Design of Valves Used in Reciprocating Compressors

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Abstract: - This paper presents the critical points in designing of valves used in reciprocating compressors. The design is focused in valve type, dimensioning of the main elements and materials choice. There are presented the results obtained in CFD of valves and the method of computing the centreline diameter of the valve rings and seats to compensate the thermal expansion during operation in compressors.

Key-Words: - valve, reciprocating compressor, fluid dynamics, FEA

1 Introduction

Designing and implementing valves to improve efficiency and reliability of reciprocating compressors can be complex due to the many paramaters that can affect performance. A designer must understand the flow of gas through the valves, the way the valves operate in the compressor and how reliability can be affected under a wide range of different gases compositions and operating conditions.

A reciprocating compressor or piston compressor is a compressor that uses pistons driven by a crankshaft to deliver gases at high pressure. Reciprocating compressors are typically used where high compression ratios (ratio of discharge to suction pressures) are required per stage without high flow rates, and the process fluid is relatively dry. The reciprocating compressors (fig. 1) are standardized in API 618: Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services. Arrangements may be of single-or dual-acting design.

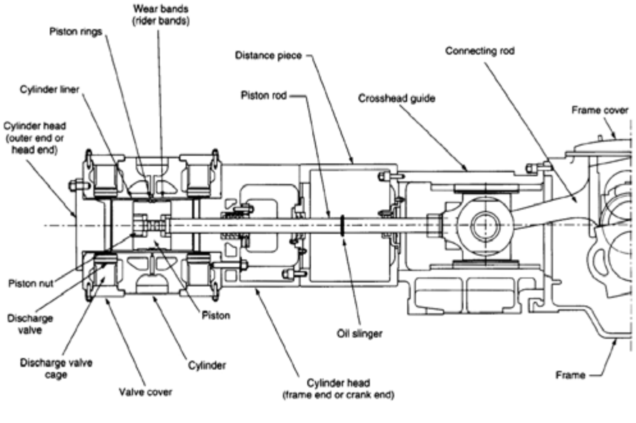

Fig.1 Reciprocating compressor section view [1]

2 Valve types

Valves are crucial components of reciprocated compressors. There are three kinds of valves that are used in reciprocating compressors: poppet valves (fig. 2), plate valves (fig. 3) and ring valves (fig. 4).

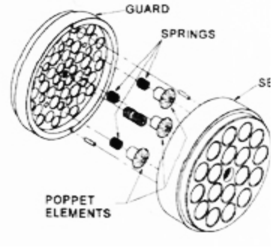

Fig.2 Poppet valve

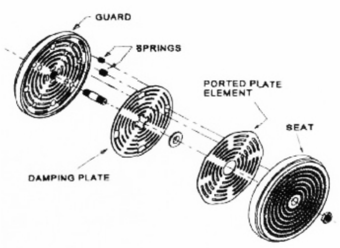

Fig.3 Plate valve

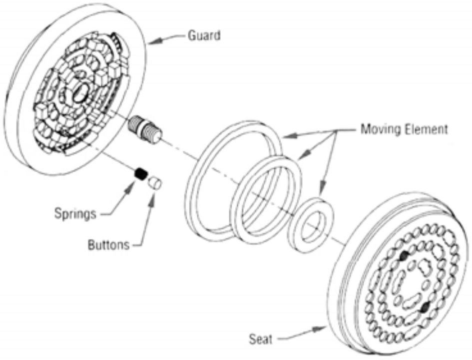

Fig.4 Ring valve

The choice of valve type is according the work conditions [2]. Poppet valves are recommended up to 15 MPa differential/30 MPa discharge pressure and 600 rpm. Plate valves are recommended up to 20 MPa differential/40 MPa discharge pressure and 1800 rpm.

Ring valves are recommended up to 30 MPa differential/60 MPa discharge pressure and 600 rpm.

Ring valves have balanced flow through the seat, lift and exit areas, creating a lower pressure drop across the valve, which limits valve losses and increases the efficiency of the valve. Conventional flat-plate designs force the gas to make two 90° turns before passing through the valve. More importantly, any impurities in gas (liquids, dirt, mechanical debris etc.) must also follow this path. At only 300 rpm, these materials have less than 100 milliseconds to pass through these turns. As a result, these inclusions often strike squarely on the valve plate at full speed, developing premature failure. These same materials pass through the ring valve with minimal impact on the rounded disc (fig. 3).

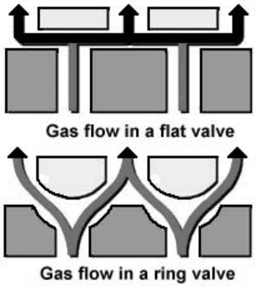

Fig.5 The gas flow in valves

The main factors that affect the performance of compressor valves [2]:

- the valves do not open and close instantly, that induces the horsepower losses;
- there must be a sufficient number of valves installed in a compressor cylinder to effectively allow gas flow into and out of the cylinder efficiently;
- valve materials must be properly selected to be compatible with the constituents in the gas stream. This is especially important when corrosives are present;
- valves in lubricated cylinders are subject to sticktion, an adhesion of the valve elements to the seat and guard, which might delay the opening or closing of the element which can be detrimental to performance and valve reliability;
- dirt and debris can prevent the valve from properly functioning;
- pulsations in the inlet and discharge gas piping can alter the timing of the valve motion and decrease efficiency and reliability.

3 Valve materials

Seats and guards are generally made of the same material. The selection of this material is important because the seats and outer rim of the suction valve guard are subjected to stresses. These stresses vary with the cylinder pressure throughout the compression cycle. Weaker materials require the seat to be thicker. Thicker seats increase the discharge valve clearance, which in turn increases the cylinder clearance, and reduces the amount of gas the cylinder will compress. Stronger materials will allow for thinner seats and eliminate this problem.

The seat is primarily liable to wear from the moving elements contacting the sealing surface. The guard is susceptible to wear from the springs cycling in the spring pockets. The material elected must be hard enough to combat this wear.

Many seats and guards are castings, usually nodular iron, which allow complex geometries to reduce losses. Others are fully machined from bar stock. This allows the use of a wide range of materials that confers flexibility to designer for different kind of applications. It also eliminates the possibility of finding porosity while machining the part.

The most common materials for non-corrosive environments are nodular iron and low carbon steel. For small quantities of hydrogen sulphide, nodular iron is preferred to steel, because there is less chance of corrosion cracking. For highly corrosive environments, 4541 or 4021 stainless steels are used.

The spring is the most highly stressed component of the compressor valve, and is typically the major cause of valve failures. The spring material should have a high stress limit, resist to taking a set at normal compressor operating temperatures, and should be able to withstand corrosion in the gas [4].

Chrome silicon and chrome vanadium have very good mechanical properties, are available in spring quality wire, and will not take a set at normal compressor operating temperatures. While these materials have poor corrosion resistance, they are known to provide acceptable service in small concentrations of corrosives in lubricated cylinders. Hastelloy and Inconel are commonly used in corrosive applications. They have good corrosion resistance when designed at stress levels acceptable for the material, but are relatively weak in dynamic applications. These materials have low mechanical properties and good quality wire is not generally available. High cobalt materials such as Elgiloy are also used in corrosive environments. These materials have good corrosion resistant properties and better mechanical properties than Hastelloy or Inconel, but are also more expensive.

The moving elements are subject to corrosives and high stress levels, but are also subject to high impacts against the guard when they open, and against the seat when they close. Therefore, material selection is very important to the success of the valve. This is where the most significant improvements affecting valve reliability have been made over the last decade.

Former valve designs used metallic plates, which are inexpensive, can withstand high differential pressures, and are not affected, by high temperatures. However, these desirable properties are outweighed by the disadvantages of metallic elements. They are prone to impact fatigue, susceptible to corrosion damage and are very unforgiving of dirt and debris.

In the 1960s, plastic elements emerged and began to replace metallic elements. Plastic materials offer several advantages over metallic elements:

- are able to withstand higher impact velocities than metal plates;
- allow them to be applied at higher lifts and speeds;
- make them more tolerant of liquids that are often present in the gas;
- are resistant to most corrosive elements commonly found in process gas streams;
- will follow the frame of the seat and provide a better seal;
- are easily applied in non-lubricate machines, because they can operate against metallic parts without causing excessive wear;
- reduce wear on the seat, so that seats do not have to be reconditioned or replaced as frequently;
- small pieces of dirt or metal can embed in a plastic element without causing a failure;
- are less likely to do damage to other components such as the cylinder liner, piston rings, and rider bands when breaks and falls into the cylinder.

In the 1970s, Nylon was the material of choice for valve elements. By the mid 1980s, PEEK (Poly Ether Ether Ketone) has been introduced and is currently the most commonly used material for valve elements.

Pure nylon is too weak to withstand the discharge temperatures of most compressors. There are many different glasses and sizes of fibres used for reinforcement, but are usually supplied with 30% of chopped glass fibres. It is essential that the fibres adhere to the nylon, so coupling agents are generally used to ensure this process.

Nylon plates tend to change their shape in service by swelling or distorting. To reduce the effects of moisture absorption, uneven fibre orientation, thermal expansion, and moulded-in stress, close control of manufacturing processes is required. Proper drying, machining, heat-treating, and moulding practices are critical in reducing distortion. Designing a valve with clearances that allow for thermal expansion is also recommended.

PEEK offers several advantages over nylon [2]:

- PEEK has temperature limits that ensure retention and stability of load-bearing properties and dimensions at high temperatures. This provides more reliable performance;
- tensile, flexural, and compressive strengths are maintained at high temperatures;
- it resists to flex fatigue;
- it has lower water absorption rates to ensure dimensional integrity;
- it resists to deformation at high temperatures.

PEEK is very difficult to mould. The moulding temperature is 335 °C, and controlling this temperature throughout the process is critical. A lower temperature will lead to a higher viscosity and the mould will not be filled properly. A higher temperature will cause the resin to oxidize and form particles referred to as “char”, which reduces the strength of the material.

PEEK is a more expensive material; so many manufacturers will use regrind or a lower viscosity resin. “Regrind” is waste material that is ground back into a powder and blended with virgin PEEK material, which will decrease the dynamic strength of the material.

According to material technology and supplier, the mechanical and thermal properties vary within a small range. Some mechanical and thermal properties for three kinds of PEEK are presented in Table 1.

4 Thermal behavior of parts

During operation in compressor the thermal regime of valves is according to the destination. The suction valves work the range (20…35) °C but the discharge valves

Table 1. Properties of 30% glass filled PEEK [7]

Property		Supplier		
		Ketron		Victrex
		Compression moulded	Extruded	Injection moulded
Mechanical	Specific gravity	1.45	1.54	1.50
	Ultimate tensile strength [MPa]	117	124	156
	Tensile Young modulus [MPa]	5171	6895	9701
	Tensile elongation at break [%]	3	3	2
	Flexural strength [MPa]	193	193	233
Thermal	Coefficient of linear thermal expansion [/ °C]	2.5E-05	2.2E-05	2.2E-05
	Heat deflection temperature [°C]	316	316	316
	Melting point [°C]	340	340	340
	Continuous service temperature [°C]	249	249	249

work the range (20…145) °C [6]. Because the coefficient of linear thermal expansion of PEEK is approximately two times greater than the coefficient of linear thermal expansion of stainless steel, if the same initial centreline is used for rings and seats, after thermal expansions the valve will not work. For this reason, it is necessary to realize different initial dimensions for centreline diameters, for both rings and seats.

The temperature variation function of time and space inside the body is given by Fourier's differential equation:

$$\frac{\partial}{\partial t}(\rho c T)=\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)+Q \quad , \qquad (1)$$

where: T is the temperature; t is the time; c is the specific heat; ρ is the specific mass; λ_i is the thermal conductivity of the mass, in "i" direction; Q is the flow of the internal sources of heat.

The finite element method is the way to solve the problem of thermal conduction, so, the differential equation (1) is equivalent to the minimum of the functional:

$$\Pi=\frac{1}{2}\int_V\left[\lambda_x\left(\frac{\partial T}{\partial x}\right)^2+\lambda_y\left(\frac{\partial T}{\partial y}\right)^2+\lambda_z\left(\frac{\partial T}{\partial z}\right)^2-2QT\right]\mathrm{d}V+$$

$$+\int_{S_2} qT\,\mathrm{d}S_2+\frac{1}{2}\int_{S_3} h(T-T_\infty)^2\,\mathrm{d}S_3 \qquad (2)$$

where: h is the convection efficiency coefficient, from the S_3 surface to the environment; T_∞ is the temperature of the environment.

The finite element equation in stationary heat transfer is [3]:

$$[k]\{\overline{T}\}=\{F\}, \qquad (3)$$

and the thermal characteristics matrix is:

$$[k]=\int_V [B]^T[\lambda]\,[B]\,\mathrm{d}V+\int_{S_3} h[N]^T[N]\mathrm{d}S_3. \qquad (4)$$

The formula of the applied thermal flow is:

$$\{F\}=\int_V [N]^T\{Q\}\,\mathrm{d}V-\int_{S_2}[N]^T\{q\}\,\mathrm{d}S_2+\int_{S_3} h[N]^T\{T_\infty\}\,\mathrm{d}S_3, \qquad (5)$$

[N] being the form functions matrix.

Due to this model, it is possible to calculate the temperature at each point and the thermal expansion as well.

After machining, each ring was heat treated one hour at 230 °C to eliminate internal stresses. The seats are machined using the computed values of the centerline diameters. During operation in compressor, the centerline diameters will vary as shown in figures 5 and 6 [6]. In figures 8 and 9 there are presented von Mises stresses on the ring and guard of the discharge valve.

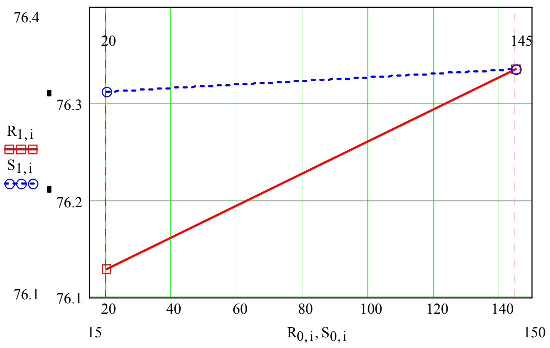

Fig.6 The thermal expansion of 2nd ring (---) and seat (—) centreline diameter stage 1, discharge valve

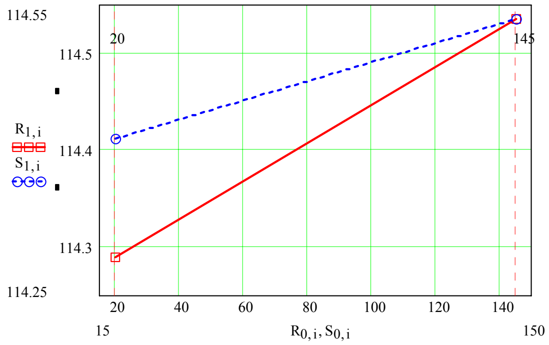

Fig.7 The thermal expansion of 3rd ring (---) and seat (—) centreline diameter stage 1, discharge valve

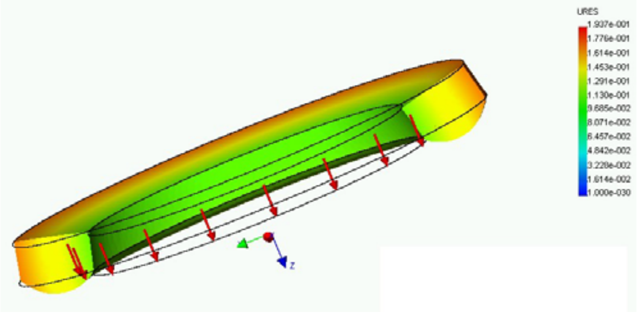

Fig.8 Bending of the ring (thickness 10mm) seated on the outer diameter, σ_{max}=22.35 MPa

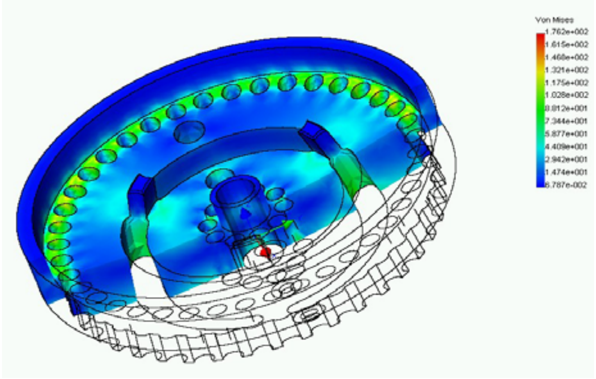

Fig.9 Von Mises stresses on the guard, σ_{max}=176.2 MPa

5 Fluid flow through valves

The main problem in fluid flow study is to ensure a gas velocity lower than 80 m/s.

More often than note, the fluid processed by the compressor is a complex mixture of chemical nonreacting compounds, usually hydrocarbons. A detailed analysis of the fluid flow through the compressor valves requires accurate knowledge of the transport properties of the mixture. Among these, the most important are the dynamic viscosity and thermal conductivity [8].

The mixture laminar viscosity is calculated using the Wilkes' mixing model [9]. First, the viscosity coefficient is computed for each individual species using Sutherland's law, as follows:

$$\frac{\mu_n}{\mu_0} = \left(\frac{T}{T_0}\right)^{\frac{3}{2}} \frac{T_0 + S}{T + S} ; \qquad (6)$$

where T is the local static temperature, μ_0, T_0, and S are constants for each component.

For N total species, the individual viscosity coefficients are combined using

$$\mu_{mixt} = \sum_i \frac{x_i \mu_i}{\sum_j \left(x_i \phi_{i,j}\right)} ; \qquad (7)$$

where $\phi_{i,j}$ is mixing coefficient computed as

$$\phi_{i,j} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{\frac{1}{2}} \left(\frac{M_j}{M_i}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}} . \qquad (8)$$

In the previous relation μ_i is dynamic viscosity and M_i is molar mass of each component of the flowing gas.

The same model was used to obtain the thermal conductivity of the flowing gas:

$$\lambda_{mixt} = \sum_i \frac{x_i \lambda_i}{\sum_j \left(x_i \phi cond_{i,j}\right)} ; \qquad (9)$$

$$\phi cond_{i,j} = \frac{\left[1 + \left(\frac{\lambda_i}{\lambda_j}\right)^{\frac{1}{2}} \left(\frac{M_j}{M_i}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}} . \qquad (10)$$

where λ_i is thermal conductivity of each component of the flowing gas and α=1.

We done studies refers to the valves of the first stage of the 285 mm diameter reciprocating compressor, with the pressures $P_{suction}$ = 1.2 MPa, $P_{discharge}$ = 2.8 MPa and temperatures $T_{suction}$ = 38ºC, $T_{discharge}$ = 118 ºC [5].

Figure 10 shows the 3D model of the fluid velocity in the suction valve. The maximum speed is 51.6 m/s.

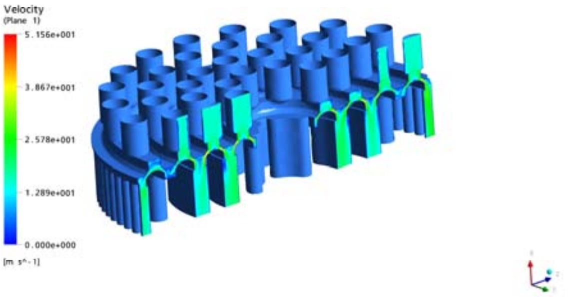

Fig.10 The fluid velocity in suction valve (3D view)

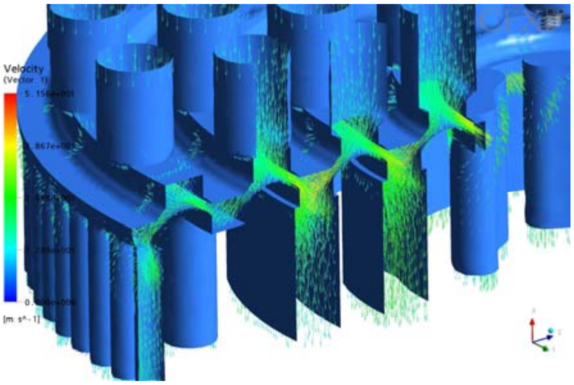

Fig.11 The fluid velocity vector in suction valve (3D view, detail)

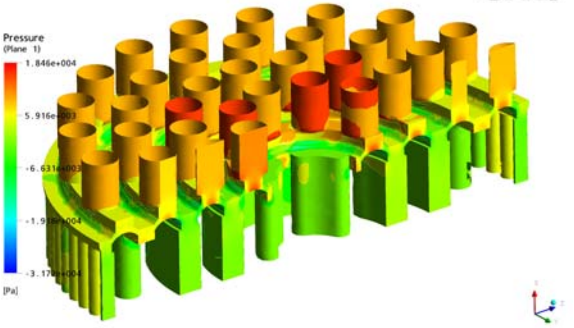

Fig.12 The fluid pressure in suction valve (3D view)

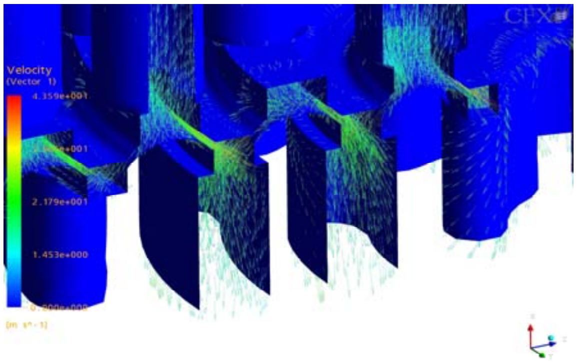

Fig.13 The fluid velocity vector in discharge valve (3D view, detail)

In figure 11, the fluid velocity vector is presented and figure 12 shows the pressure map in the same valve. The fluid velocity vector in discharge valve is presented in figure 13.
The F.E.A. was done using CFX 5.7.1 and Ansys Workbench 9.0

6 Conclusion

The design of valves ensures the compression process' parameters and the reliability.
Using the FEA the designer can calculate the centerline diameters of the rings and seats for machining. In operation, with thermal expansion, good response of the valve is obtained and adequate tightness is achieved.
Having the values of the velocities and pressure, the designer can establish the adequate dimensions of the suction and discharge channels and holes, the value of the closing element lift and the contact areas.
An important parameter determined from the CFD analysis is the pressure drop across the valve. The designer may choose to minimize it in order to allow for lower input work requirement and thus better compressor efficiency while considering the geometrical restrictions imposed by the compressor.

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