

Evolution of compressor valve technology



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Introduction

It is generally well known that piston compressors have suction and discharge valves. How they work and the developments in this field are often not known. The aim of this article is provide more insight into this. The first part of this article describes the construction and operation of the valves. After an explanation of the design requirements, we will go into a few important developments in more depth, developments that further improve the reliability and efficiency of Grasso piston compressors.

A. The construction and operation

Compressors take care of the gas flows to and from the cylinder area. Figures 1a and 1b show the compression process with the corresponding gas flows. The whole process takes place in one revolution of the crankshaft. When the piston moves downwards from the top dead centre (TDC), the remaining gas expands in the clearance volume. When the pressure of this remaining gas drops to a little below the suction pressure, the suction valve opens and suction gas is sucked in from the suction chamber around the cylinder. At the top dead centre (TDC) the suction valve closes and compression starts. When the gas is compressed to just above the condenser pressure, the discharge valve opens and starts expelling to the discharge area above the cylinder. The expulsion ends at the TDC.

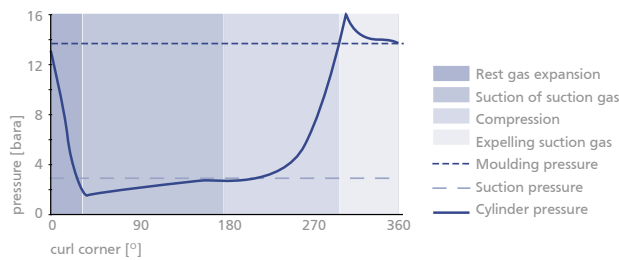


Figure 1a The compression process

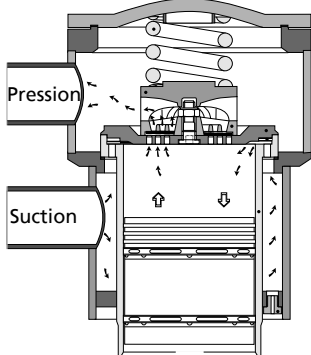


Figure 1b Gas flowing around the cylinder.
Right: suction. Left: expulsion.

In contrast to engine technology, compressor valves work on pressure difference, because the timing of opening and closing depends on the pressure ratio. If the pressure below the valve is greater than the pressure above the valve plus the spring force, it opens. In brief: the valves function as spring-loaded non-return valves, with the gas only being able to flow in one direction through them.

Deciding which type of valve to use is determined mainly by the swept volume of each cylinder and the revolutions.

Small commercial cooling compressors, characterized by low cylinder volume and a high revolution speed, often use finger valves. Large, slow-running double-action process compressors often use plate valves. Finger valves have insufficient flow capacity and plate valves are too slow for industrial cooler compressors. That is why ring valves are often used in industrial cooler compressors.

Figure 2 shows the construction of a cylinder head with ring valves. Note that the suction valve ring only has single flow around, while the discharge valve ring has double flow.



- 1 suction valve ring
- 2 suction sinusoidal spring
- 3 valve plate
- 4 discharge valve ring
- 5 discharge valve sinusoidal spring
- 6 stroke limiter
- 7 liquid return protection

Figure 2:
Construction of a cylinder head
with ring valves

B. General design requirements

Valves are essential to the operation of the compressor; that is why the reliability and efficiency must meet stringent requirements. In addition, valves are expected to function well over a wide area of deployment. Consider the variation in suction and discharge pressure, revolution speeds and different types of refrigerant. All these factors influence the gas density and speed.

A valve design is therefore actually a satisfactory compromise between conflicting requirements. On the one side increasingly longer service intervals, higher reliability and high efficiency are demanded, while on the other side the design must resist higher speeds of revolution, higher pressures and higher gas densities at the same time.

It is essential that the development of valve technology is given continual attention to be able to meet these increasing and sometimes contradictory demands. In addition you also see more and more different models of valves in practice, to optimize the efficiency and the lifetime.

C. Developments to increase reliability

In practice, the load on a valve is impact speed and flexural strain. When it opens, the valve collides with the valve lift limiter, and when it closes it hits the valve seat. In addition, the spring, but to a lesser degree also the valve ring, is under strain of bending. This is caused by forces of gas, spring and acceleration. These acceleration forces are extremely high; they will be discussed in more detail later.

The Robustness Safety Margin (RSM) is a good indicator of the reliability and lifetime of a valve design. It is defined as the difference between the maximum allowable impact speed of the design and the maximum impact speed occurring in practice. That is:

$RSM = \text{max. allowable impact speed of the design} - \text{max. impact speed in practice}$

Figure 3 shows an example of a valve improvement from the late 1990's for the Grasso 6 series.

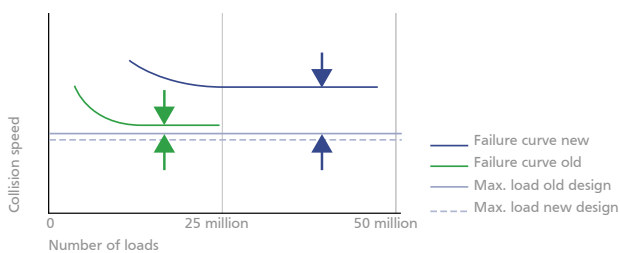


Figure 3: RSM comparison of suction valve of new and old design of Grasso 6

So there are two ways to improve the RSM

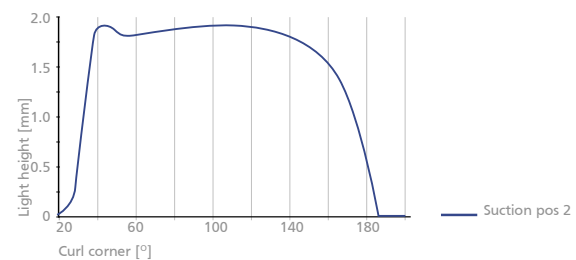
1. reduce the maximum occurring impact speed in practice.

To achieve a low impact speed, the flow capacity of the valve design must be sufficiently large. Then the valve movement can be optimized by tuning the lift height, spring force and gas damping.

At Grasso this is done by means of real-time valve lift measurement with "lichtleiters". This logs the valve lift at a frequency of 20,000 Hz. Figure 4 shows an example of a measured valve lift.

Figure 4: Example of a suction valve lift

The valve opens in about 10 crankshaft degrees. That



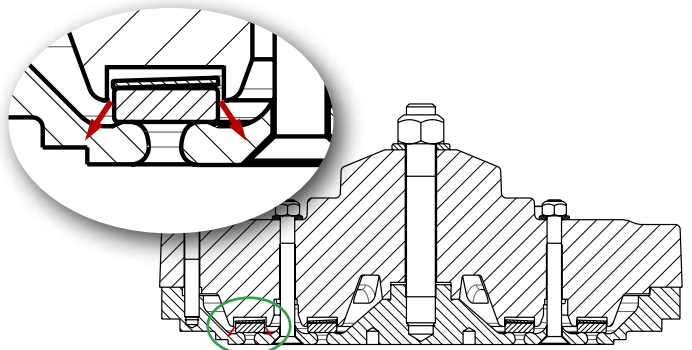
means that the valve accelerates from zero to its maximum speed and back again to 0 m/s in about 1 ms. The average acceleration is 800 times gravitational force.

Because the valve slows down, the maximum speed upon opening is not the same as the impact speed during opening. Among other things it is the gas damping that ensures this; figure 5 shows its principle of operation. The gas between the valve and the stroke limiter is driven out through the splits. Upon closing, the impact speed is the same as the maximum closing speed.

Figure 5: principle of gas damping during valve opening

2. increase the maximum allowable load of the design

This concerns the quality of the design and that of the



selected materials.

Due to the significantly higher allowable load, Grasso is the first to have chosen definitively for Polyether Ether Ketone (PEEK) as valve material instead of steel.

With PEEK it is possible to increase the thickness of the valve ring while the weight remains the same, so the valve ring becomes stiffer and more robust. In addition, PEEK has many better elastic and damping properties. They greatly reduce the impact load, making the allowable impact speed considerably higher. The allowable impact strain of PEEK is twice as high as that of steel: 4 m/s versus 2 m/s. An additional advantage of the damping/elastic properties is that the compressor becomes significantly quieter.

After introducing valve designs specifically aimed at PEEK valve rings, Grasso has finally been able to make full use of these advantages.

The robustness of the sinusoidal springs has been increased by applying spring steel with a greater fatigue strength.

Beside the use of better materials, robustness can also be increased by lower load. A good design does not have any high local peak loading of parts. In addition, the load must be divided so that the weakest part is spared. This can be found in the design in the relatively wide seats, the robust dimension of valve rings and sinusoidal springs and the rounding used.

Contact surfaces may not have any sharp edges or transitions. If required, contact surfaces are hardened. If this is not done, the valve fails prematurely due to fatigue or excessive wear.

D. Improvement of efficiency through reduction of flow resistance

When gas flows through a valve, it meets resistance, or pressure loss.

A good design limits this pressure loss, for the following reasons:

- To obtain a higher energy efficiency.
- To reduce the impact speed during closing.
- To increase the resistance against high gas densities (high pressures, heavy refrigerants).

On the basis of Bernoulli's principle, the stationary mass flow can be approached by:

$$\dot{m} = A_{\text{eff}} \sqrt{2\rho_u(p_u - p_d)} \quad \text{with} \quad A_{\text{eff}} = \frac{A_0}{\sqrt{\zeta}}$$

where

\dot{m}	= mass flow [kg/s]
ζ	= valve resistance coefficient [-]
p_u	= upstream pressure [N/m ²]
p_d	= downstream pressure [N/m ²]
ρ_u	= upstream gas density [kg/m ³]
A_0	= geometric flow surface area [m ²]
A_{eff}	= effective flow surface area [m ²]

The formula shows that there are therefore two ways to limit flow losses:

1. More flow surface area A_0

- Increase the effective seat length.

The seat length is determined by the dimensions of the valve ring and the number of valve rings. The percentage that is effective depends on the possible gas flow to and from the seat. For suction valves, where only the internal diameter is effective, the effective seat length is therefore less than 50%. Increasing available seat length is the best way to create flow surface area. This is because when the valve starts opening, more flow surface area is immediately released. In addition, there is no risk of unstable valve behaviour, because it is independent of the lift height of the valve.

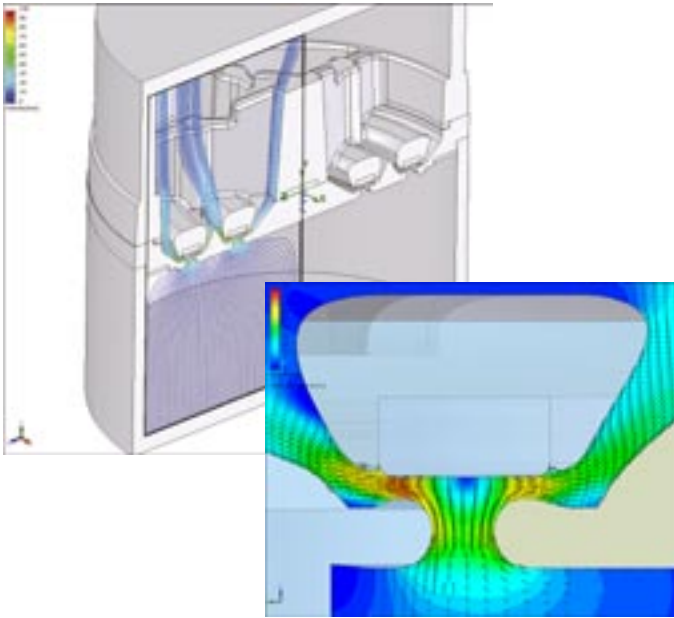
- Increase lift height

The effect of increasing the lift height is limited. Excessive lift height does not provide much extra flow capacity and creates the risk of unstable valve behaviour (consider premature closing and reopening).

2. Reduce the resistance coefficient by ζ shape optimization

The availability of Computational Fluid Dynamics (CFD) software makes it possible to calculate the flow resistance. This means the valve geometry can be optimized so it has a minimum flow resistance. During the flow optimization iron has to disappear, to create more space for gas flow. Finite Element Modelling (FEM) can be used to calculate the distortion and tension of parts and to optimize this.

Figure 6. Examples of flow calculations



E. Example of the valve evolution of the Grasso 12

In figure 7 we compare a discharge valve with steel valve rings with a recent PEEK discharge valve design. A number of matters strike the eye immediately.

- Narrow and thin steel valve rings have made way for wide, thicker PEEK rings.
- The shape and the size of the stroke limiter have been drastically changed. This stroke limiter has evolved into the central part that positions all components and determines the strength and stiffness of the design.
- In the steel design, the gas flows through drilled holes in the valve plate. In the latest design, the shared valve plates hang on the stroke limiter, so the flow can pass unhindered through the valve plate.
- Two large valve rings have been used instead of three small valve rings close together. Now it is impossible for the one valve ring to disrupt the flow of the other valve ring.
- And finally, what catches the eye is the shape of the channels that is much smoother and tapers more gradually. This lowers the flow resistance.

Conclusion

To meet the increasingly high demands made of cool compressors in terms of lifetime and efficiency, it is necessary to pay continual attention to the continuous development of essential parts such as valves. The use of the unique properties of technical plastics such as PEEK and the modern design tools such as FEM and CFD calculations have enabled a great step forward

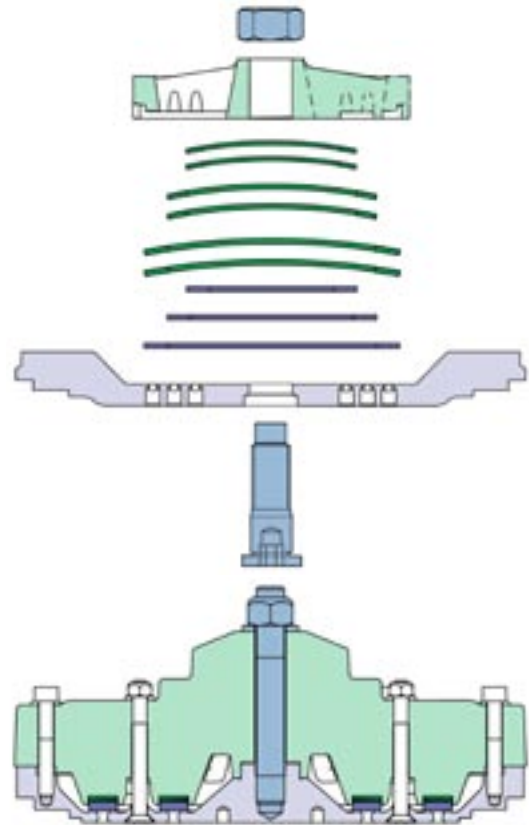


Figure 7. Top, original steel valve design. Bottom, latest PEEK valve design.

to be made in valve development.

Grasso's definitive choice of PEEK and continual attention to valve development have finally got an evolution of the valve design going. The advantages will eventually be translated into a lower "Total Cost of Ownership". This has been realized on the one hand by lower energy use and on the other hand by longer tool life of parts, so longer service intervals.

Next month the Grasso article will discuss Indirect systems. If you would like to react to this article or one of the previous articles, or have questions, you can contact: Grasso Products b.v., Jan-Pieter Habraken, tel: 073 6203 845, jphabraken@grasso.nl.