fig. 13), being connected to this chamber, and / or a contact pressure gauge will stop the compressor. This ensures, that gas and oil will never come into contact with each other, or that gas escapes to the atmosphere through the open hydraulic system downstream the overflow valve.

Since it is almost impossible that the oil-side and gas-side diaphragm will reach the limit of their service life and will break at the same time, this type of supervision is extremely reliable. It is even possible to continue to operate the compressor for some hours with one diaphragm broken, so to be able e.g. to shut down the whole production unit correctly (if no stand-by compressor is available).

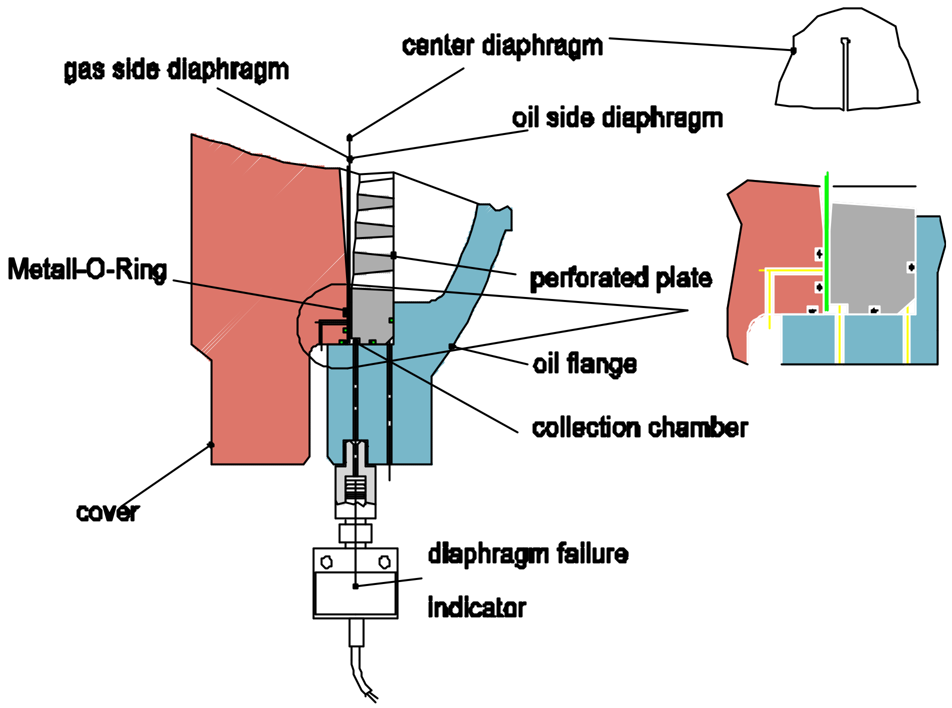


Fig. 13: Diaphragm failure indicator with pressure switch

4. Types of construction

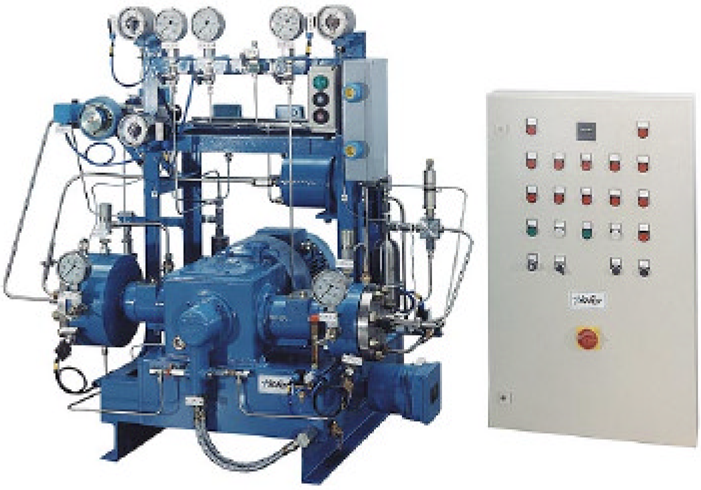
Diaphragm compressors are preferably of the horizontal design. Vertical diaphragm compressors require less space for installation, however, they have the disadvantage of an insufficient air-bleeding, as the overflow valve cannot be mounted at the highest point of the hydraulic system. Furthermore, maintenance can be somewhat problematic, because the diaphragm head may possibly be arranged in 2 meters' height.

The crankdrives enable a nearly complete compensation of the free mass forces. For the installation of such compressors, no foundation is required, a good bearing bottom plate is suifficient.

The following pictures show the different types of diaphragm compressor designs and sizes.

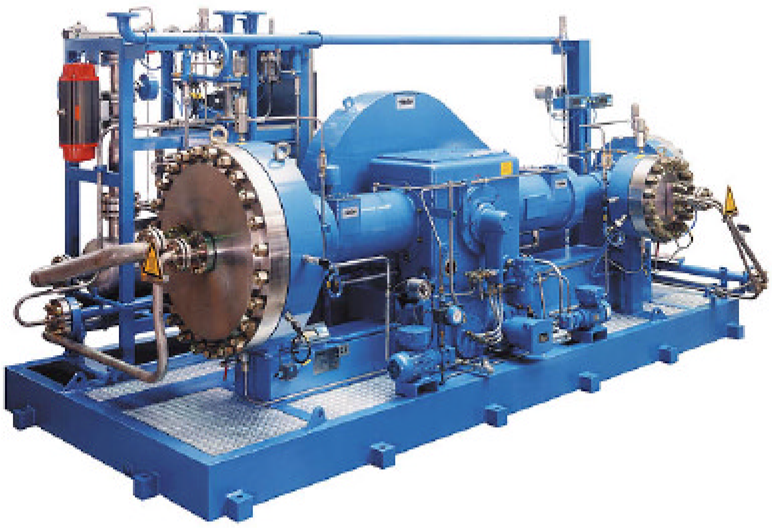
Picture 14:

Type:	*Diaphragm Compressor MKZ450-10/280-25*
No. of rev.:	*460 rpm*
Stages:	*2*
Medium:	*high purity Hydrogen*
Suction press.:	*10-14 bar abs*
Disch. press:	*251 bar abs*
Capacity:	*142 m^3/h (VN)*
Motor power:	*33 kW*
Execution:	*ready for operation*



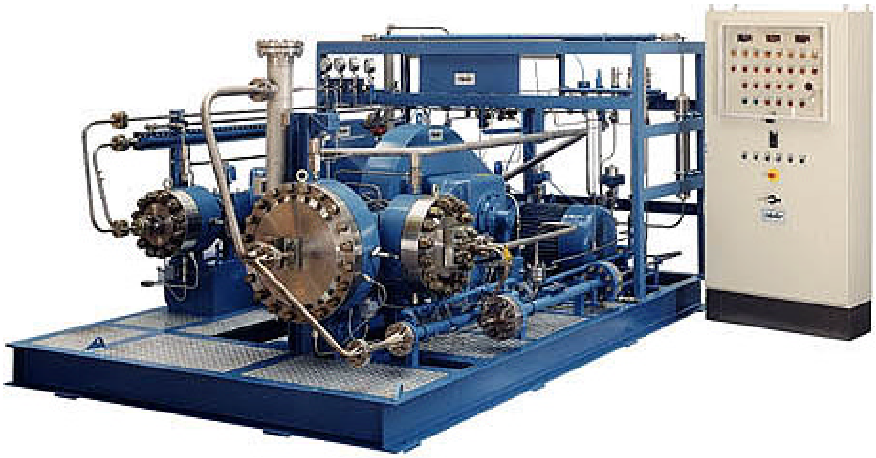
Picture 15:

Type:	*Diaphragm Compressor MKZ185-5/120-15*
No. of rev.:	*720 rpm*
Stages:	*2*
Medium:	*Hydrogen*
Suction press.:	*5 bar abs*
Disch. press:	*151bar abs*
Capacity:	*5,5 m^3/h (VN)*
Motor power:	*2,6 kW*
Execution:	*ready for operation*



Picture 16:

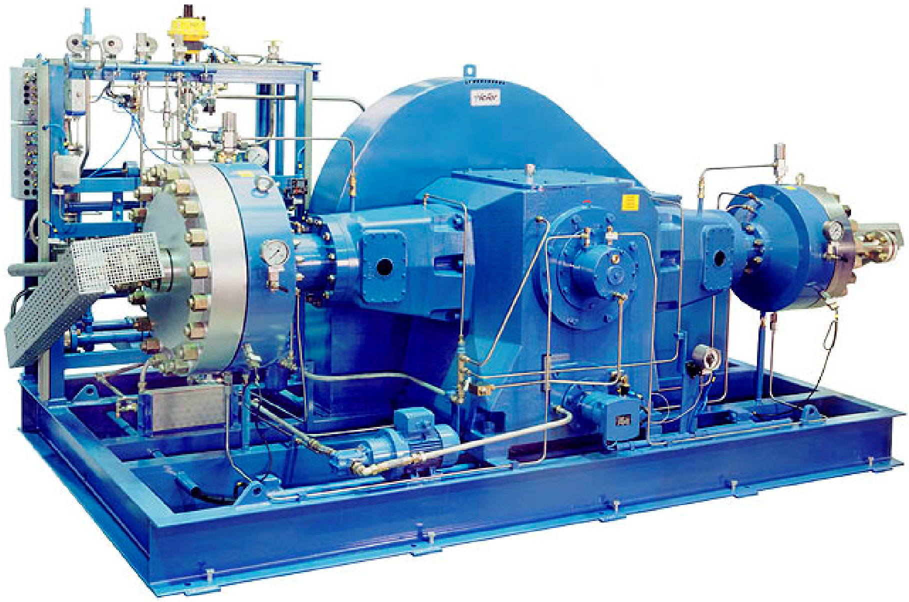
Type:	*Diaphragm Compressor MKZ800-5/470-10/315-25*
No. of rev.:	*360 rpm*
Stages:	*3*
Medium:	*high purity Hydrogen*
Suction press.:	*5 bar abs*
Disch. press:	*201 bar abs*
Capacity:	*250 m^3/h (VN)*
Motor power:	*68 kW*
Execution:	*ready for operation*



Picture 17:
Type: Diaphragm Compressor MKZ450-10/280-25 & MKZ200-70
2 compressors (pre compressor and booster) on one common base plate

No. of rev.: 380/350 rpm
Stages: 3
Medium: Ar/O_2 mixture
Suction press.: 8,3 bar abs
Disch. press.: 621 bar abs
Capacity: 142 m^3/h (VN)
Motor power: 44/14,7kW
Execution: ready for operation

Picture 18:
Type: Diaphragm Compressor MKZ280-10/185-25/120-100
No. of rev.: 400 rpm
Stages: 3
Medium: Hydrogen
Suction press.: 8 bar abs
Disch. press.: 801 bar abs
Capacity: 20 m^3/h (VN)
Motor power: 11 kW
Execution: ready for operation



Picture 19:
Type: Diaphragm Compressor MKZ680-10/450-40
No. of rev.: 360 rpm
Stages: 2
Medium: Hydrogen
Suction press.: 18 bar abs
Disch. press: 281 bar abs
Capacity: 580 m^3/h (VN)
Motor power: 135 kW
Execution: ready for operation

5. Application and operation

In all sectors of gas compression, diaphragm compressors gained a firm place because of their operational advantages. Wherever flammable, explosive, radioactive or toxic gases, or gases of highest purity have to be compressed, where particularly stringent measures have to be taken into account for environmental protection, they often considerable advantages compared to the classic piston-type compressor. Diaphragm compressors meet the rigorous requirements of the food-, pharmaceutical- and nuclear industry.

For the different applications, following adequate conceptions are available

- basic compressors, they are compressing gas, one- or multi-stage, from a relatively low suction pressure to a higher discharge pressure.
- booster compressors, they are compressing from a high suction pressure to a still higher discharge pressure.
- transfer compressors, they are pumping gas from one tank into another. Significant for this machine type is the decreasing suction pressure at simultaneously increasing discharge pressure.
- circulators, these are under a higher static pressure and are feeding gas within a system in a loop circuit. In these cases, the difference pressure between suction- and discharge pressure is normally not very high.

5.1 Control unit

Start and stop of a diaphragm compressor system should preferably be done by an automatic control unit. The actuation of the valves pertinent to the compressor, such as inlet-, outlet-, relieve-, and bypass valve (starting bypass) has to be effected in a timely adjusted sequence. In view of safety aspects of the system, this is of particular importance for compressors used in production systems (Fig. 20).

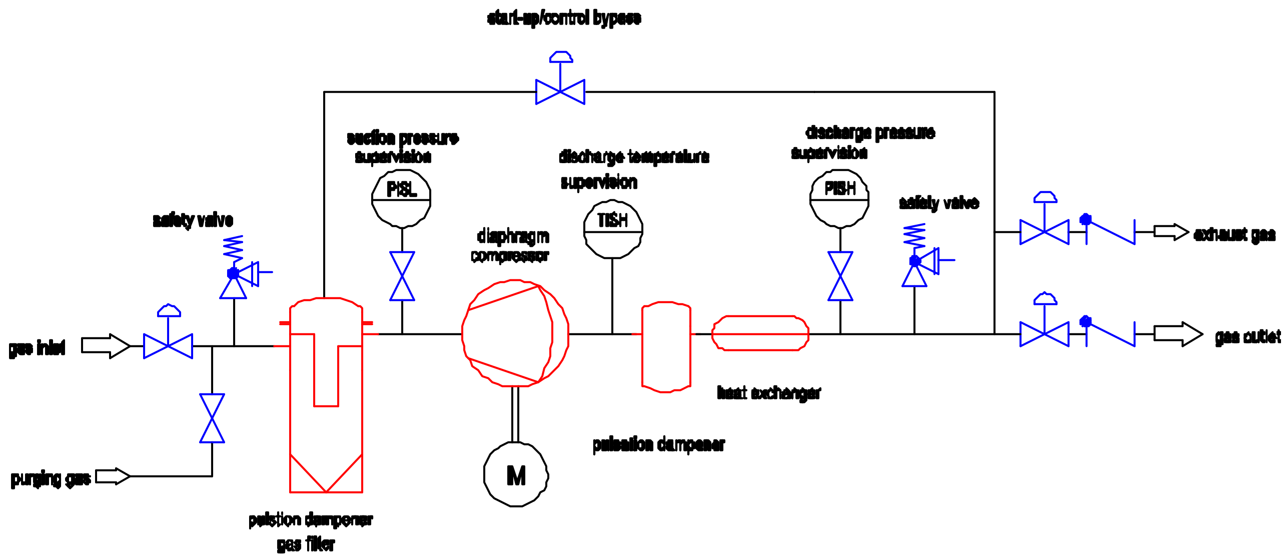


Fig. 20: simple P&ID

5.2 Drive mechanism

Larger-sized diaphragm compressors are nearly always motor-driven by asynchronous motor via V-belt transmission. The drive pulley on the crankshaft of the compressor is designed as flywheel. Smaller-sized compressors can also be directly coupled to the motor shaft.

5.3 Capacity regulation

According to the specified theoretical data, the compressor capacity can be regulated either manually or automatically via a speed-variable drive or via a bypass system. Single-stage diaphragm compressors can also be regulated in capacity by adding the clearance volume. The classic type of regulation, i.e. via valve lifts, is not applicable for diaphragm compressors.

6. Operational safety

Diaphragm compressors, same as any other machine or instrument, have to be carefully incorporated into the safety philosophy of the complete unit. The basic safety requirements are specified in the European directive for machinery 98/37/EC (which has force of law in EC countries). A compressor, built ready for operation, gets the CE-mark, and the compliance of its design and construction with the directive for machinery is attested in a certificate of conformity. If only a ,,bare" compressor without accessories and control unit is supplied, it is accompanied by a manufacturers certificate of the delivered scope.

In any case, the operator of the plant or his authorised representative is obliged to carry out a HAZOP-analysis. Such analysis has to specify all hazards, which may originate from the compressor, e.g. due to failures at the compressor itself, failures at upstream and downstream components, or due to mishandling. Hazardous operations have to be avoided by taking suitable preventive measures.

The DIN EN 1012 - standard, valid for compressors, and other technical regulations covering the actual state of technology are stipulating, that the compressor is stopped immediately in case, the operational situation becomes critical. In addition to the diaphragm failure indicator, typical for the described type of diaphragm compressor, and depending on possible hazards originating from the compressor (high pressures, large flows, dangerous process media), following supervising instruments have to be provided:

- limit switch and indicator for suction pressure and -temperature
- limit switch and indicator for interstage pressure and -temperature
- limit switch and indicator for discharge pressure and -temperature
- safety valve for each stage

Further monitoring instruments, such as

- flow switch to avoid cooling water shortage
- flow switch to avoid hydraulic oil shortage
- differential pressure gauges for filters
- vibration control

are often requested by the customer to get additional equipment for increasing the operational safety.

Increasing rationalisation in most companies requires more and more a fully automatic control of the compressor. The conventional way of a relay control is steadily losing importance and is mainly replaced by the PLCs, the programmable logic controls. The PLC is flexible and can easily be incorporated via various bus systems into a modern process control systems.

7. Summary

Diaphragm compressors are in use for decades already in industrial application and there they meet the specified demands for operational safety, availability and economical efficiency.

When designing production plants, they help to comply with environmental requirements, they simplify production processes, where the purity of the compressed gas is an important factor and their very smooth running is a special merit.

Their figures of suction capacities cover the range of some litres / hour up to several 100 m^3/h. Discharge pressures of up to 3000 bar can be achieved with diaphragm compressors.

Literature:

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