Study of the Early Development Factors of Failure in Valves of Reciprocating Compressors by Experimental and Numerical Simulation

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Abstract: Nowadays most of the reciprocating compressors have one-way valves that act by difference pressure between behind and front of valves. In this article, experimental and numerical studying of one-way valves in reciprocating compressors was done. In this experimental test, one–way valve with two different materials for rings; stainless steel with the material number 1.5022 and sign 38si6, and carbon-peek composite, were used. Numerical simulation for one-way valves with identical characteristics of experimental tests was done by CFX 5.7.1 and Ansys workbench 9.1. Experimental tests showed that the life of carbon-peek composite ring was more than stainless steel. The most important cause of failure in the stainless steel ring was an inappropriate distribution of forces due to the springs below the ring. Another common cause of failure in these valves was the stresses on walls in the location of springs that were approved by numerical simulation. The difference in the reaction of one-way valves in opening and closing was another cause of failure because they were different in thermal expansion coefficient, thickness and diameter of carbon-peek composite and stainless steel rings. The appropriate thickness of rings was determined by flow equation. The results obtained from numerical simulations have a good agreement with experimental tests.

Keywords: Experimental Test, Failure, Numerical Simulation, One–Way Valve, Reciprocating Compressor

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1 INTRODUCTION

The compressor is one of the mechanical machines which are used widely in big and small industries. In fact, compressors are machines that by using lots of mechanical energy, sucks the gas in and then compress it. Compressors are divided into two general types of dynamical and positive movement. One of the positive movement types is reciprocating compressors that the most usage of them is in the oil and gas industries. These compressors have significant use in chemical industries, building's ventilation, tunnels, mines and furnaces, refrigeration systems, supply the pressure of pressured tanks and injecting gas in the oil fields [1].

Reciprocating compressors are used in cases that in each stage, without any high-rate flow, high compression is required and the fluid is almost dried [2]. The components of reciprocating compressors are divided into three types of fixed, moveable and sideways. In this article, we study the components of a fixed compressor. Reciprocating compressors have valves for dense-gas suction and evacuation at the end of the cylinder, these taps are unilateral. Their movement is fixed with cylinders. In unilateral taps, gas enters in a way and exits in another. The reverse flow is not possible. Each valve is made of some connected sheets. Their opening is either automatic or with the help of gas pressure and springs. These valves are broken or banned because of some studied reasons in this article. They will affect the compressor's functions. Figure 1 shows the place and the way of placing these valves [3].

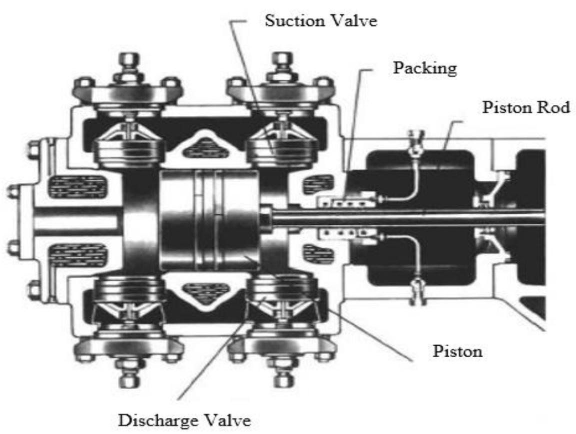


Fig. 1 The location and method of placing the valve in the compressor [3].

Unilateral valves used in reciprocating compressors have different components which the most important ones in different valve patterns are ring, sheet, and the seat area of the valve, the valve protector and the springs. Designing and manufacturing valves for improving the efficiency and reliability of reciprocating compressors can affect a compressor's operation through a wide range of complex parameters. The working cycle of a reciprocating compressor results in the periodic impact of compressor valves. In a research conducted by Dress-rand Company, the compressor valves were clearly identified as the main reason for the shutdown of reciprocating compressors that will result in heavy losses [4].

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.

Raimund Arztmann [5], with the empirical review of the reciprocating compressors, found that the suction and discharge valves are the key components of each compressor, which is the main reason behind the failure of reciprocating compressors for valves, also selecting an appropriate valve for different usages is known as an important factor of the life span of these things.

In the field of simulation of one-way valves, studies have also been carried out, part of these studies, such as Dr. Tyren and Dr. Balts [6], used a simulation method to examine the fluid velocity between valves and thermal behaviour of valve components which are addressed in a first-stage valve, that results in reaching the standard speed of the examined valve. Michael and Roman [7], by a one-dimensional and unilateral study of valves with short-flow channels, "Fig. 2", worked on a preliminary design of the mathematical description of a reciprocating and reciprocating compressor and its valves with the help of the Newton's second law.

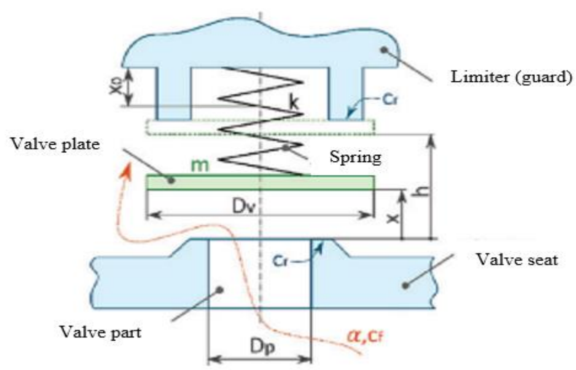


Fig. 2 Generic Model of a Valve Assembly [7].

However, this model with a degree of freedom has limitations such as the inability to predict behaviours such as abnormal effects etc. But in general, due to advantages such as very little time in the calculations, this kind of model provides a powerful tool for examining the process of valves, and serves as a powerful tool for examining the effects of internal and external factors on the behaviour of the valves. Khoshnevis and coworkers in 2014 [8], due to the importance of incoming flow turbulence intensity into the combustion chamber, experimentally investigated the tripping wire effect on the flow wake within a linear compressor cascade. According to what is known from the history of relevant research, studies in this field often have a very high significance for these valves and have not been accurately spoken about the critical points in these valves.

In this research, considering the different types of rings with stainless steel and Carbon fibre- peek composite, their behaviour in the experimental and numerical simulation is investigated. This paper presents the critical points in designing of valves used in reciprocating compressors. The design is focused on valve type, dimensioning of the main elements and materials choice. 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 were presented.

2 ANALYTICAL RELATION

In this section, the equations for the valves are expressed. Using these relationships, the suitable thickness of the ring is determined. In fact, due to the thermal behaviour of the valve components, it is possible to determine the appropriate thickness and the proper shape of the ring. On the other hand, using the equations of fluid flow, the velocity of the flow rate of the valves and its critical value, which causes the valve to fail, is determined.

The equations for dynamical modelling of the valve are expressed [7]:

$$m\frac{d^2x}{dt^2}+F_f+F_s=F_g \tag{1}$$

Where m represents the mass in motion, x is the distance of the ring from the seat, F_f indicates the friction force with “Eq. (2)”, F_s is the force of the spring with “Eq. (3)” and F_g is the gas force with “Eq. (4)”.

$$F_f=C_f\frac{dx}{dt} \tag{2}$$

Where C_f, is friction coefficient, and dx/dt, represent the instantaneous speed of the valve ring.

$$F_s=K_0X \tag{3}$$

$$F_g=C_gA_v\left(P_u-P_d\right) \tag{4}$$

Where C_g, is the gas coefficient of the valve, A_v is the area between the ring and the valve seat (flow area), P_u, is the gas pressure in the downside and P_d, is the gas pressure in the upper side of the valve.

The temperature variation function relative to the time and space inside the valve body is determined by the Fourier differential equation [9]:

$$\frac{\partial}{\partial t}(\rho cT)=\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right)+Q \tag{5}$$

Where T is the temperature, c is the specific heat, ρ is the specific mass, λ is the thermal conductivity of the mass in different directions and Q is the heat generated by the internal flow of flow. Finite element method is a way to solve the heat transfer problem and to evaluate the performance of various components in a piece, so the differential “Eq. (6)” is the minimum function equation.

$$\Pi=\frac{1}{2}\int_V\begin{bmatrix}\lambda_x\left(\frac{\partial T}{\partial x}\right)^2+\lambda_y\left(\frac{\partial T}{\partial y}\right)^2\\+\lambda_z\left(\frac{\partial T}{\partial z}\right)^2-2QT\end{bmatrix}dV+\int_{S_2}qTdS_2+\frac{1}{2}\int_{S_3}h\left(T-T_\infty\right)^2dS_3 \tag{6}$$

Where h is the coefficient of the effect of the displacement from the surface to the environment, and T - T_∞ is the environment temperature.

The equation of finite element in constant heat transfer is given by “Eq. (7)” [10]:

$$[K]\{T\}=\{F\} \tag{7}$$

The matrix of thermal properties is in “Eq. (8)”:

$$[K]=\int_V[B]^T[\lambda][B]dV+\int_{S_3}h[N]^T[N]dS_3 \tag{8}$$

And the practical thermal flow formula is “Eq. (9)”:

$$\{F\}=\int_V[N]^T\{Q\}dV-\int_{S_2}[N]^T\{q\}dS_2+\int_{S_3}h[N]^T\{T_\infty\}dS_3 \tag{9}$$

Where [N] is the matrix of form functions.

The main problem in studying the flow of fluids in the valves is to ensure that the gas velocity is less than 80 m/s. In most articles, the compressed fluid is a complex combination of non-reactive chemical compounds, which are usually hydrocarbons. The accurate analysis of the flow of fluid through the compressor valves requires careful consideration of the combustion transfer properties. One of the most important of them is dynamic viscosity and thermal conductivity [11]. The layered and mixed viscosity is calculated using the Wilkes' mixing model [12]. Initially, using the Sunderland law for each unique member, the viscosity coefficient is calculated using “Eq. (10)”:

$$\frac{\mu_n}{\mu_o} = \left(\frac{T}{T_o}\right)^{\frac{3}{2}} \frac{T_o + S}{T + S} \tag{10}$$

Where T is the constant local temperature, and T_O, μ_O, and S are constant for each element. For each N, the unique viscosity coefficient is calculated using the combined “Eq. (11)”:

$$\mu_{mixt} = \sum_i \frac{x_i \mu_i}{\sum_j x_i \phi_{ij}} \tag{11}$$

Where φ_{ij} is the mixing factor and is calculated from “Eq. (12)”:

$$\phi_{ij} = \frac{\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{\frac{1}{2}} \left(\frac{M_i}{M_j}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}} \tag{12}$$

Where μ_i is the dynamic viscosity and M_i is the molecular mass of each gas. This is used to achieve the thermal conductivity of the gas in flow.

$$\lambda_{mixt} = \sum_i \frac{x_i \lambda_i}{\sum_j x_i \phi_{cond_{ij}}} \tag{13}$$

$$\phi_{cond_{ij}} = \frac{\left[1 + \left(\frac{\lambda_i}{\lambda_j}\right)^{\frac{1}{2}} \left(\frac{M_i}{M_j}\right)^{\frac{1}{4}}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}} \tag{14}$$

Where λ_i is the thermal conductivity coefficient of each component of the gas in the flow.

3 TYPES OF VALVES

The valves are the vital components of the reciprocating compressors. There are three kinds of valves that are used in reciprocating compressors: poppet valves, plate valves (“Fig. 3”) and ring valves (“Fig. 4”) [13].

Fig. 3 Plate valve [13].

Choosing the type of tap is based on the function and the conditions. Poppet valves are recommended up to 15 MPa differential, 30 MPa discharge pressure and speed of 600 rpm, plate valves up to 20 MPa differential pressure, 40 MPa discharge pressure and speed of 1800 rpm, Ring valves to 30 MPa of differential pressure, 60 MPa of discharge pressure and speed of 600 rpm [14].

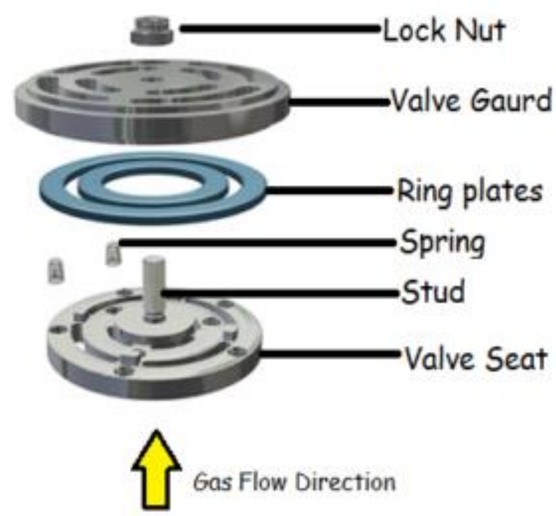
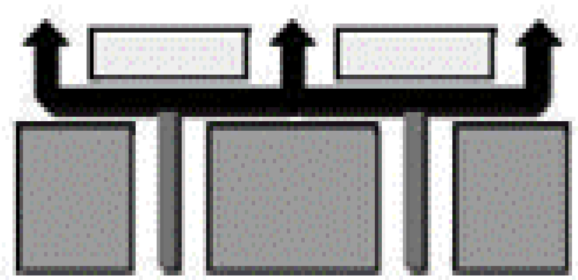
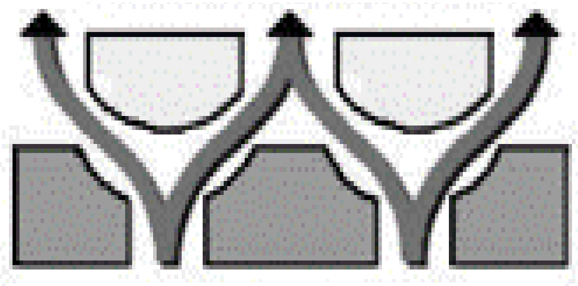


Fig. 4 Ring valve [13].

The ring valves retract the balanced flow through the valve seat and lifting the rings to the valve protector which cause a drop in pressure across the valve, that it reduces valve damage and increases the efficiency of the tap. The simple designs of the valves convert the gas force to 90 ° before passing through the valve (“Fig. 5”). 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 compounds often directly affect the valve plate at high speeds and cause premature failure. Also similar to these materials, pass through the ring with minimal impact on the circular disks.



Gas flow in a flat valve



Gas flow in a ring valve

Fig. 5 The gas flow in valves [9].

Many factors affect the performance of the valves, which are [14]:

- 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.
- The type of valves 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 the lubrication of the cylinders (lubrication) are subject to the adhesion of the valve components to the seat and protector, which may delay the opening and closing of the valve and can damage the functionality and reliability of the tap.
- Pollutants can prevent proper operation of the valves.
- Fluctuations in the gas inlet and outlet pipes can slow down the valve timing and reduce efficiency and reliability.

4 VALVES MATERIAL

Seats and guards are generally made of the same material. Choosing this material is important because the seat and outer edge of the suction valve protector are under pressure. These stresses are changed by the cylinder pressure during compression cycles. Weaker materials need thicker seat. Thicker seats increase the free space of the suction valve, which in turn increases the free space of the cylinder, and it results in the reducing the amount of compressed gas in the cylinder. Stronger material will allow you to make thinner stretchers and cause the problem to be disappeared. The seat is mainly subject to corrosion by contacting the moving parts of the watertight surfaces. The valve protector is subject to corrosion by means of springs in the spring compartment. The selected materials should be sufficiently hard against corrosion-resistant contacts and collisions. Many seats and protectors are cast and are usually cast-in-place, which, in complex geometries, reduces casualties or friction. Other components are made entirely of the primary material machining. These factors allow the use of a wide range of materials that make the designer flexible for different types of different usages. The most well-known materials are for non-inflammable, spherical, and low-carbon steel. Studying low sulphur hydrogen sulphide, spherical cast iron is preferred to steel, as it is less likely to crack. For corrosive environments, 4541 and 4021 stainless steel is used.

The spring is one of the main components of the compressor valve and is normally the main cause of the valve failure. The spring should have a high tensile strength to withstand compressor operating temperature variations and should be able to withstand gas corrosion [15]. Silicon-Chrome and Vanadium-Chrome have very good mechanical properties. They have the ability to turn into a spring-loaded wire and do not come at the normal operating temperature of the compressor. While these materials have poor corrosion resistance, they are known as low corrosion materials in oily cylinders. Hastelloy and Inconel are Commonly used in corrosive applications.

These materials have good corrosion resistance when stresses on surfaces are considered acceptable. But in dynamic applications, they are relatively weak. These materials have low mechanical properties and also generally are not available in high quality wires. High cobalt materials such as Elgiloy are also used in corrosive environments. These materials have the same properties as corrosion resistance and mechanical properties better than Hastelloy and Inconel but are more expensive. Rolling elements (rings and plates) are subject to corrosion and high surface tensions, and also when exposed, they are exposed to destructive effects in dealing with the guard and close when they collide with the seat. Therefore, it is very important to select the appropriate material for the proper operation of the valve.

In the past, the valves were made using inexpensive metal sheets, which could withstand high differential pressure and also not be exposed to high temperatures. Still, the advantages of these properties are more than the disadvantages of the metal elements. These materials are exposed to fatigue and corrosion and are very vulnerable to pollutants.

In the 1970s, nylon was the preferred material for valve components. In the mid-1980s, the peek (Poly Ether Ketone) was introduced, which is currently the most commonly used component of the valves.

Pure nylon also had a slight resistance at outlet temperatures in 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 imperative that these fibres and strings stick to the nylon; in general, bonding elements are used to ensure this process. Nylon plates show a tendency to change their form in work by swelling and wrapping. To reduce the effects of moisture absorption, uneven fibre orientation, thermal expansion, and moulded-in stress, close control of manufacturing processes is required. Machining, heat treatment and melding are crucial in reducing distortion. It is also recommended in the design of the valve to provide a space for expansion of the gas.

Peek is very difficult to meld and form. The forming temperature is 335^0C, and control of this temperature is critical during the process. The low temperature will result in higher viscosity and the meld will not be filled properly. The higher temperature causes the resin to oxidize and form semi-burned substances that reduce the strength of the material. Peek is an expensive material. Many manufacturers use regrind or low viscosity resins. Regrind changes the waste products into a powder and mixes with pure peek materials, which increases the dynamical strength of the material. Due to the technology of materials and their examination, mechanical and thermal properties differ in a small range.

5 EMPIRICAL STUDIES

In its empirical studies, two types of ring-shaped valves of "Fig. 6", made by the machine of the main material (stainless steel and carbon-fibre composite), are also applicable to other valves. The components of the valves are also shown in "Fig. 7".

The compressor valve used in this study is used for applications in the chemical and processing industries, in refineries and the energy sector for the transportation of heavy gases such as carbon dioxide, carbon monoxide or propylene.

All stages of construction, including manual machining, CNC machining with a Mazartrol cam T2 controller, milling, drilling has been carried out in "Jahan Tarash Aria" company.

Fig. 6 Ring valve case study.

Fig. 7 Elements of ring valve Case Study.

For the seat, protective, antistatic 420 AISI bolts with the properties in "Table 1" and the 67Sicr5 springs with the properties shown in "Table 2" are used. We also used once for stainless steel rings, 38si6 and once made from Carbon-Peek composite. Properties of Carbon-Peek composite in "Table" 3" and properties of stainless steel are given in "Table 4.

Table 1 Stainless steel properties 4021/1 [16]

Properties	Amount
(kg/m3) Density	7800
Modulus of elasticity (Gpa)	200
Poisson Coefficient	0.285
Compressive stress (Mpa)	600
Tensile stress (Mpa)	860
Thermal conductivity ($wm^{-1} k^{-1}$)	30

Table 2 Properties of carbon steel 7103/1 [16]

Properties	Amount
(kg/m3) Density	7700
Modulus of elasticity (Gpa)	200
Poisson Coefficient	0.3
Compressive stress (Mpa)	1325
Tensile stress (Mpa)	1570
Strength coefficient of spring (N/m)	4457

Table 3 Properties of rings with Carbon- fiber composite [17]

Properties	Amount
Young's modulus on page xy (Mpa)	148900
Young's modulus on page xz (Mpa)	8825
Young's modulus on page yz (Mpa)	8825
Poisson coefficient on page xy (Mpa)	0.342
Poisson coefficient on page xz (Mpa)	0.342
Poisson coefficient on page yz (Mpa)	0.35
Shear modulus on page xy (Mpa)	5378
Shear modulus on page xz (Mpa)	5378
Shear modulus on page yz (Mpa)	2976
Tensile stress along the fiber (Mpa)	2413
Pressure tension along the fiber (Mpa)	1151
Tensile stress perpendicular to the main direction (Mpa)	64.9
Pressure stress perpendicular to the main direction (Mpa)	244.8
Shear stress (Mpa)	244.8

Table 4 Properties of rings with Stainless steel [16]

Properties	Amount
(kg/m3) Density	7850
Modulus of elasticity (GPa)	210
Poisson Coefficient	0.3
Compressive stress (MPa)	1030
Tensile stress (MPa)	1275
Thermal conductivity ($wm^{-1} k^{-1}$)	25

The tested valve has a diameter of 81 mm and a suction pressure of 12 MPa. The operating conditions are normal, and there are no problems with other components of the compressor.

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 work the range (20-145) °C. Since 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 centerline 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 centerline diameters, for both rings and seats. The temperature variation function of time and space inside the body is given by 5-6-7-8-9 differential equations. Due to these equations, it is possible to calculate the temperature at each point and the thermal expansion as well.

Experimental results:

After applying normal conditions and after 145 days of using the valves with steel rings, the compressor initially lost capacity and then stopped. After stopping and observing the rings, we noticed a break in the large ring of one of the valves in "Fig. 8" and the fracture in one of the compartments of the springs in "Fig. 9". In "Fig. 10", the break in the spring compartment is shown in another view. Since the compressor continues to operate after 210 days of its work using composite-coated valves, it shows that the composite is overtaken by a stainless steel composite. The break in the ring and the springboard enclosure may be unsuitable for reasons such as wall-to-wall abrasion, compressed fluid corrosion, or improper machining.

Fig. 8 Break in a large steel ring.

Fig. 9 Break in the compartment of the spring from the inside view.

Fig. 10 Break in the spring compartment from the outside view.

6 NUMERICAL SIMULATION

In this study, The F.E.A. was done using CFX 5.7.1 and Ansys Workbench 9.0. the Ansys software has been used for numerical analysis of critical valve points, fluid velocity and Fluid velocity vector. The generated model is shown in "Fig. 11".

Fig. 11 Cut-off valve model.

In this form, a valve is modeled that includes the valve body, spring holes, springs, rings on the springs, and the bolts and retainers of the two valves.
In the compressor and according to the position of the valves, the valve can be tightened in a radial direction. Therefore, in the software environment, the valve is restrained in every six degrees of freedom. In this study, valve assembly components such as bolts and nuts are considered as analytical rigidity.

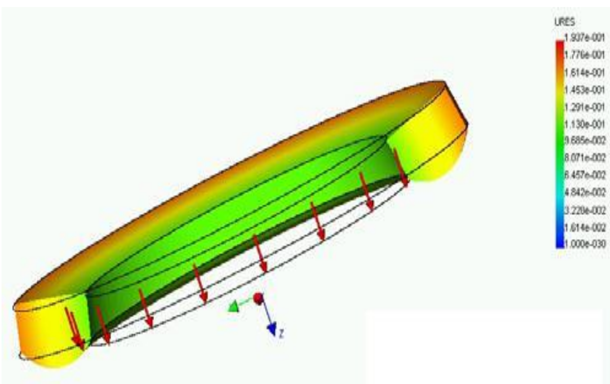


Fig. 12 Bending of the ring (thickness 10mm) seated on the outer diameter, σ_{max}=22.35 MPa.

Numerical simulation result:
We have done studies that refer to the valves of the first stage of the 81 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.
In this analysis, after selecting a one-way ring valve used in reciprocating compressors, the thermal behavior of the valve's critical points has been investigated.
In "Figs. 12 and 13", von Mises stresses on the ring and guard of the discharge valve are presented. 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 no reacting 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 ones are the dynamic viscosity and thermal conductivity.

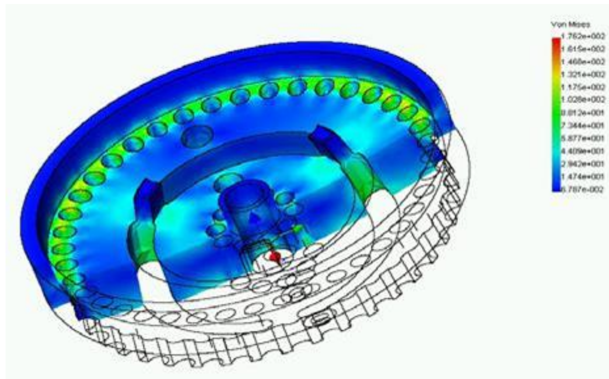


Fig. 13 Von Mises stresses on the guard, σ_{max}=176.2 MPa.

Figure 14 shows the 3D model of the fluid velocity in the suction valve. The maximum speed is 51.6 m/s. In "Fig. 15", the fluid velocity vector is presented and "Fig. 16" shows the pressure map in the same valve. The fluid velocity vector in the discharge valve is presented in "Fig. 17".

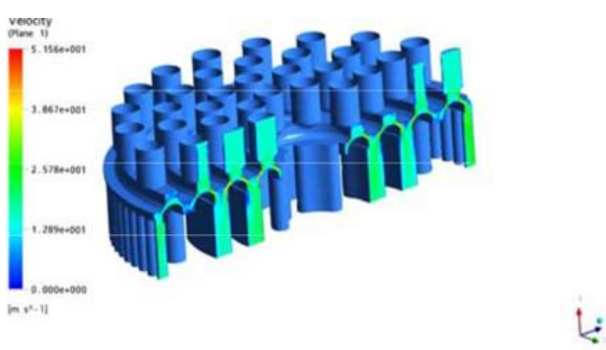


Fig. 14 The fluid velocity in the suction valve (3D view).

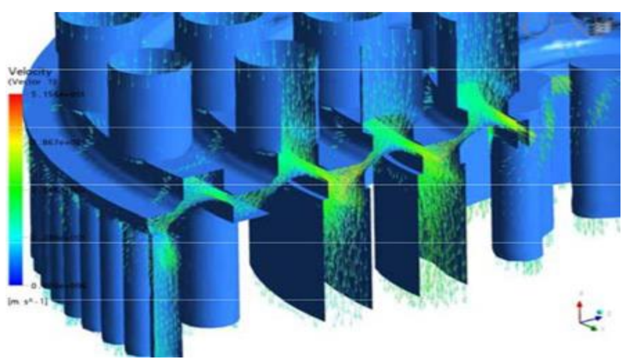


Fig. 15 The fluid velocity vector in the suction valve (3D view, detail).

In the following, the shear stress distribution diagram in the height of the hole of the spring's location is discussed. In "Fig. 17", this chart is visible.

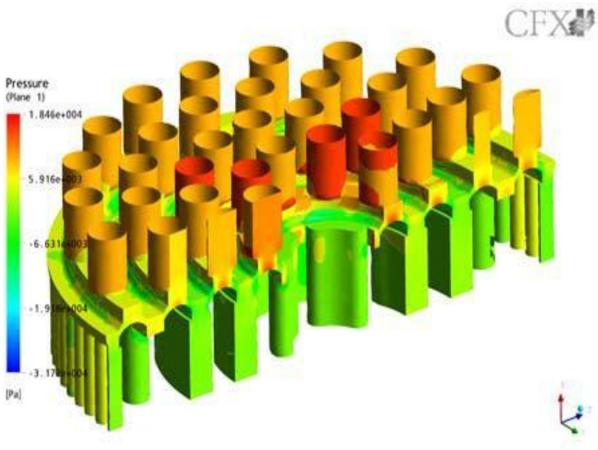


Fig. 16 The fluid pressure in the suction valve (3D view).

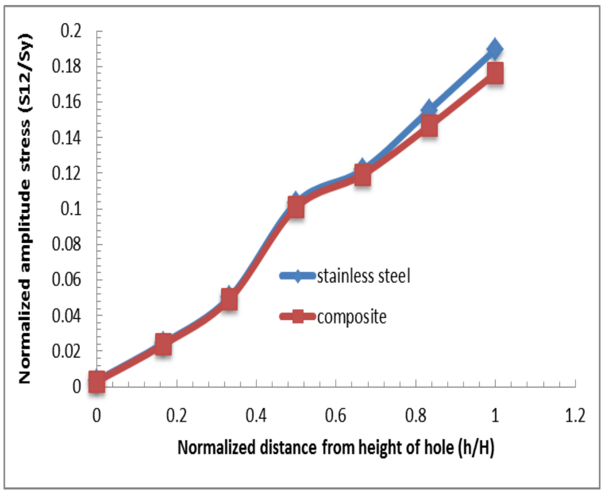


Fig. 17 Dimensional distribution of stress in the direction of the shear in the compartment of the placement of the springs.

7 CONCLUSION

The following results were obtained from the experiments carried out to investigate the breakdown locations of the valves and the break of the valves and comparison with the simulated models:

1- Since the thermal expansion coefficient is twice as high as the thermal expansion coefficient of stainless steel, if the same dimensions are used for shelves and chairs, the valve will not be applied after the heat is applied. Therefore, for both rims and chairs, it is necessary to change the dimensions of the initial diameter and initial storage. According to the formulas expressed.

2- Using the FEA, the designer can calculate the centerline diameters of the rings and seats for machining. In operation, with thermal expansion, the good response of the valve is obtained and adequate tightness is achieved.

3- 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.

4- 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.

5- From the important experimental results, the piston velocity and the volume of the compression chamber at the valve opening moment have a direct impact on the maximum impact velocity.

8 APPENDIX OR NOMENCLATURE

m	Mass (Kg)
M_i	Molecular mass of each gas (kg.mol^{-1})
T	Temperature (F)
T_∞	Ambient Temperature (F)
C_f	Friction coefficient
h	Convection heat transfer coefficients
K_0	Strength coefficient of the spring (Nmm^{-1})
C_g	Gas coefficient
x	Distance (mm)
P_d	Gas pressure in the top-end (Pa)
P_u	Gas pressure at the bottom (Pa)
Q	Heat exchanged between fuzzy (Wm^3)
c	Special heat (JKg^{-1} k^{-1})
A_v	Flow area (mm^2)
F_f	Friction force (N)
F_s	Spring force (N)
F_g	Gas force (N)

Greek signs

ρ	Density (kgm^{-3})
ϕ_{ij}	Mixing factor
λ	Thermal conductivity coefficient (Wm^{-1} K^{-1})
μ	Dynamic Viscosity (kgm^{-1}s^{-1})
Σ	Total

Subtitles

v	Volume
s	area

mixt	Blended
cond	Thermal conductivity

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