DEVELOPMENT OF ROTARY VANE EXPANDER FOR CO$_2$
TRANS-CRITICAL REFRIGERATION CYCLE

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ABSTRACT

The trans-critical CO$_2$ refrigeration cycle has a very high potential in various applications. One of the factors which limits its application is the relatively poor performance compared with other conventional cycles. However, the adoption of an expander can greatly improve its efficiency. This paper presents a new type of rotary vane expander for this purpose, which is used to replace the throttling valve to reduce the throttling losses. And an electrical generator is used to extract the work generated by the expander. The design of port positions and the selection of the vane materials are discussed. A test rig is built to carry out experimental research. The expander-generator unit is measured extensively in the CO$_2$ trans-critical refrigeration cycle. The recorded Pressure-Time (P-T) diagrams indicating the working process of the expander is also presented in the paper. This prototype is made to test the functionality of the expander and get elementary test results, and it provides valuable insight and experimental results for the next step and for validating the simulation model of the device.

Keyword: CO$_2$, Trans-critical Cycle, Rotary Vane, Expander

1. INTRODUCTION

Carbon dioxide, a natural refrigerant, is one of the candidates for the HFC refrigerants replacement in the refrigeration field, because of its characteristic such as non-toxic, non-flammable, zero ozone depletion potential, and low global warming potential and so on[1]. The trans-critical CO$_2$ refrigeration cycle has achieved a very high potential in various applications. One of the factors, which limit its application, is the relatively poor performance compared with other conventional cycles. However, the adoption of an expander can greatly improve its efficiency. Till now many researches have conducted for minimizing the throttling loss by using an expander as an expansion device [2, 3]. Many types of the expanders, such as the reciprocating expander, free piston expander, rolling piston expander, scroll expander and so on, have been discussed before. Baek et al. proposed a piston cylinder work producing expansion device [4]. In this paper, the work-producing expander replaced the expansion valve in an experimental trans-critical CO$_2$ cycle and increased the system performance by up to 10% as characterized by COP. Li Min-xia proposed a CO$_2$ rolling piston expander [5]. The author mentioned in the paper that the two-generation CO$_2$ rolling piston expander has been improved compared with the first generation. But there are still many problems, especially the vane. However, there are few papers, which present the rotary vane expander. Fukuta et al. proposed a vane type expander for CO$_2$ cycle [6]. The authors developed a mathematical model to analyze the expansion process of CO$_2$ and to examine the performance of an
expander for the CO\textsubscript{2} trans-critical cycle. Also the authors mentioned that the total efficiency of the prototype is 43 percent, though they did not show any design and experiment details. And in their recent research they claim that the efficiency of their new prototype has been improved to 60 percent.

In this paper, a rotary vane expander prototype has been designed, constructed and tested. Precise manufacturing and many new material of the vane are used to reduce the leakage, which is one of the critical problems of rotary expander. In addition, a CO\textsubscript{2} trans-critical refrigeration test rig is set up to test the performance, and some pressure sensors are placed in the cylinder to record the P-T diagram. Though we just finished testing the functionality of the expander and start to get useful test results, and the prototype is not the final product, it provides valuable insight and experimental results for the next step and for validating the simulation model of the device.

2. DEVELOPMENT RESEARCH OF THE ROTARY EXPANDER PROTOTYPE

2.1 Design of the rotary expander

In this paper, a rotary vane expander is discussed, which has simple structure, small size, and light weight and also the inlet and outlet valves can be avoided. The expander is designed according to the rotary compressor, which is used in the car air condition system. Figure 1 shows the structure of the rotary vane expander and in Figure 2 we can see the main parts of the expander such as the inlet and outlet ports, vanes, rotor, pressure sensor holes, and so on. In this prototype the sizes of all the parts are determined by the system requirement. And the cylinder profile, the number of the vanes and the size of the ports are optimized by the simulation model.

![Figure1 Structure model of the rotary expander](image1)

![Figure 2 Cut view of the rotary expander](image2)

As the expander is open-type and the operating pressure is very high, there are two problems. One is the axial force. In Figure 1 the shaft of the expander is open to the air, so the pressure difference of the two ends of the shaft is very large which causes a large axial force. And in our prototype a floating rotor is used to solve this problem. The other problem is the shaft seal. Four sealing pieces are used to prevent CO\textsubscript{2} with high pressure from leaking out of the working volume.

2.2 Manufacture of the rotary expander

The prototype only has a few parts, but precise manufacturing is needed in the prototype. Because the pressure of the CO\textsubscript{2} application is very high, so all parts of the prototype are made of steel. Precise manufacturing is needed to minimize the gaps between the rotor, vane, and the cylinder. The vane is one of the most important parts in the expander, which is used to seal the different chambers with different pressure. And the leakage from the vane and the friction loss of the vane
are the main losses of the expander. Several types of the vane materials and many kinds of the vane shapes are tested to improve the performance of the expander.

2.3 Work recover method
There are many ways for the refrigeration system to benefit from the output work of the expander. Electrical generator is used to convert the work into electric power. In Figure 3, the unit has three main parts, from left to the right, which is the expander, the torque instrument, and the generator. The shafts of the three parts are connected together. By varying the load of the generator, the rotating speed of the expander has been adjusted. At the same time, the torque instrument measures the rotating speed and the output work.

![Figure 3 Expander and generator unit](image)

2.4 P-T diagram measured method
According to the working theory, one pressure sensor cannot get the whole P-T diagram. In Figure 2 two pressure sensor holes are placed to get the P-T diagram, which indicates the internal work process of the expander. The ideal P-T diagram has been shown in Figure 4. The whole working progress has been divided into 3 parts, the suction process, expansion process and the discharge process. Pressure sensor 1 can record the suction process and part of the expansion process, and pressure sensor 2 can record part of the expansion process and the discharge process. So the expansion process has been cut into 3 parts. First it is recorded by pressure sensor 1 only. Second is recorded by both pressure sensors. And the last process is recorded by pressure sensor 2 only.

![Figure 4 Ideal P-T diagram](image)

![Figure 5 Leakage paths in the expander](image)
2.5 Leakage path
Leakage problem is one of the most important issues in the rotary expander. There are 5 kinds of leakage paths, see in Figure 5. The first is the gas leakage from the clearance between the rotor and the end cover to the working chamber; second is the gas leakage from high pressure working chamber to the low pressure working chamber from the top of the vane; third is also gas leakage of the two chamber from the clearance between the vane and the end cover; fourth is from the vanes and the vane slot in the rotor; and the last is the leakage from the inlet port to the outlet port through the seal arc of the cylinder.

3. EXPERIMENT RESEARCH OF THE ROTARY EXPANDER
The CO\textsubscript{2} trans-critical refrigeration test rig includes a CO\textsubscript{2} trans-critical refrigeration system; a cooling water system, an expander and work recovering system, and a data collection system as in Figure 6. In the CO\textsubscript{2} trans-critical refrigeration system, the main compressor is a reciprocating compressor, and the expander is an open type rotary vane expander. A mass flowmeter is arranged in the system to measure the CO\textsubscript{2} mass flow rate. Water is used in the heat exchanger to control the temperature of the CO\textsubscript{2}. The expander and work recovering system has been discussed before. In this test rig, many pressure and temperature signals especially the pressure in the expansion process of the expander are measured by sensors. All the signals are transferred to the computer. During the experiment, the system will start first without the expander. After the system has reached the steadily condition, the inlet valve of the expander will be opened. The system will run with the expander and the throttling valve. By fully closing the throttling valve totally, the system will operate with the expander as an expansion device only. After the system is working stably, the load of the generator will be adjusted to vary the speed of the expander.

Figure 6 CO\textsubscript{2} trans-critical refrigeration test rig
4. RESULTS AND DISCUSSION

Experiments were performed at different working conditions and different types of vanes are used. From the results, it can be found that the rotary vane type expander can start easily and work stably in the CO₂ trans-critical refrigeration system, but the designed pressure difference cannot be reached due to the loss leakage in the expander.

When the expander is working, the vanes in the expander are moving under several forces, such as the centrifugal force, friction force, gas force and so on [7]. As a result of the simulation model, an extra force is needed on the bottom of the vane. If not, the vane will not adhere to the expander cylinder, and the leakage is very big. In the experiment, different kinds of vanes, which are shown in Figure 6, are used in the rotary expander and also several methods are used to change the force on the bottom of the vane in order to make the vane stick to the cylinder to decrease the leakage. In Figure 7, there are three kinds of vanes, from the left to the right, first is made of self-lubricating material, the next is made of steel but the top of the vane is in special shape and the last is also a steel vane with traditional top surface. On the bottom of all the vanes with three holes are placed to put in springs, shown in Figure 8.

There are many kinds of working conditions we have done in the experiment, for example three kinds of vanes with and without springs. From all the results we can find there are two typical P-T diagrams, which are shown in Figure 9 and Figure 10. In Figure 9 there is larger internal leakage and in Figure 10 it seems better. In all the combinations of the three vanes and the springs, only steel vanes without special shape on its top can get the P-T diagrams like Figure 10.

After analyzing these two diagrams, some conclusions can be made. First the internal leakage is very large especially in the expansion process, because from the actual P-T diagram the expansion process 2 and 3 are not very good, especially when the vane is plastic vane or no spring set on the vanes, because the high pressure gas leak to the low pressure chamber from the leakage paths. In Figure 9 the plastic vane, a kind of self-lubricated material, is used instead of steel. We can see the pressure signal, which was recorded by pressure sensor 2, is almost like the pressure sensor 1. It can be explained that the vanes are not sticking on the cylinder surface, so there is a large gap between them. When the working process is in the expansion process and in ideal the pressure will decrease along the increasing volume, but in the P-T shown in Figure 9, the pressure does not drop until it connected to the outlet port. In Figure 10, it seems good that the pressure which was recorded by pressure sensor 2 is not as high as the pressure sensor 1, but it is almost the same as the discharge pressure. That is because there is much leakage from the fifth leakage path in Figure 5. Because there is large amount of working fluid flowing directly from the inlet to the outlet port, which makes that the pressure difference can not reach the design condition. From the experimental results the steel vanes without the special shape with springs on its bottom have the best performance.

We also could find the pressure drop became larger when increasing the rotating speed, which is shown in Figure 11 and Figure 12. In Figure 12, when the rotating speed is increased to 1500rpm, there is almost no suction process, which means the pressure difference in the inlet passage is fluctuating large. Increasing speed can make the mass of suction process not sufficient. In Figure 11 and Figure 12 the discharge pressure is larger than the expansion pressure, which was recorded by the pressure sensor 2. That is because higher rotating speed can make the pressure in the expansion chamber decreasing faster, but the evaporator sets the discharge pressure in the refrigeration system. Thus the pressure in the expansion chamber will be lower than the discharge pressure, and over-expansion occurs.

Increasing the rotating speed, the internal leakage decreases but the friction will be increased. Therefore an optimal efficiency exists at a certain speed. The output work is very low and the
efficiency was very low during our tests, because the leakage and friction of the first prototype are very large.

Figure 7 three kinds of vanes  
Figure 8 vane with springs

Figure 9 P-T diagram of plastic vane in 850 rpm  
Figure 10 P-T diagram of steel vane in 850 rpm

Figure 11 P-T diagram of steel vane in 1150 rpm  
Figure 12 P-T diagram of steel vane in 1500 rpm

After adding a sealing vane in the seal arc in order to change the clearance seal into a contact seal,
and also decrease the gap clearances of the leakage paths, performance has been improved. From Figure 13, some improvements can be found. First the pressure of the inlet pressure is above the critical point; second the inlet pressure loss is very small (marked in circle 1 in figure 13); third the trans-critical expansion process has been recorded and the pressure drop above the critical point is very fast (marked in circle 2 in figure 13); fourth the expansion 2 is better than before, there is an obvious expansion process which is marked in circle 3 in figure 13. But there is also a big problem, shown in the circle 4 in figure 13, the pressure increase is unreasonable. And when the outlet port is open the pressure will drop to the discharge pressure soon. It was suggested that the volume variance ratio of the working chamber is much smaller than the beginning of the process and there was a leakage from the high pressure chamber to the expansion chamber, thus the pressure difference increase by the leakage gas is larger than the expansion process.

![Graph](image)

Figure 13 P-T diagram in the Trans critical process

In order to decrease the gas leakage, many methods have been taken. The result is that at the same time of the decreasing of the leakage, the friction loss becomes larger. Thus the speed of the expander can not reach the design condition, the pressure difference is smaller than at the design condition, and also the output work is very small.

5. CONCLUSIONS

A rotary vane type of expander, which is used to replace the throttling valve to reduce the throttling losses, was discussed in this paper. And an electrical generator is used to recover the work generated by the expander. A test rig is constructed to carry out experimental research. The expander-generator unit is measured extensively in the CO₂ refrigeration cycle. From the results, the expander can start easily and work stably but the internal leakage is very large. After finishing testing the functionality of the expander, much work will be done in the future to the expander.

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