Performance Comparison of Single-stage and Two-stage Hermetic Rotary CO2 Compressor

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Performance Comparison between a Single-stage and a Two-stage Hermetic Rotary CO₂ Compressor

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ABSTRACT

As a natural refrigerant, CO₂ gets more and more attention in recent years. The CO₂ system runs at a trans-critical cycle. This leads to a high running pressure and high pressure difference for the CO₂ compressor. In this paper the single stage and two stage rolling piston compressors with same displacement have been developed for CO₂ heat pump water heater. And a comprehensive performance comparison has been made with these two kinds of compressor at different pressure ratio and superheat. With these results, a better understanding for the single stage and two stage CO₂ compressors could be got.

1. INTRODUCTION

Carbon dioxide (CO₂) as a nature refrigerant has attracted many attentions again because of global warming issue. As a natural refrigerant, CO₂ has been used in the past and proved to be environmentally friendly. The physical properties of CO₂ make it particularly suitable for heat pump water heaters. Compared with the traditional Freon refrigerants heat pump water heater, CO₂ heat pump water heater has higher energy efficiency, higher outlet water temperature (up to 90 °C in winter), and lower performance degradation in low temperature environment.

The research and development of CO₂ refrigeration system have been paid more attention in recent years. The compressor is a key component of CO₂ refrigeration system. Due to the high pressure difference for CO₂ compressor, the initial products mainly were two-stage compressor. With the in-depth of development, single-stage compression products have gradually been adopted. The performance comparison between single-stage and two-stage CO₂ compressor, especially at a wide running condition, were mentioned less in previous literature.

In this paper, a single-stage and a two-stage hermetic rolling piston CO₂ compressor with same displacement were developed. The performance of the two types of CO₂ compressor at different pressure ratio and superheat were tested and compared. With these results, a better understanding for the single-stage and two-stage CO₂ compressor could be got.
2. DEVELOPMENT OF CO\textsubscript{2} COMPRESSOR

In this paper, a single-stage and a two-stage hermetic rolling piston CO\textsubscript{2} compressor were developed.

![Diagram of compressors](image)

**Figure 1:** The schematic view of the compressors

Figure 1(a) shows the schematic view of the two-stage compressor in conjunction with the refrigerant flow path. The low pressure refrigerant flows into the first-stage compression unit located in the lower part of the whole compression unit. And then it is compressed to an intermediate pressure determined by the suction pressure and the structure of the compressor. After that, the refrigerant is directly discharged out of the compressor from the first-stage compression unit. After a cooling process in the intercooler, the refrigerant enters into the second-stage compression unit located in the upper part of the compression unit. In this compression unit, the refrigerant is compressed to high pressure, and then discharged into the shell of the compressor. Flowing through the gaps of motor on the upper of the compressor, the refrigerant is discharged out of the compressor to gas cooler of CO\textsubscript{2} transcritical refrigeration cycle.

Obviously, the discharge pressure in the shell of the two-stage compressor is much higher than that of the intermediate pressure compressor. According to this special compression arrangement, the oil on the bottom of the compressor can be easily pumped into the clearance between the movement parts. The lubrication becomes better and compressor reliability is improved. In addition, before being discharged out of the compressor, the refrigerant flowing through the gaps of motor can reduce the oil flow rate ratio (defined as the ratio of the oil flow rate to the refrigerant mass flow rate) and improve the efficiency of the refrigeration system.

Figure 1(b) shows the schematic view of the single-stage compressor in conjunction with the refrigerant flow path. It’s simpler than the two-stage compressor. The low pressure refrigerant flows into the compression unit located in the lower part of the compressor. In the compression unit, the refrigerant is compressed to high pressure, and then discharged into the shell of the compressor. The high pressure refrigerant flows through the gaps of motor on the upper of the compressor, and then is discharged out of the compressor.

Table 1 shows the basic parameters of these two kinds of compressors.

<table>
<thead>
<tr>
<th>Structure of compressor</th>
<th>Rolling piston compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td>Single-stage</td>
</tr>
<tr>
<td></td>
<td>Two-stage</td>
</tr>
<tr>
<td>Displacement</td>
<td>3.26cm\textsuperscript{3}/rev</td>
</tr>
<tr>
<td></td>
<td>3.26cm\textsuperscript{3}/rev</td>
</tr>
<tr>
<td>Power</td>
<td>220～240V/50Hz</td>
</tr>
<tr>
<td></td>
<td>220～240V/50Hz</td>
</tr>
<tr>
<td>Motor</td>
<td>Single phase asynchronous</td>
</tr>
<tr>
<td></td>
<td>Single phase asynchronous</td>
</tr>
</tbody>
</table>
3. PERFORMANCE TEST

3.1 Performance Test Rig

Figure 2 shows the schematic view of the test rig. The test rig consists of the main components such as tube-in-tube gas cooler, evaporator, intercooler, electronic expansion valve and super heater and auxiliary components such as oil separator, filter and vapor-liquid separator. A water tank whose temperature can be controlled is used as heat source and heat sink for evaporator and gas cooler. The mass flow meter was installed at the outlet of the gas cooler where the density of the refrigerant is the highest. During the tests, the suction pressure of compressor is controlled by adjusting the water flow rate flowing through the evaporator. The super heater is used to fine-tune the suction temperature and the discharge pressure of the compressor is controlled by the opening degree of the electronic expansion valve.

The measurement range and uncertainties for pressure, temperature, mass flow rate and power consumption are summarized in Table 2. The resulting uncertainties for volumetric efficiency and isentropic efficiency were about ±0.5% and ±0.6% respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Range</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0~16MPa</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Temperature</td>
<td>-20~150℃</td>
<td>±0.15℃</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0~200kg/h</td>
<td>±0.5%</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0~2000W</td>
<td>±0.25%</td>
</tr>
</tbody>
</table>

![Figure 2: The performance test rig for hermetic CO₂ compressor](image)

1—compressor, 2—oil separator, 3—gas cooler, 4—electronic expansion valve
5—evaporator, 6—filter, 7—suction superheater, 8—mass flow meter, 9—gas-liquid separator

3.2 Compressor Efficiency Calculation

In this paper, the volumetric efficiency \( \eta_v \) and isentropic efficiency \( \eta_i \) were used to evaluate the performance of the compressor. The formulas are as following.

\[
\eta_v = q_{v,2} / q_{v,1}
\]  

(1)
Where, $q_{vc}$ is measured volumetric flow rate, and $q_{tvc}$ is the theoretical volumetric flow rate, and the unit is m³/h. $q_m$ is measured mass flow rate, and the unit is kg/h. $h_1$ is the specific enthalpy of the refrigerant at inlet of the 1st stage of the compressor, and the unit is kJ/kg. $h_2$ is the theoretical specific enthalpy of the refrigerant at the discharge pressure after a isentropic compression from the suction state of the compressor, and the unit is kJ/kg. $P$ is the measured input power of the compressor, and the unit is W.

### 3.3 Compressor Operating Conditions for Performance Test

For the purpose of getting a comprehensive performance comparison between the single-stage compressor and two-stage compressor, the two kinds of compressors were tested at different operating conditions. The suction pressure range is 3.5~4.5MPa, the discharge pressure range is 8.0~11.0MPa, and suction superheat range is 10~20K.

For the tested two-stage compressor, the discharge pipe of the first stage was connected directly to the suction pipe of second stage, so there is no intercooler in the test.

### 4. RESULTS AND ANALYSIS

#### 4.1 Effect of Pressure Ratio on Volumetric Efficiency

Figure 3 shows the relationship between volumetric efficiency $\eta_v$ and pressure ratio (defined as the ratio of the discharge pressure to the suction pressure of the compressor) under different discharge pressure for tested compressors. It can be seen that the volumetric efficiency of single-stage CO₂ compressor is higher than that of two-stage CO₂ compressor at lower pressure ratio. With the increase of pressure ratio, the volumetric efficiency will decrease, and the dropping speed of $\eta_v$ of single-stage CO₂ compressor is faster than that of two-stage CO₂ compressor. The volumetric efficiency gaps between the two kinds of compressors become small. When the pressure ratio is closed to 2.8, the $\eta_v$ of two-stage CO₂ compressor will be higher than that of single-stage CO₂ compressor.

Furthermore, there is an optimal pressure ratio for two-stage CO₂ compressor, at that pressure ratio the $\eta_v$ reaches a peak.

For a two-stage compressor, the pressure ratio of the first stage (defined as the ratio of the discharge pressure of the first stage to the suction pressure of the first stage) mainly is determined by the displacement ratio of the first stage to second stage which is a structure parameter. For the developed two-stage compressor, this pressure ratio is about 1.8. When the pressure ratio of the compressor is small, the load coming from the pressure difference and pressure ratio mainly acts on the first stage. At this situation, the second stage almost doesn’t play the role of compression unit. However the frictional loss and heat loss coming from the second stage remains, so the performance of the compressor will be affected. Only when the first stage and the second stage can undertake the load evenly, the compressor can get a higher performance. That’s why there is an optimal pressure ratio for the two-stage compressor.

![Figure 3: The $\eta_v$ at different pressure ratio](image-url)
4.2 Effect of Pressure Ratio on Isentropic Efficiency

Figure 4 shows the relationship between isentropic efficiency $\eta_i$ and pressure ratio under different discharge pressure for tested compressor. The trend is similar to volumetric efficiency. At lower pressure ratio, the isentropic efficiency of single-stage CO$_2$ compressor is higher than that of the two-stage CO$_2$ compressor. With the increase of the pressure ratio, the isentropic efficiency will decrease, and the dropping speed of $\eta_i$ of single-stage CO$_2$ compressor is faster than that of two-stage CO$_2$ compressor. The isentropic efficiency gaps between the two kinds of compressors become small. Similarly there is an optimal pressure ratio for two-stage CO$_2$ compressor; at that pressure ratio the $\eta_i$ reaches a peak. The reason is same as the volumetric efficiency as mentioned above.

![Figure 4: The $\eta_i$ at different pressure ratio](image)

4.3 Effect of Superheat on Volumetric Efficiency and Isentropic Efficiency

Figure 5 shows the trend of $\eta_v$ and $\eta_i$ with suction superheat for the tested compressor. It can be seen that the superheat has very small effect on the volumetric efficiency and isentropic efficiency under the testing conditions whether for the single-stage compressor or two-stage compressor.

![Figure 5: The $\eta_v$ and $\eta_i$ at different superheat](image)

5. CONCLUSIONS

A single-stage and a two-stage CO$_2$ compressor used for heat pump water heater with same displacement have been developed. A test rig for performance test of the CO$_2$ compressor has been built and the two kinds of compressors were experimentally compared. Based on the tested results, the effects of pressure ratio and superheat on performance have been analyzed. It is shown that the volumetric efficiency and isentropic efficiency of single-stage...
CO\textsubscript{2} compressor are higher than that of the two-stage CO\textsubscript{2} compressor at lower pressure ratio. With the increase of pressure ratio, the volumetric efficiency and isentropic efficiency will decrease, and the gaps of efficiencies between the two kinds of compressors become small. Furthermore, there is an optimal pressure ratio for two-stage CO\textsubscript{2} compressor, at that pressure ratio the volumetric efficiency or isentropic efficiency reaches maximum. And the superheat has very small effect on the volumetric efficiency and isentropic efficiency under the testing conditions whether for the single-stage compressor or two-stage compressor.

REFERENCES


