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Development and Performance Analysis of a Two Cylinder Rolling Piston Expander for Transcritical \( \text{CO}_2 \) System

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ABSTRACT

In order to improve the efficiency of the transcritical \( \text{CO}_2 \) cycle, a new two-cylinder rolling piston expander was proposed. Compared with the traditional rolling piston expander the suction valve of this expander could be removed, and therefore the expansion process becomes continuous. Both of the reliability and performance of the expander could be improved. In order to analyze the work process and forces acting on main components, a mathematical model of this kind of expander was developed.

1. INTRODUCTION

Carbon dioxide (\( \text{CO}_2 \)) is receiving high attention as a possible candidate replacement refrigerant of HCFCs and HFCs due to its environmentally benign. But in most of the higher temperature applications, such as stationary air conditioning system, \( \text{CO}_2 \) is not yet competitive concerning the COP. One main reason is the large throttling thermodynamic loss associated with the throttling process. The most effective method to improve the efficiency of the transcritical \( \text{CO}_2 \) cycle is to replace the throttling valve with an expander.

In this paper a new two-cylinder rolling piston expander was proposed. Figure 1 shows the schematic view of the expander. This expander consists of two expansion units, which are named the first expansion unit and the second expansion unit separately. Similar to the twin cylinder rolling piston compressor, each expansion unit is made up of cylinder, rolling piston (roller), vane, spring, bearing and intermediate plate. For the first expansion unit, the rolling piston and the vane divide the space between cylinder wall and rolling piston outer surface into two chambers: suction chamber and the first expansion chamber. For the second expansion unit, this space is divided into two chambers: the second expansion chamber and discharge chamber. The expansion chambers in the first expansion unit and second expansion unit are linked with an oblique hole in the intermediate plate, therefore the two expansion chambers constitute the expansion chamber of the expander. The two expansion units use a common crankshaft which have two eccentricity in the same direction. In order to realize the expansion process, the displacement of the second expansion unit is larger than that of the first expansion unit.

For this expander, a complete cycle includes three working processes. In the first process, the high pressure refrigerant enters the suction chamber from the inlet port. After which, the high pressure refrigerant turns into expansion chamber. As the crankshaft rotates, the volume of expansion chamber increases and the refrigerant pressure decreases, which is called the expansion process. At the end of this process the expansion chamber is filled with low pressure refrigerant. During the next process, which is called discharge process, the low pressure refrigerant turns into the discharge chamber then is discharged out of the expander through the outlet port.

Compared with the traditional rolling piston expander, the suction valve of this expander can be removed, then the expansion process becomes continuous and the reliability and performance of expander could be improved.

2. MATHEMATICAL MODEL

In order to study the working process and the dynamics of the moving elements of this kind of expander, a thermodynamic mathematical model was developed.
2.1 Control volume

Control volume were selected based on different working process, which means, control volume was suction chamber during suction process, expansion chamber during expansion process and discharge chamber during discharge process.

During the suction and discharge processes, the pressure in control volume was assumed equal to suction and discharge pressure. If the leakage and heat transfer between control volume and its surroundings was neglected, during the expansion process, the energy equation in terms of the derivative of temperature with respect to angular displacement of crankshaft was expressed as follows:

\[
\frac{dT}{d\theta} = - \frac{T}{c_v m} \left( \frac{\partial p}{\partial T} \right)_v \frac{dV}{d\theta},
\]  

(1)

Where \( m \) was the refrigerant mass in control volume, \( V \) was the volume of control volume and \( \theta \) was the rotational angle of crankshaft.

During the expansion process the refrigerant flows from the first expansion chamber to the second expansion chamber through the hole in intermediate hole. The flow velocity through this hole would be written as:

\[
u = \frac{dm_1}{dt} / (\rho A)
\]  

(2)

where \( m_1 \) was the refrigerant mass in the first expansion chamber, \( \rho \) was the refrigerant density in expansion chamber and \( A \) was the sectional area of the hole in intermediate plate.

2.2 Dynamics

For the CO\(_2\) expander, the load acting on crankshaft mainly caused by refrigerant force has a great effect on the power consumption and reliability. In each expansion unit the refrigerant force acting on crankshaft (delivered by roller) could be written as:

\[
F = DH\Delta p \sin \left( \frac{\theta + \alpha}{2} \right),
\]  

(3)

where \( D \) was the outer diameter of roller, \( H \) was the height of roller, \( \Delta p \) was the pressure difference between two chambers, the definition of \( \alpha \) is shown in fig 2. Therefore the total refrigerant force acting on crankshaft was:

\[
\vec{F}_{\text{total}} = \vec{F}_1 + \vec{F}_2,
\]  

(4)

where the \( \vec{F}_1 \) and \( \vec{F}_2 \) were the force acting on the first expansion unit and the second expansion unit separately.

Furthermore the refrigerant torque acting on crankshaft could be written as:

\[
M_{\text{total}} = M_1 + M_2 = e_1 F_1 \sin \left( \frac{\theta_1 + \alpha_1}{2} \right) + e_2 F_2 \sin \left( \frac{\theta_2 + \alpha_2}{2} \right),
\]  

(5)

where the \( e_1 \) and \( e_2 \) were the eccentricity of the first expansion unit and second expansion unit respectively.

3. RESULTS AND DISCUSSION

The basic specifications of the CO\(_2\) expander and the calculating conditions were summarized in Table 1 and Table 2 separately.
Table 1 Specification of the CO$_2$ expander

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First expansion unit</th>
<th>Second expansion unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement (cm$^3$)</td>
<td>0.43</td>
<td>1.29</td>
</tr>
<tr>
<td>Cylinder height (mm)</td>
<td>9.5</td>
<td>33</td>
</tr>
<tr>
<td>Cylinder diameter (mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Calculating conditions

<table>
<thead>
<tr>
<th>Suction pressure</th>
<th>Suction temperature</th>
<th>Discharge pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0MPa</td>
<td>35</td>
<td>3.48MPa</td>
</tr>
</tbody>
</table>

Figure 3 and figure 4 show the volume and pressure varied with rotational angle of crankshaft in a control volume. In the fist rotation of crankshaft the refrigerant is sucked in the suction chamber with the increased volume of suction chamber. In the second rotation of crankshaft the refrigerant enters the second expansion unit from the first expansion unit through the hole in intermediate plate and realizes the expansion process. In the final rotation of crankshaft the refrigerant is discharged from the discharge chamber while the volume of discharge chamber decreases.

The PV diagram of this expander is shown in Fig 5. In the expansion process the decrease of pressure becomes slow when the CO$_2$ enters the vapor-liquid two phases region, which is different from other subcritical refrigerants cycle.

Figure 6 shows the flow velocity through the hole in the intermediate plate at different diameter. The maximum value appears at about 140 degree, which can markedly decrease while the diameter of the hole increases.

Figure 7 shows the refrigerant force acting on crankshaft versus rotational angle. The force increases from about 0 degree and reaches maximum at about 180 degree, followed by decrease, at the end of one rotation this force approaches zero.

Figure 8 shows the variation of torque acting on crankshaft. It has the similar trend to the refrigerant force acting on crankshaft. At the beginning and end of one rotation of crankshaft it approaches zero, and reaches maximum at about 140 degree.

4. CONCLUSIONS

In order to improve the efficiency of the transcritical CO$_2$ cycle, a new two-cylinder rolling piston expander was proposed. This expander can run continuous without inlet valve. The decrease of pressure at expansion chamber becomes slow when the CO$_2$ enter the vapor-liquid two phases region. The refrigerant force and torque acting on crankshaft of expander increases with rotational angle, and reach maximum at a certain degree, then begin to decrease.

REFERENCES

Fig.1 The schematic view of Expander

Fig.2 The refrigerant force acting on crankshaft
Fig. 3 The volume of control volume

Fig. 4 The pressure in control volume

Fig. 5 The PV diagram

Fig. 6 The flow velocity through the hole

Fig. 7 The Force acting on crankshaft

Fig. 8 The torque acting on crankshaft