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Investigation on Ring Valve Motion and Impact Stress in Reciprocating Compressors

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ABSTRACT

This paper presented the theoretical and experimental investigation on ring valve motion and impact stress in a reciprocating compressor for a purpose of extending the life time of valve. A simulation model was established to describe the motion of valve plate and the physical behavior of valve plates during compressor operation was measured using an eddy current displacement sensor to validate the mathematical model. Meanwhile, a finite element model was established to simulate the impact process of ring valves. The results indicated that great impact speed and inclining motion could result in high impact stress and it increased nearly in a direct proportional with the growth of impact speed and inclining angle. In order to reduce the magnitude of impact stress, the lift of valve was controlled by adjusting the design parameters and it was also validated experimentally. The comparison of impact between valve plate to seat and limiter has also been conducted in this paper, showing that valve plate suffered more impact stress when it impacted the seat, and a new method to reduce the impact magnitude had been presented.

1. INTRODUCTION

The operating characteristics of self-acting valves in any reciprocating compressor can have a profound effect upon the overall performance of the compressor (Tramschek and Boyle, 1988), and they are typically the controlling factor for scheduling compressor maintenance downtime. According to an industry investigation mentioned by Leonard(1996), compressor valves also contribute to almost 36% of unscheduled shutdowns of reciprocating compressors. Thus, to improve the efficiency and extend the lifetime of valve is of great meaning for compressors.

The excessive impact stress of compressor valve plate against the lift limiter and the valve seat is one of the main causes for the valve failure (Soedel W. 1974). The impact stress is related to the valve impact velocity. Soedel(1974) proposed a supposed velocity V_s , which was defined as the product of valve lift and angular velocity of the crank, and suggested that V_s was not more than 0.1-0.2 m/s. But the defined V_s was not the practical impact velocity, and the practical V_s of a high speed compressor was much higher than 0.2 m/s. So it was necessary to investigate the practical permissible impact velocity in detail. The stress of impact is also related with the amplitude of inclined motion of valve plate. Pan et al. (1995) established a mathematical model to calculate the inclined motion of a plate valve, and analyzed the influence of the inclined motion on the reliability of the plate valve. With the emergence of new reinforced plastic materials, non-metallic valve rings can withstand higher impact stress. To clarify the difference between metallic and non-metallic valve rings when they impact the seat and guard is very essential for further improvement in compressor valves.

The aim of current study is to improve the durability of compressor ring valves. Theoretical model was established to predict the valve motion and test apparatus was set up to validate the model. On the basis of valve motion, a finite-element model was established to simulate the valve impact process in compressors. The key factors influencing the reliability of valve were identified and effective measures were recommended.

2. INVESTIGATION ON VALVE MOTION

2.1 Theoretical modeling of valve motion

The mathematical model of working process in a reciprocating compressor was established to obtain the valve motion. First of all, some proper assumptions are considered:

- (1) Thermal parameters of the gas in everywhere of the cylinder are the same;
- (2) Gas inflow or outflow the compressor cylinder is assumed isentropic;
- (3) The flow coefficient of valves is constant;
- (4) The gas pulsation in the suction and discharge plenums is negligible, where the pressure and temperature are constant.

On the basis of above assumptions, the cylinder is considered as the control volume, and the governing equations can be established.

The energy conservation equation:

$$\frac{dp}{d\theta} = \frac{\frac{1}{v}[(\frac{\partial h}{\partial v})_T - \frac{(\partial h / \partial T)_v \cdot (\partial p / \partial v)_T}{(\partial p / \partial T)_v}] \frac{dv}{d\theta} - \frac{1}{V_c} \{ \sum [\frac{dm_i}{d\theta} (h_i - h)] + \frac{dQ}{d\theta} \}}{1 - \frac{1}{v} \cdot \frac{(\partial h / \partial T)_v}{(\partial p / \partial T)_v} - \frac{1}{v} \cdot \frac{(\partial h / \partial T)_v}{(\partial p / \partial T)_v}} \quad (1)$$

The mass conservation equation:

$$\frac{dm}{d\theta} = \frac{dm_i}{d\theta} - \frac{dm_o}{d\theta} \quad (2)$$

where, m_i and m_o mean the mass flow rate into and out the cylinder respectively.

The gas state equation: R-K equation is used to calculate its property.

$$p = \frac{RT}{v-b} - \frac{a}{T^{0.5}v(v+b)} \quad (3)$$

The valve plate movement equation:

$$\frac{d^2y}{d\theta^2} = \frac{F_g - F_s}{M_v \omega^2} \quad (4)$$

where, y is the displacement of valve plate, ω is the angular velocity of crank angle, M_v is the mass of valve, F_g and F_s are the gas force and spring force acting on the surface of valve plate.

Thus, simultaneous equations are established and can be solved with the fourth-order Runge-Kutta method for the working process, and the performance parameters of the compressor can be obtained, such as displacement, indicator power, efficiency, as well as the valve plate movement.

2.2 Experimental validation of valve motion

In order to get the practical valve plate movement, a test rig was constructed, which could measure the displacement of the ring-type valve. The schematic diagram of test was shown in Fig. 1. A threaded hole was tapped in the lift limiter, where an eddy current displacement sensor was installed. Then the distance between the valve plate and seat could be recorded instantaneously.

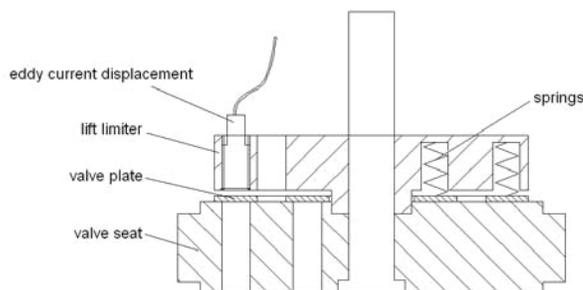


Fig.1 Schematic diagram of the test for valve motion

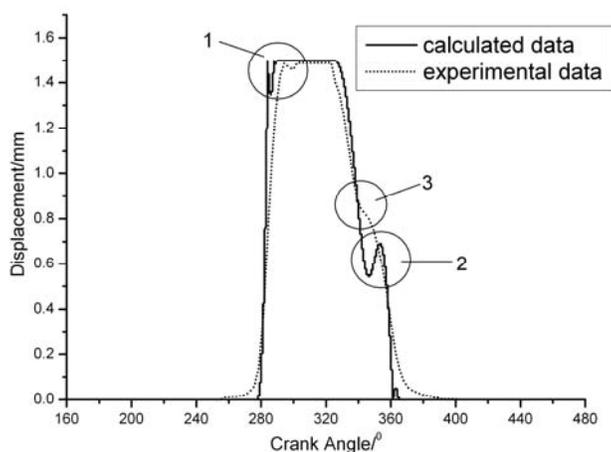


Fig.2 The movement of the discharge valve plate

Fig. 2 showed the movement of a discharge valve, and the result was compared with the calculated one. Generally, the experimental result compared well with the calculated one, so the mathematical simulation could be used for calculating the valve motion and investigating its characteristics. But there were still some differences between them. As could be seen in point 1 in Fig. 2, the rebounding amplitude of the calculated result was a little larger than that of the experimental one. The reason was that the rebounding coefficient was 0.3 in the simulation, and the viscous influence of oil was not considered. However, the experimental result showed that the oil could reduce part of the impact stress. When the valve plate returned back to the valve seat, the area of the valve passage decreased, which made the pressure in the compression chamber increase, and the gas force was bigger than the spring force, so the displacement of the valve rose again in simulation result as could be seen in point 2 of Fig. 2. While considering point 3 of the experimental result, the returning speed of the valve plate was also decreased, which implied that the pressure in compression chamber was rising too and slowing down the valve plate to the valve seat, and this agreed well with the calculated result.

2.3 Discussion on valve motion

The characteristic parameters of the valve include the Mach number of flow through the valve passage, the lift, and the stiffness coefficient of the springs, all of which the lift had significant influence on valve performance. Firstly, the reason for a great part of valve failure for compressors was high impact speed. Generally, according to the calculated result, the maximum impact speed for a certain valve was no more than 6m/s which is a pretty big value even for non-metallic valve material. In order to decrease the impact speed, manufacturers tend to reduce the lift, but the flow loss across the valve increases accordingly. Thus, to keep a balance between the lower impact speed and high valve efficiency is very important for valve designers. Most designers are inclined to sacrifice a little efficiency for longer valve lifetime.

Secondly, when inclined motion happened, the maximum inclined angle would grow almost linearly as the lift increased. It could be obtained from the diameter of valve ring and the lift.

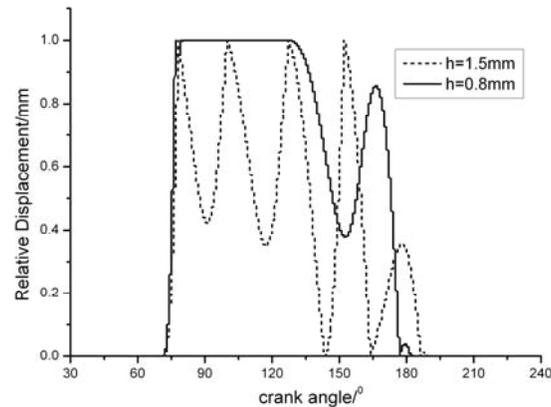


Fig.3 suction valve motion with different lift

Finally, large lift may result in flutter, especially for those small molecular gas, since they are very sensitive to flow areas. As Fig. 3 showed, the lift of a suction valve in hydrogen compressor had changed from 0.8mm to 1.5mm. Obviously, the latter one fluttered more severely than the former one.

Above all, bigger lift may contribute to high impact speed, large inclined angle and flutter, all of which would bring along excessive impact stress and finally lead into valve failure.

3. IMPACT STRESS ON VALVE

3.1 Mathematical model

The impact of ring valve to the seat and lift limiter is a kind of complicated nonlinear contact problem. The valve is considered to be homogeneous isotropic elastic body, based on which ANSYS/LSDYNA was used to simulate the impact process and calculate the stress on the valve.

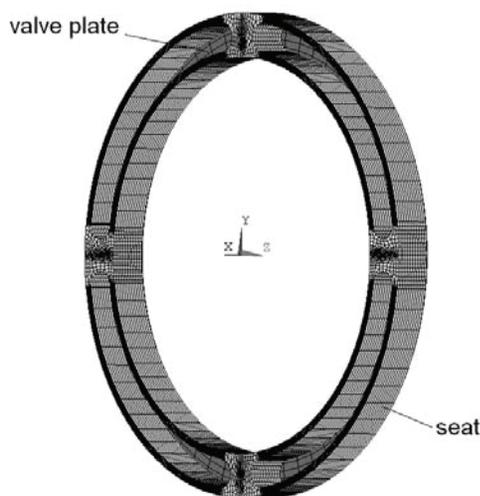


Fig.4 finite element model of valve plate and seat

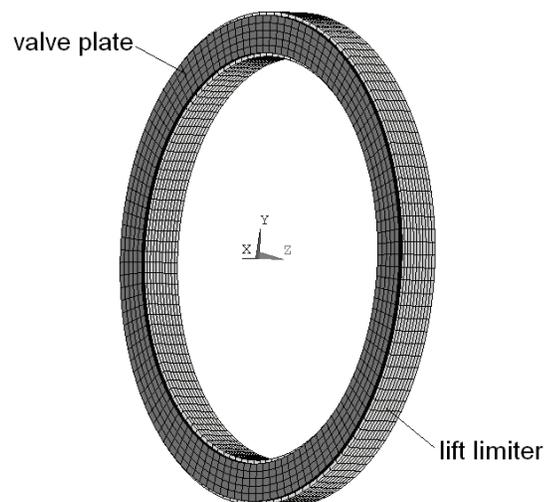


Fig.5 finite element model of valve plate and lift limiter

Fig.4 shows the finite element model of the impact between valve plate and seat. Solid164 is used to discretize the physical model. It advances in reducing (one point) integration plus viscous hourglass control for faster element formulation. Through several times of mesh generation, it is found that the mesh density of seat should be larger than valve plate so that the iteration result could be stable. When adding the constraints, all displacement DOF at the bottom of the seat were restricted, and the acceleration load was applied on the valve plate vertically with the value 800 m/s^2 . In order to save the iteration resources, the distance between the valve plate and seat is almost zero at the beginning, and the velocity of the first impact to the seat is 2 m/s .

Fig.5 shows the finite element model of the impact between valve plate and lift limiter. Similar initial and boundary conditions have been defined.

3.2 Results and discussion

Through the analysis on valve motion, generally, the impact velocity is not more than 6 m/s to the lift limiter and less than 3 m/s to the seat. However, they experienced exactly different level of impact stress. As shown in fig.6, comparisons about the impact stress on the valve plate had been made when it impacted frontly the limiter and seat with different velocity. Different valve material was also taken into consideration. Fig.6 indicated that the stress increases in a direct proportion to the increment of impact velocity. And the stress on the valve was much larger when it impacted the seat although its impact velocity was much less than that on the limiter. That's because the impact surface of the limiter was very smooth while the flow passage in the seat made the valve suffer larger bending and impact stress. When the valve material changed from 3Cr13 to PEEK, the impact stress was much smaller. This agreed well with the practical condition and explained why PEEK could withstand high impact speed.

Since the impact with the seat produced larger stress, comparisons had been made when inclining impact with the seat happened with different valve material, as Fig.7 showed. With the increment of inclining angle, the impact stress grew almost linearly. But PEEK could afford larger impact stress brought about by inclining motion.

In order to reduce the impact stress, it is essential to control impact velocity and the amplitude of inclining motion. To reduce valve lift could shorten the time of gas force on the valve and decrease the distance between the valve plate and the seat, so that the impact velocity and inclining angle could be controlled at the same time. In addition, non-metallic valve material could withstand high impact velocity and inclining motion with low impact stress.

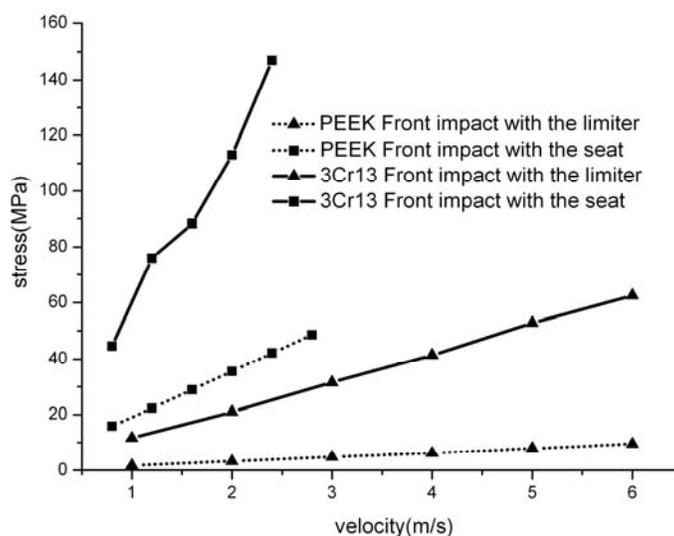


Fig.6 comparisons between front impacts with the limiter and seat

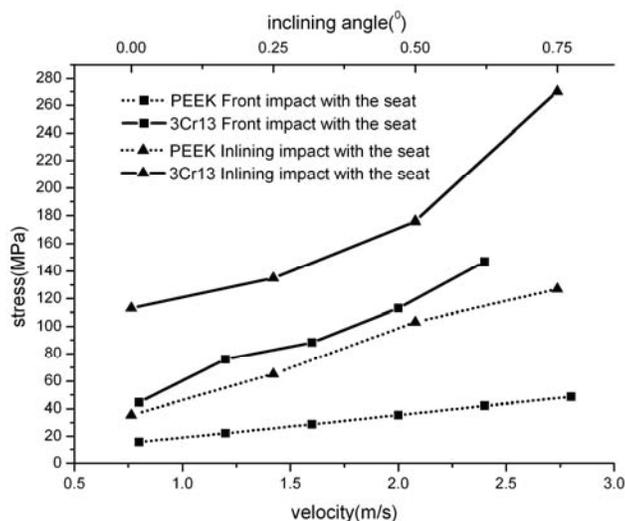


Fig.7 comparisons between front impacts and inclining impact with the seat

4. CONCLUSION

By simulating and measuring the valve motion during the compressing process, several characteristics about valve motion had been analyzed and the factors influencing the performance and reliability were identified.

- (1) The valve plate suffered larger impact stress when it impacted the seat compared with the limiter because the flow passage in the seat made the valve plate undertook addition bending and impact stress.
- (2) The valve impact stress increased when inclining motion happened, and it grew almost linearly with the increment of inclining angle. That's because only one point of the valve plate nearly suffered all the impact force, which resulted in stress concentration and valve failure.
- (3) Compared with metallic valve material, nonmetallic material, such as PEEK, can withstand larger impact velocity and inclining angle.

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