2000

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Optimal Valve Design for Reciprocating Compressor

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ABSTRACT

We developed a novel discharge valve characters using the stopper to obtain the high efficiency reciprocating compressor for refrigerators. Generally, the sticky force occurred due to the shape of valve, stopper and oil between the valve and valve seat changed the process of valve motion and valve dynamics of compressor. In this paper, we can measure the characteristics of the sticky force and develop the experimental system to measure the time-lag due to the sticky force. Also we optimize the discharge valve motion to minimize the over-compression loss of discharge valve system. We verify the volumetric efficiency of a novel valve system by experiments.

INTRODUCTION

Compressor is one of the important parts to increase the performance and to optimum design of refrigeration cycles for refrigerating systems. Recently, high efficiency compressor is developed to reduce the energy consumption for the home appliances, refrigerators. Opening and closing time of suction and discharge valve system are very important to determine the volumetric efficiency of reciprocation compressor. Especially, the discharge valve is opened by the gas compression force in the cylinder, static and dynamic stiffness of the valve and the sticky force by acting the refrigerant oil between the valve and its seat, and a compressed gas is discharged to the discharge plenum by the discharge port and the lift of the valve. The hydraulic loss increases because the less the lift of discharge valve is the more the velocity of discharge gas is. If the lift of valve exceed the critical value then the noise level increase. The later the discharge valve opens the more the pressure of a cylinder compresses. Therefore the over-compression loss increases when the pressure difference between a cylinder and a discharge plenum is large. The discharge valve is opened when the pressure difference is larger than the stiffness of the discharge valve and then the
pressure in the cylinder is dropped. The moment the pressure difference is smaller than the stiffness of the discharge valve, it begins to close at that time the valve is contacted to the stopper cause of the sticky force due to the viscosity. When the sticky force is strong then the closing time of discharge valve is delayed, and the volumetric efficiency decreased because the discharged gas flowed backward to the suction plenum. In this paper, we study the physical phenomena of the discharge valve system due to the sticky force and optimal volumetric efficiency under the operating conditions of reciprocating compressor.

**TOTAL STICKY FORCE ACTING ON A DISCHARGE VALVE AND A STOPPER**

As shown in Fig. 1, it is assumed that the discharge valve is a single degree of freedom mass-spring system, and let the dimensionless radial distance $\xi = r/R$, a dynamic viscosity of oil film $\mu$. From the Reynolds equation [Brooker, 1983, Khalifa and Liu, 1998] of hydrodynamic lubrication and the continuity equation, the total sticky force, $F_s$ arising from oil film between the discharge valve and its stopper is like an Equation (1).

$$F_s = \int_0^R 2\pi r (p - P_d) dr$$
$$= \int_0^1 2\pi R^2 R'\xi (p - P_d) d\xi$$
$$= -\frac{3\pi \mu}{2} R^4 \left[ \frac{1}{y^3} \frac{dy}{dt} \right]$$

(1)

We note that the total sticky force depends on the contact area and the distance between a discharge valve and its stopper.

**Fig. 1 Analytic Model of Discharge Valve System**
I Experiment 1. Measuring the Lift Force of a Discharge Valve with a Oil

The difference of a sticky force resulted in varying the contact area of a discharge valve and the lift of a discharge valve is evaluated by experiments. Fig. 2 shows the discharge valve system, and the two different shapes of a section in a sample (a) and a sample (b). The contact area between the discharge valve and sample (a) stopper is 20% that of a sample (b). The lift force of a discharge valve is measured by using a force gauge. The sticky force, $F_{\text{sticky}}$ occurred when oil film is formed according to rising a discharge valve lift. The lift force, $F_{\text{lift}}$ is represented in Equation (2). It is shown in Fig. 3 that the lift force increases as the lift of the discharge valve increases. The lift force of a sample (a) which contact area is smaller than sample (b) is large.

![Discharge Valve System Geometry](image)

\[ F_{\text{lift}} = F_{\text{spring}} - F_{\text{stiction}} \]  
(2)

![Lift Force Acting on Discharge Valve and Stopper](image)

I Experiment 2. Time-lag of a Discharge Valve with a Oil

The sticky force which the oil film is formed between discharge valve and its stopper, acts on the discharge valve when the discharge valve opened. According to the viscosity of the oil the
time-lag occurred because of the difference of the sticky force between the discharge valve and its stopper. We can obtain the characteristic of the time-lag due to the sticky force by experiments. As shown in Fig. 4, the discharge valve is fixed with a rivet on the valve plate. And the stopper, rivet and discharge valve are insulated one another in addition to the electrical pointer-electrode is used to attach the discharge valve to the stopper. Also to find the time-lag an electric circuit in Fig. 4 is applied. [Ozu, M and Itani, T, 1980] At first, the discharge valve comes into contact with a stopper by a electrode

![Diagram of Measuring System of a Time-lag by a Sticky Force](image)

**Fig. 4 Measuring System of a Time-lag by a Sticky Force**

then the stopper, discharge valve and the valve plate are transmitted as being a current path one another. The instant that the electrode falls apart, an electric potential difference between point ② and point ③ occurs because the electrode is insulated to the valve plate. When the electrode falls apart from the stopper, the electric potential difference between point ① and ③ occurs. If the sticky force resulted from dilating the oil film between the discharge valve and its stopper exists, after the electrode falls apart from the discharge valve an electric potential difference between point ① and ③ arises a few later. A point of a different time occurred and the electric potential difference, Δt in Fig. 5 is the time-lag that results from sticky force between discharge valve and its stopper. Fig. 5 presents typical results of the time-lag.

![Graph of Typical Time-lag Results from Sticky Force](image)

**Fig. 5 Typical Time-lag Results from Sticky Force**
In general, the viscosity of refrigerant oil exponentially decreases as the oil temperature increases. Fig. 6 shows the time-lag that results from applying a sample (a) and a sample (b) in Fig. 2 to the valve plate. As shown in Fig. 6, the parts of changing from 8msec to 2msec are the experimental data of time-lag result from applying a sample (b), the parts of few changed are the time-lag of applying a sample (a). The more an oil temperature increases the more a time-lag exponentially decreases in Fig. 6. The time-lag of a sample (a) which narrowly contacted with the discharge valve than that of a sample (b) is shorter than that of a sample (b).

![Figure 6: Time-lag Results from Sticky Forces between Stopper and Discharge Valve](image)

**Fig. 6 Time-lag Results from Sticky Forces between Stopper and Discharge Valve**

**Experiment 3. Measuring of a Suction and Discharge Valve Motions**

The motions of a suction and a discharge valve are measured in normally operating reciprocating compressor (ASHRAE/T, refrigerant: R134-a). As shown in Fig. 7, an experimental apparatus is designed to observe the suction valve motion that opens and closes from measuring the contact and separate time to the electrode in the valve seat according to the piston's reciprocating motion. Also two gap sensors are used to measure the motion of a discharge valve and the piston location by using an encoder fixed at the top of the shaft.

Fig. 8 shows the experimental results of the motion of suction and discharge valves in the case of sample (a) and (b) in Fig. 2. A crank-angle sets to 0° when a piston is located at TDC (top dead center). Table 1 shows the crank-angle during discharge valve's open in each case. As shown in Fig. 8 and Table 1, an oil film between the discharge valve and its stopper causes the sticky force. Therefore the sticky force has changed the motion of discharge valve in each case. In case of a sample (a) that has a small sticky force, it is shown that the duration of a discharge valve being opened is shorter than in case of a sample (b) within a single cycle of piston.
Fig. 7 Experimental Set up to Measure the Motion of Valves

Fig. 8 Suction and Discharge Valve Motion in case of Sample (a) and Sample (b)
dashed line : Motions of Suction Valves, solid lines : Motions of Discharge Valves
Table 1. Discharge Valve Opening Angle (degree)

<table>
<thead>
<tr>
<th></th>
<th>discharge valve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>open angle(deg)</td>
</tr>
<tr>
<td>Sample (a)</td>
<td>337.8</td>
</tr>
<tr>
<td>Sample (b)</td>
<td>333.5</td>
</tr>
</tbody>
</table>

■ Experiment 4. Measuring of a PV-Diagram

To verify that the difference of the volumetric efficiency resulted from the existing time-lag due to a sticky force between discharge valve and its stopper, we measured the pressure of a cylinder and a discharge plenum. And then the results are compared. Fig. 9 (a) is a typical PV-diagram and Fig. 9 (b) is a typical over-compression loss.

![PV-diagram and Over-compression Loss](image)

For the sample (a) and (b) stopper in Fig. 2, the amounts of an over-compression loss are 59.8[kgf·cm] and 61.4[kgf·cm] respectively.

CONCLUSION

A refrigerant oil in a reciprocating compressor flows to a cylinder and suction, discharge valve system, and plays an important role to lubricate the mechanical pairs, to seal the piston-cylinder, and so on. The sticky force resulted from the oil film between a discharge valve and its stopper delays the closing time of a discharge valve. The time-lag causes a compressor to decrease the efficiency. We find out the sticky force resulted from the oil film between a discharge valve and its stopper, and the time-lag of a discharge valve due to a sticky force by experimental methods. We verify that the compressor efficiency can be enhanced by decreasing the sticky force.
REFERENCES

