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# Analysis of Dynamic Behavior of Suction Valve Using Strain Gauge in Reciprocating Compressor

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## ABSTRACT

The motion of the suction valve of a hermetic reciprocating compressor for a domestic refrigerator was measured with a strain gauge. The valve motion at a low rotation speed varied widely because of the sticking force of the lubricant oil. The motion of the suction valve was found to have an effect on the volumetric efficiency. The number of valve vibrations over the suction port caused periodic fluctuation of the volumetric efficiency with respect to the operation speed of the compressor.

## 1. INTRODUCTION

In recent years, the increased awareness of environmental issues has led to growing consumer demand for domestic electrical appliances that have greater energy-saving properties and that reduce the impact on the environment. Domestic refrigerators with low power consumption are also in high demand because the amount of electricity consumed by refrigerators is among the highest for all consumer household products. It is therefore important to develop a highly efficient compressor to reduce the power consumption of refrigerators.

The required cooling capacity of the compressor depends on the design of the refrigerator. To develop a highly efficient compressor, it is important to keep the required cooling capacity of the compressor at a low input power. Therefore, the compressor must have high volumetric efficiency. A number of factors affect the volumetric efficiency of a reciprocating compressor. A dead volume in the cylinder is one factor that can decrease the volumetric efficiency. The clearance between the piston and the cylinder head, the volume of gas in the discharge port, and the space for the suction valve comprise a dead volume in the cylinder. Another factor that decreases the volumetric efficiency is rising temperature of the suction gas. If the suction gas is heated in the suction process in the compressor chamber, the density of the suction gas decreases. The mass flow of a refrigeration cycle depends on the suction-gas density. Therefore, low temperature suction gas leads to high volumetric efficiency. Additionally, leakage of the refrigerant gas from the clearance between the piston and the cylinder is another factor that decreases the volumetric efficiency.

Many refrigeration compressors have reed valves as suction and discharge valves. These valves are moved by the differential pressure between the inside cylinder and the suction and discharge plenums. The motion of these valves significantly affects the compressor efficiency because the valve motion influences the pressure drop in the suction and discharge processes and the refrigerant gas flow rate. To fully understand the inner workings of a reciprocating compressor and to improve the compressor efficiency, it is very important to understand the motion of these valves. However, it is difficult to predict the valve motion because the fluid force of the refrigerant gas and the viscosity of the lubricant oil make the valve motion complicated.

To discern the reed valve motion experimentally, high-speed cameras are sometimes used. However, it is difficult to use an ordinary high-speed camera in a small hermetic compressor due to the extremely small observation area and the use of oil mist in the compressor chamber. In this study, a strain gauge was used to measure the motion of the suction valve of a hermetic reciprocating compressor for a domestic refrigerator.

## 2. CONSTRUCTION OF EXPERIMENTAL APPARATUS

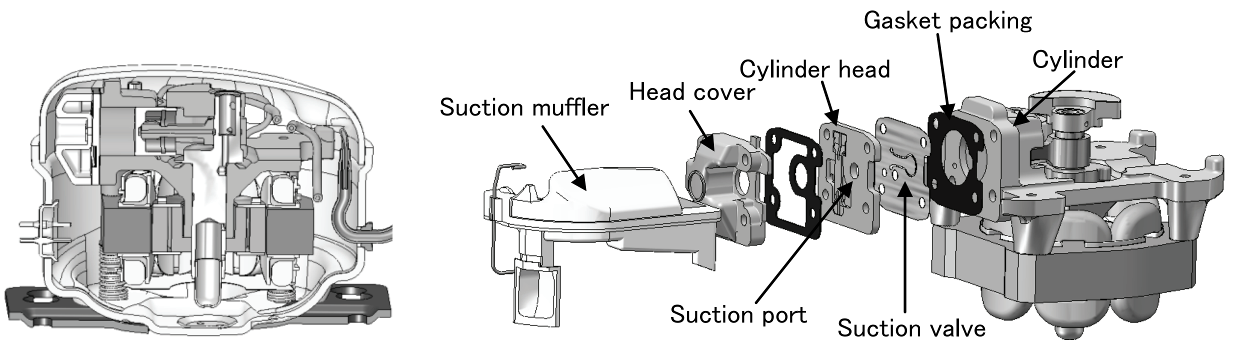
Figure 1(a) illustrates a cross section of the reciprocating compressor with the commercially produced chamber. In this study, the special chamber that has some feedthroughs for electrical signal was used. This compressor has a pressurizing structure (cylinder and piston) on the DC motor, and these structures are supported by four springs in the chamber. This compressor is driven by an inverter and uses R600a (isobutane) as a refrigerant.

Figure 1(b) shows an exploded view of the assembly around the suction and discharge valves. The discharge valve is located in the groove of the cylinder head. The suction valve is clamped between the cylinder head and the cylinder with the gasket packing. The suction valve is 0.2 mm thick and is fabricated from spring steel. These reed valves are moved by the differential pressure between the upside and downside of each valve. In the case of the suction valve, the valve opens when the cylinder pressure falls below the pressure of the suction muffler.

The refrigerant gas in the chamber flows into the cylinder through the suction muffler and suction port on the cylinder head. In the cylinder, the refrigerant gas is compressed and discharged to the discharge plenum through the discharge port.

A strain gauge was used to measure the motion of the suction valve. The valve displacement from the suction port is calculated from the strain of the suction valve. Figure 2 shows the arrangement of the strain gauge on the suction valve. The strain gauge was attached at the base of the reed valve because the maximum strain occurs at the base of the reed valve when the valve is displaced. To determine the relationship between the pressure in the cylinder and the motion of the suction valve, a pressure transducer was set at the cylinder.

The motion of the suction valve was measured at the compressor during operation. The operating conditions are listed in Table 1. The pressure conditions, for example, discharge pressure and suction pressure, were set at a constant value in this study.




(a) Cross section of compressor (b) Exploded view of assembly around suction and discharge valves

Figure 1: Reciprocating compressor

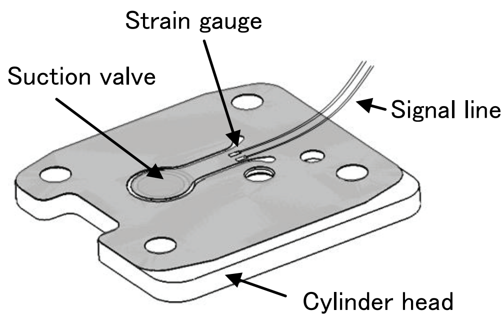



Figure 2: Strain gauge on suction valve

Table 1: Operating conditions of compressor

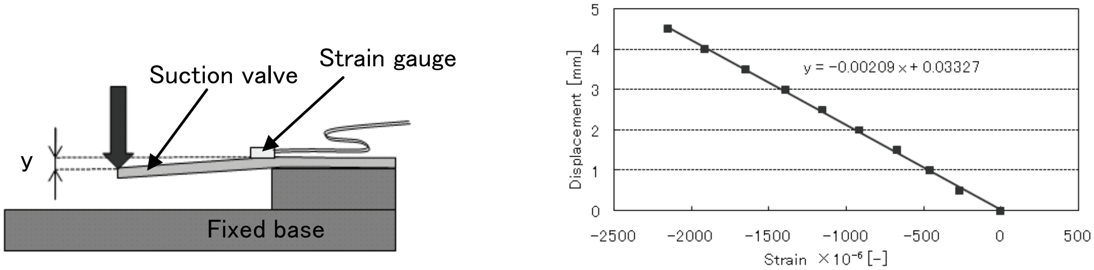
| | |
|---|---|
| Rotation speed | 1500–4000 $min^{-1}$ |
| Discharge pressure | 438 kPa |
| Suction pressure | 55 kPa |
| Refrigerant | R600a |
| Lubricant viscosity | 10 cSt |

## 3. DISPLACEMENT OF SUCTION VALVE

### 3.1 Relation between Strain and Displacement of Suction Valve

The static relation between the signal from the strain gauge and the displacement of the suction valve was obtained using the experimental setup shown in Figure 3(a). The suction valve was set on a fixed base, and the strain was measured while a displacement was applied to the head of the suction valve.

Figure 3(b) plots the relation between the strain data and the displacement at the head of the reed valve. The displacement of the valve increases linearly with the strain. The valve displacement in the operating compressor was calculated using this relation.




(a) Experimental set up (b) Experimental data

Figure 3: Relation between strain and displacement

### 3.2 Motion of Suction Valve

Figure 4 plots the dynamic motion of the suction valve at 1500 $min^{-1}$, 2000 $min^{-1}$, 3000 $min^{-1}$, and 4000 $min^{-1}$. The horizontal axis represents the time from the moment at which the signal rises. The vertical axis represents the displacement of the top of the suction valve calculated by the method previously explained. Each figure shows five histories of the motion of the suction valve under the same experimental conditions. The maximum displacement becomes larger with the rotation speed of the compressor. This occurs because the rate of change of the cylinder pressure becomes larger, and the difference in pressure between the cylinder and the suction muffler becomes larger as the rotation speed gets faster. A large pressure difference leads to a large displacement of the suction valve.
The vibration period of the valve is constant with the rotation speed. This means that the suction valve vibrates with a certain characteristic vibration.

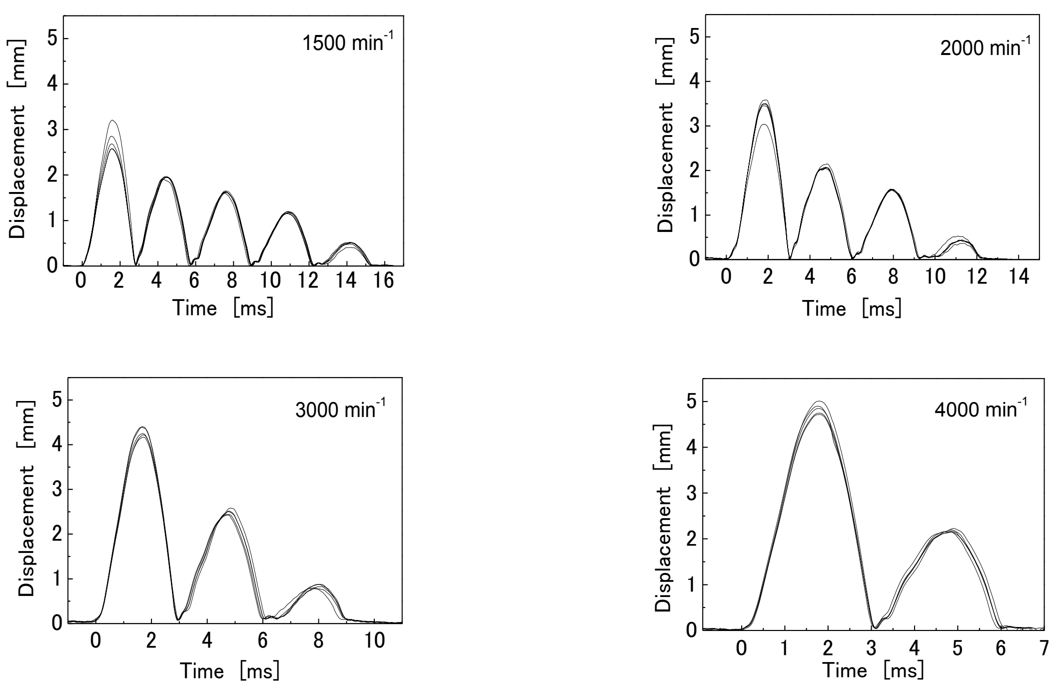



Figure 4: Motion of suction valve

Table 2 indicates the relation between the number of vibrations (shown as peaks on the graphs in Figure 5) of the suction valve and the rotation speed. The number of vibrations decreases as the rotation speed increases because the time span between the opening of the suction valve and the end of the suction process is short at high rotation speeds.

Table 2: Number of vibrations of suction valve

| Rotation speed ($min^{-1}$) | 1500 | 1700 | 2000 | 2500 | 2700 | 3000 | 3300 | 3700 | 4000 |
|---|---|---|---|---|---|---|---|---|---|
| Number of vibrations | 5 | 5–4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |

### 3.3 Variability of Maximum Valve Displacement

Figure 5 shows the Maximum displacement of the suction valve at several rotation speeds. Numbers 1, 2, and 3 in the figure legend represent the data of different valves under the same experimental conditions. Each plot in the figure is the average value of data from five measurements of the same valve. The maximum displacement varies widely at speeds under 2500 $min^{-1}$. In addition to piece-to-piece variations, there is large variation for individual valves. Figure 6 shows the cylinder pressure and suction valve behavior at a rotation speed of 1700 $min^{-1}$. The thin black line and the heavy gray line in the figure represent data obtained in the same experiment. The maximum displacement of the thin black line is about 1.5 mm larger than that of the gray line. The valve represented by the gray line begins to open earlier than that represented by the black line. If the valve opening is delayed, the pressure in the cylinder drops further, and the pressure difference between the cylinder and the suction muffler increases. Therefore, the delay of the valve opening results in a larger displacement. One reason the valve opening might be delayed is due to the adhesive force of the lubricant oil viscosity. The suction valve begins to open when the pressure difference between the cylinder and the suction muffler overcomes the sticking force of the oil. Thus, a variation of the sticking condition of the oil on the suction port causes a variation of the maximum valve displacement. The valve motion is particularly affected by the sticking force of the oil at low rotation speeds. At low rotation speeds, the change ratio of the pressure in the cylinder is small, and the pressure force applied to the valve is relatively weak compared to the sticking force of the oil. On the other hand, the change ratio of the pressure in the cylinder increases at high rotation speeds, and the effect of the lubricant oil becomes relatively small. As a result, the variation of the valve motion becomes conspicuous at low rotation speeds.

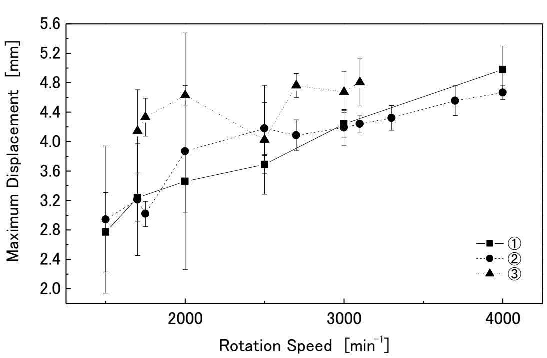



Figure 5: Maximum displacement of suction valve

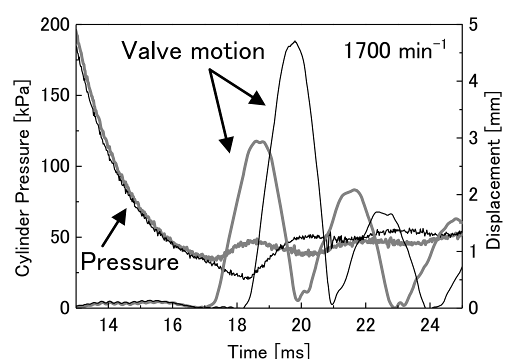



Figure 6: Cylinder pressure and suction valve behavior

## 4. EFFECT OF VALVE MOTION ON VOLUMETRIC EFFICIENCY

The dynamic behavior of the suction valve has a significant influence on the circulating volume of the refrigerant gas in the refrigerating cycle. In this chapter, the influence of the suction valve on the volumetric efficiency is discussed using experimental data.

### 4.1 Period Characteristics of Volumetric Efficiency

Figure 7 plots the relation between the rotation period and the volumetric efficiency. The pressure conditions for this experiment are given in Table 1. The rotation period in this figure is the inverse number of the rotation speed of the compressor. Increasing the rotation period slows down the rotation speed. In this figure, volumetric efficiency is normalized with the volumetric efficiency at a certain rotation period. The curved line of the volumetric efficiency has a wavy characteristic. The cycle of this wave is approximately constant, and the amplitude becomes smaller as the rotation period becomes longer.

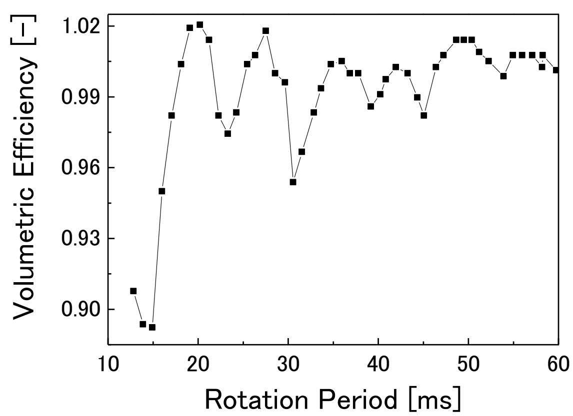



Figure 7: Volumetric efficiency of reciprocating compressor

### 4.2 Relation between Volumetric Efficiency and Vibration of Suction Valve

The dynamic behavior of the suction valve changes with the rotation speed, as previously shown in Figure 4, and this change in the valve motion affects the volumetric efficiency. In principle, the refrigerant gas can flow into the cylinder from the time the suction valve opens until the time the piston arrives at the bottom dead center. If the suction valve does not close completely when the piston passes the bottom dead center, refrigerant gas flows back from the cylinder to the suction muffler. In other words, it is better to close the suction valve completely before the piston passes the bottom dead center for higher volumetric efficiency. This late closure of the suction valve that reduces the volumetric efficiency is caused by the relation between the rotation period of the compressor and the vibration period of the suction valve.

Figure 8 is a conceptual diagram of the suction valve motion. The horizontal axis is the crank angle of the shaft. This crank angle at the bottom dead center is $2\pi$ radians. The vertical axis indicates the displacement of the suction valve. In this figure, three valve motions at different rotation speeds are plotted. Line (A) is the valve motion at the lowest rotation speed and line (C) is at the highest rotation speed. $\theta_s$ is the start point of the valve opening. First, we focus on the behavior of line (A). At this rotation speed, the valve vibrates three times over the suction port. The time span of late closure of the valve (late closure time) is indicated by arrowed line (a). The refrigerant gas flows back from the cylinder in this late closure time. As the rotation speed of the compressor increases, the motion of the valve changes to line (B), and the late closure time changes to arrowed line (b). The wave profile of the valve motion extends transversally from (A) to (B) on this figure because the rotation period becomes shorter as the rotation speed increases and the vibration period of the valve is constant. As a result, the late closure time becomes longer, and the volume of backflow of refrigerant gas increases. Then, the rotation speed gets faster, and the wave motion changes to line (C). At this rotation speed, the valve vibrates over the suction port two times. This reduction in the number of vibrations results from prolonging the late closure time and increasing the rotation speed. A force to close the valve is exerted on the valve in the late closure time because the pressure in the cylinder increases when the piston moves from the bottom dead center to the top dead center. This force closes the suction valve in the compression process and becomes stronger as the rotation speed gets faster, and finally, the vibration at the time of the late closure is suppressed by the compressed pressure in the cylinder. As a result, the time span of the late closure decreases because of the reduction in the number of valve vibrations.

Volumetric efficiency will be the highest at the rotation speed of (C) and the lowest at the rotation speed of (B). This means that the volumetric efficiency fluctuates as the rotation speed gets faster. According to this mechanism, the volumetric efficiency curve as shown in Figure 8 has a peak when the suction valve closes completely at the bottom dead center. Consequently, the period of the peak of volumetric efficiency is approximately constant because the vibration period of the suction valve is constant.

Figure 9 shows the relation between the number of valve vibrations and the rotation period at peak volumetric efficiency of some compressors that have the same suction valves. The number of vibrations was estimated using the data from the experimental results in Table 2. The number of vibrations at the rotation period at which volumetric efficiency has the peak value increases by one as the rotation speed gets slower. This result is consistent with the mechanism described above.

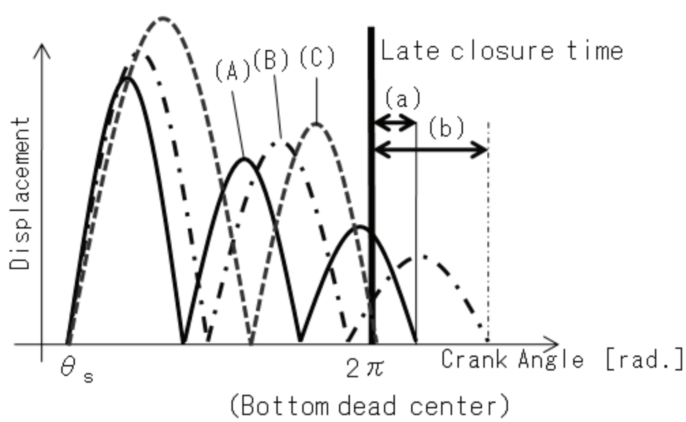



Figure 8: Conceptual diagram of valve motion

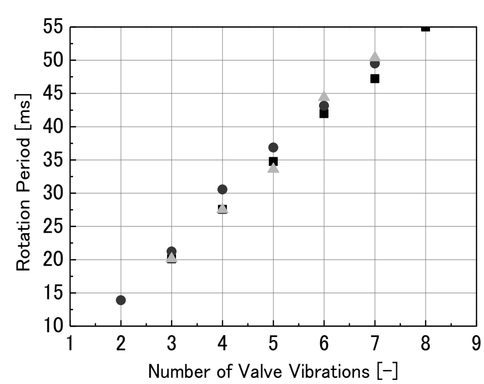



Figure 9: Number of valve vibrations and rotation period at peak of volumetric efficiency

## 5. CONCLUSION

The dynamic behavior of the suction valve in a reciprocating compressor was measured using the strain gauge, and the relation between the volumetric efficiency and the valve motion was analyzed. The results of this study can be summarized as follows.

- The maximum displacement of the suction valve increases, and the number of vibrations over the suction port decreases as the rotation speed gets faster.
- The valve motion at the low rotation speed varies widely because of the sticking force of the lubricant oil.
- The number of valve vibrations causes the periodic fluctuation of the volumetric efficiency with respect to the rotation speed of the compressor.

## NOMENCLATURE

| | | |
|---|---|---|
| $\theta_s$ | Crank angle at suction valve opening | (rad.) |

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