Observation of CO₂ Trans-Critical Expansion Process

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ABSTRACT

An expander is used to improve cycle performance of a CO₂ trans-critical refrigeration cycle. An expansion process occurring in the expander operated under typical condition goes from super-critical to sub-critical. When the process goes into the two-phase region through a saturated gas line on a p-h diagram, the liquid phase will appear in the gas phase in an expansion chamber, while the gas phase will appear in the liquid phase with the process passing across a saturated liquid line. In general, that kind of transition occurs under non-equilibrium condition. Therefore, the expansion process is complicated and still not clear.

In this study, the expansion process in a vane type expander is examined at first. Then, the expansion process is investigated in detail by a simple piston-cylinder expander having a glass window. It is shown that a pressure change under the trans-critical expansion process has an inflection point and it appears with a certain time delay in comparison with an ideal case when the inlet temperature is low. However, no change of appearance inside the expansion chamber is observed even at the inflection point and it takes relatively long time to become a complete two-phase condition. Further study will be done to make clear a flash inception phenomenon and to examine the influence of expansion speed, existence of oil and surface roughness of an inside wall on the trans-critical expansion process.

1. INTRODUCTION

Carbon dioxide (CO₂), a natural refrigerant, is one of the candidates of alternative to HFC refrigerants for refrigeration or heat pump cycles. Since the inherent COP of an air-cooled CO₂ cycle is lower than that of HFCs, both compressors and the cycle performance must be improved. Several types of new CO₂ compressors have been developed and the studies for increasing cycle COP by using a suction line heat exchanger or a heat exchanger with micro-channels have been done. In addition, since throttling loss which occurs in an isenthalpic expansion process of the CO₂ cycle is larger than that of the HFC cycles, it was shown that the use of an expander as a throttling device is effective to increase the CO₂ cycle performance (Lorentzen, 1995, Robinson and Groll, 1998). Several types of expanders were developed and their performance and characteristics were presented (Driver and Davidson, 1999, Beak et al., 2002, Fukuta et al., 2003, Huff et al., 2003, Fukuta et al., 2006a, Tøndel, 2006, Yang et al., 2006). The expansion work recovered by the expander is used to drive a compressor and the performance of a
expander/compressor combined machine was investigated experimentally and theoretically (Heyl et al., 1998, Fukuta et al., 2000, Nickl et al., 2005, Okamoto et al., 2005, Kim et al., 2006, Kohsokabe et al., 2006, Kruse et al., 2006, Liu et al., 2007). Besides that, operating characteristics of the cycle having the compressor/expander combined machine were discussed (Fukuta et al., 2001, Hiwata et al., 2003, Fukuta et al., 2006b, Fukuta et al. 2007).

The CO2 cycle operated under normal operating condition is so-called trans-critical refrigeration cycle. The expansion process of the CO2 cycle is, therefore, the process from super-critical condition to two-phase one. When the process goes into the two-phase region through a saturated gas line on a p-h diagram, the liquid phase will appear in the gas phase in an expansion chamber, while the gas phase will appear in the liquid phase with the process passing across a saturated liquid line. In general, that kind of transition occurs under non-equilibrium condition. Therefore, the expansion process is complicated and still not clear.

In this study, the expansion process in a vane type expander is examined at first. Then, the expansion process is investigated in detail by a simple piston-cylinder expander having a glass window. The expansion process is observed by a high speed camera with a measurement of pressure change and compared with an isentropic expansion process.

2. EXPANSION PROCESS OF VANE EXPANDER

A rotary vane type expander was developed because the vane expander has small size, light weight, and simple structure such that inlet and outlet valves and their controls are not necessary. In addition, pressure change during the expansion process is easy to be measured with the vane expander and the trans-critical expansion process is investigated with the expander.

2.1 Experimental set-up

Figure 1 shows an appearance of the vane expander. The specifications of the expander are as follows; the number of vane is 10, chamber volume when the inlet port closes is 64mm³, geometry of a stator is Bosch type (ellipse type), and a built-in expansion volume ratio is 2.0. A vane backpressure groove is machined on a side plate to pressurize a vane back chamber. The pressure change in the expansion chamber is measured by three piezo-electric type pressure transducers mounted on a side plate of the expander.

The vane expander is connected to a CO2 refrigeration cycle as shown in Fig. 2. Two CO2 compressors are used so that the experiment can be done over the wide range of the mass flow rate. A gas cooler and an evaporator are double tube type. An output shaft of the expander is connected to an oil pump to control the rotational speed by changing its load. A torque meter is installed between the expander and the pump. Pressures and temperatures at each position in the cycle are measured by Bourdon tube pressure gauges and T-type thermocouples respectively. Mass flow rate through the expander is measured by a Coriolis type mass flow meter.

In the experiment, the inlet absolute pressure of the expander is 9.1 MPa and the outlet absolute pressure is
4.1 MPa. Inlet temperature of the expander is varied from 35°C to 45°C. Rotational speed of the expander is changed in the range of 1000-2500 rpm and the mass flow rate, the output power and pressure change in the expansion chamber are measured.

2.2 Performance of vane expander
The performance of the vane expander is examined based on the mass flow rate through the expander, $P-V$ diagram and the output power. The ideal mass flow rate is given as follows.

$$G_{\text{ideal}} = nV_s \rho_s$$  \hspace{1cm} (1)

where, $n$ is the number of discharge per unit time, $V_s$ is a chamber volume when the inlet port closes and $\rho_s$ is inlet density of CO$_2$. The ratio of the ideal flow rate to the experimental flow rate $G_{\text{exp}}$ is defined as the volumetric efficiency $\eta_v$.

$$\eta_v = \frac{G_{\text{ideal}}}{G_{\text{exp}}}$$  \hspace{1cm} (2)

The indicated efficiency $\eta_i$ is the ratio of area enclosed by the measured $P-V$ diagram to the ideal one under full expansion, i.e. without neither under-expansion nor over-expansion.

$$\eta_i = \frac{\int P \, dV}{\int P_{\text{ideal}} \, dV_{\text{ideal}}}$$  \hspace{1cm} (3)

where, $V_{\text{ideal}}$ is the volume of an imaginary expansion chamber in case of the full expansion. The indicated efficiency includes a loss due to mismatch between the expansion pressure ratio corresponding to the built-in volume ratio of the expander and an operating pressure ratio.

The ratio of shaft power $L_s$ to the indicated power is the mechanical efficiency $\eta_m$.

$$\eta_m = \frac{L_s}{\frac{1}{n} \int P \, dV}$$  \hspace{1cm} (4)

The ratio of the shaft power to the ideal power for the measured mass flow rate is the total efficiency $\eta_t$ and is product of the partial efficiencies as follows.

$$\eta_t = \frac{L_s}{G_{\text{exp}} \int P_{\text{ideal}} \, dV_{\text{ideal}} / (V_s \rho_s)} = \eta_m \eta_v \frac{1}{\eta_i}$$  \hspace{1cm} (5)

Figure 3 shows the efficiencies of the vane expander with taking the inlet temperature as a parameter. The indicated efficiency (square) exceeds 1.0 when the rotational speed is low because the $P-V$ diagram becomes fat due to an internal leakage into the expansion chamber. The indicated efficiency is about 1.0 and slightly decreases with the rotational speed due to a flow restriction at an inlet port and a slime $P-V$ diagram resulted from less leakage under high rotational speed. The mechanical efficiency (triangle) is about 0.8-0.9 and decreases with increasing the rotational speed. Since the vane expander has relatively long seal length in the expansion chamber, the influence of the internal leakage on the performance is a dominant factor. The volumetric efficiency (diamond) is about 0.6-0.7, and increases with the rotational speed. As a consequence, the total efficiency (circle), the product of the partial efficiencies, has a convex shape against the rotational speed and the maximum value is about 0.6 when
the rotational speed is 2000 rpm. There is no significant difference between the results under the different inlet temperature conditions tested in this study.

2.3 Expansion process of vane expander

The $P-V$ diagram under the condition that the rotational speed is 1000 rpm and the inlet temperature is 45°C is shown in Fig. 4. Calculated results were obtained by an analytical model which takes account of the flow resistances at the inlet and outlet ports, leakage through clearances, heat transfer between CO$_2$ and the expander body and heat generated by the mechanical loss (Fukuta et al., 2003). The model assumes an equilibrium condition and thermodynamic properties are calculated by Refprop Ver.6 (NIST). There is obvious inflection point when CO$_2$ enters the two-phase region. Since the vane expander has large internal leakage into the expansion chamber, the pressure becomes larger than the ideal one during the two-phase expansion process. The calculated result agrees well with the experimental one. This means that the expansion process proceeds under equilibrium condition. Figure 5 shows calculated temperature and quality changes against the rotational angle of a rotor. Although the quality in the supercritical region can not be defined, it set to be 1.0 expediently. When CO$_2$ enters the two-phase region, the liquid phase appears in the gas phase and the quality changes in a complicated manner due to the leakage and sudden pressure reduction at a beginning of exhaust process. The quality slightly increases during the exhaust process because of a heat transfer from the expander body. Figures 6 and 7 shows the $P-V$ diagrams and temperature and quality changes respectively with the inlet temperature of 35°C. The experimental pressure change includes a certain fluctuation. This fluctuation is caused at the point that the expansion chamber connected to the pressure transducer is switched to the next chamber. In this case, at the point that CO$_2$ enters the two-phase region in Fig. 6 the expansion process seems to have a certain time delay of flash inception. The gas phase appears in the liquid phase when CO$_2$ enters the two-phase region (Fig. 7).
3. OBSERVATION OF EXPANSION PROCESS

As shown in Figs. 5 and 7, the expansion process is greatly influenced by the inlet temperature and the flash inception likely takes place with the time delay when the inlet temperature is low. The trans-critical expansion process is, therefore, investigated with a simple piston-cylinder expander in this study.

3.1 Experimental expander for visualization

Figure 8 shows the experimental piston-cylinder expander. The cylinder diameter is 15mm. A piston can move freely. There is a pressure chamber behind the piston and the piston is driven by pressure difference between the expansion chamber and the pressure chamber. The piston is made of aluminum alloy to make its inertia small. The piston has two piston rings to prevent leakage. The expansion chamber has a glass window so that the expansion process is visualized. The piezo-electric pressure transducer and a T-type thermocouple are installed. Note that the thermocouple used in this study does not have enough response speed to measure the temperature change in the expansion chamber during the expansion process and is used to measure the initial temperature in the expansion chamber.

An experimental set up is shown in Fig. 9. The high pressure side in Fig. 9 is connected to an exit of the gas cooler of the CO₂ cycle and the low pressure side is connected to an exit of an expansion valve. The piston displacement is measured by a laser displacement sensor at a bar fitted to the piston. The inside of the expansion chamber is observed by a high speed camera with an incident light through a half mirror. In the experiment, high pressure CO₂ is firstly charged in both the expansion chamber and the pressure chamber, a valve 1 is closed and a valve 3 is slightly opened to decrease the pressure in the expansion chamber so that the piston moves toward a top dead center. Then a valve 2 is closed and the pressure chamber is quickly connected to the low pressure side by a three way valve. The piston displacement and the pressure change are measured during the expansion process under different initial temperatures. The condition of the CO₂ inside the expansion chamber is recorded by the high-speed camera with a frame rate of 4000 fps.

3.2 Trans-critical expansion process

Figure 10 shows the pressure change on the $P-V$ diagram when the initial pressure is 8.9 MPa abs. and initial temperature is 30°C. This process takes 81.5 msec and corresponds to a rotational speed of 368 rpm in a reciprocating expander. A solid line is the experimental result and a broken line is the ideal expansion process, i.e. the isentropic one. The experimental pressure decreases more steeply than the ideal case at first. This is because a leakage from the expansion chamber to the pressure chamber occurs since the pressure difference across the piston is developed when the piston starts to move against the inertia of the piston. At the last half of the expansion, as the chamber pressure approaches the low side pressure the piston speed decreases and the rate of pressure reduction

![Fig. 8 Experimental expander for visualization](image1)

![Fig. 9 Experimental setup](image2)
becomes small due to the leakage from the pressure chamber. Therefore, the experimental pressure is larger than the ideal one at the last half of the expansion. The inflection point appears at the pressure lower than the ideal point. It is thought that an inception of flash of CO₂ under the trans-critical expansion process occurs with a certain time delay.

Figure 11 shows photographs taken by the high-speed camera during the expansion process [(a) to (g)] and after the expansion process [(h) to (j)]. Each point taking these photographs is labeled in Fig. 10. As shown in the photographs (a) to (c), no change of appearance of the CO₂ inside the expansion chamber is observed even at the inflection point. At the point (d), a dark part appears in the chamber and the frame blacks out instantaneously [(e),(f)]. After finishing the expansion process, the CO₂ starts to become complete two-phase condition at about 245 msec and the liquid phase appears [see (h) to (j)].

Figure 12 shows the expansion process when the initial pressure is 8.9 MPa abs. and initial temperature is 40°C, and the observed result during the process is shown in Fig. 13. This process takes 60 msec and corresponds to a rotational speed of 500 rpm. Although the CO₂ is dark and the inside of the chamber is hardly observed under the

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initial condition since this condition is near the pseudo-critical one, the expansion process proceeds in almost the same as that when the initial temperature is 30°C. After finishing the expansion at about 340 msec, the CO₂ starts to turn into the two-phase condition [(f)-(h)], but blacks out again [(i)], and becomes the two-phase condition [(j),(k)]. This condition, therefore, seems to be unstable.

Figures 14 and 15 shows the expansion process when the initial pressure is 10 MPa abs. and the initial temperature is 50°C. The expansion process is similar to other conditions except that the delay of the inflection point is relatively small. In all cases, although the inflection point is observed clearly on the pressure curve, the flash inception is not made clear by the visualization. Further study will be done to make clear the flash inception phenomenon and to examine the influence of expansion speed, existence of oil and surface roughness of an inside wall on the transcritical expansion process.

4. CONCLUSIONS

In this study, an expansion process in a vane type expander is examined at first. Then, the expansion process is investigated in detail by a simple piston-cylinder expander having a glass window. It is shown that a pressure change under the trans-critical expansion process has an inflection point and it appears with a certain time delay in comparison with an ideal case when the inlet temperature is low. However, no change of appearance inside the expansion chamber is observed even at the inflection point and it takes relatively long time to become a complete two-phase condition. Further study will be done to make clear a flash inception phenomenon and to examine the influence of expansion speed, existence of oil and surface roughness of an inside wall on the trans-critical expansion process.

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NIST Thermodynamic and Transport Properties of Refrigerants and Refrigerant mixture Database Ver.6.02


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