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Characteristics of CO2 Transcritical Expansion Process

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ABSTRACT

In order to improve the performance of CO_2 refrigeration cycle, the use of expander as an expansion device has been examined. CO_2 expansion process in the expander is a transcritical expansion process in which the condition of CO_2 changes from supercritical to two phase. In this study, the transcritical expansion process is investigated in detail by using a single piston expander having glass windows. The expansion process is observed by a high speed camera and heat transfer coefficient in the expansion chamber is examined based on enthalpy change during the process. It is shown that the transcritical expansion process is accompanied by a non-equilibrium condition (delay of flash) when an initial temperature of the expansion process is low. When the expansion process passes across the saturation gas line, a blackout phenomenon occurs by generation of fine mist of the liquid phase. In addition, the heat transfer coefficient in the expansion chamber is found to be about 2 - 7 kW/(m^{2}K) in the two phase region.

1. INTRODUCTION

Carbon dioxide(CO_2), a natural refrigerant, is one of alternative candidates to hydroflorocarbon refrigerants (HFCs) for refrigeration or heat-pump cycles because of its nontoxic, nonflammable, and good thermodynamic properties. Since COP of the CO_2 cycle is lower than that of HFCs, the use of an expander is recommended to improve the cycle performance of the CO_2 cycles by recovering a throttling loss (Lorentzen, 1995). The CO_2 expander is generally operated under a transcritical condition in which the CO_2 expands from supercritical to two phase condition. Therefore, the transcritical expansion process is very complicated and not clear yet (An, 2008 and Fukuta, 2009), although there are many studies on the performance of the expanders.

In this study, the CO_2 transcritical expansion process is observed by a high speed camera with measuring pressure and density in a single piston expander having glass windows. Underpressure which is the pressure difference between the saturation pressure and a flash inception pressure caused by delay of flash is examined under several conditions. In addition, heat transfer coefficient during the expansion process is examined based on enthalpy change during the process.

2. EXPERIMENTAL APPARATUS

2.1 Experimental setup

The transcritical expansion process is investigated by the simple cylinder/piston expander having a visualized expansion chamber with glass windows. Figure 1 shows a sectional view of the expander and its appearance. The expander consists of the piston, the cylinder, the expansion chamber and a valve through which CO_2 is charged into the expansion chamber. The two glasses are mounted on both sides of the expansion chamber to observe the expansion process by a transmitted light, and distance between the glasses is 1 mm so that the inside of the expansion chamber is observed clearly. The piston movement is controlled by a rotation of an eccentric cam. The eccentric cam has a stopper and is stopped at the top dead center. Since the piston is pressed against the eccentric cam by a pressure force, when a shaft of the eccentric cam is flipped, the piston begins to move toward to the bottom dead center. As a result, the expander has a single expansion action, and the expansion occurs in the expansion chamber. The piston stroke is 10 mm and the displacement of the piston is measured by a laser displacement sensor. Since the piston equipped an O-ring, there is no leakage. The density change during the expansion process in the expansion chamber, therefore, is calculated from an initial charge amount in the expansion chamber and the piston displacement. The initial charge amount is obtained by the initial volume at the top dead center and the initial density corresponding to the initial pressure and temperature. The pressure and the temperature inside the expansion chamber during the expansion process are measured by a piezo-electric pressure transducer and a K-type

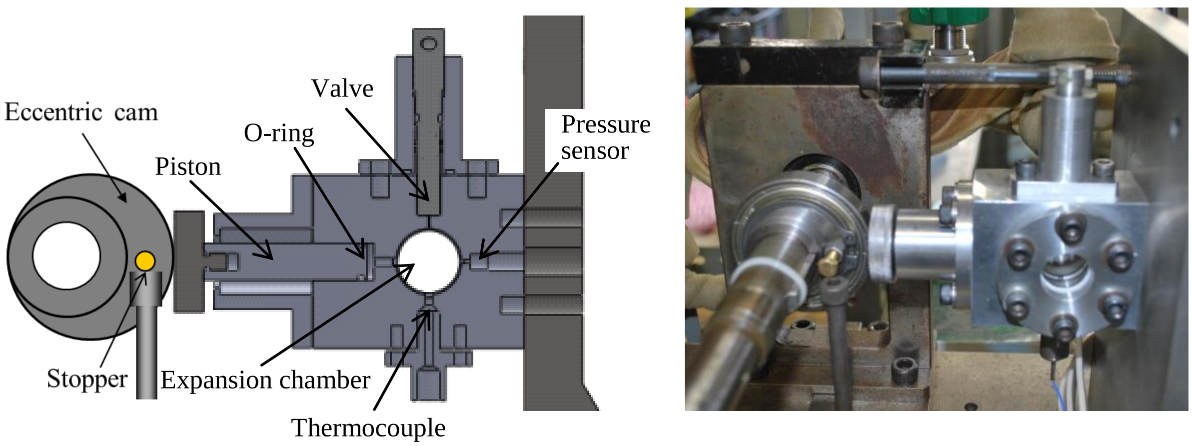

Figure 1: Visualization expander

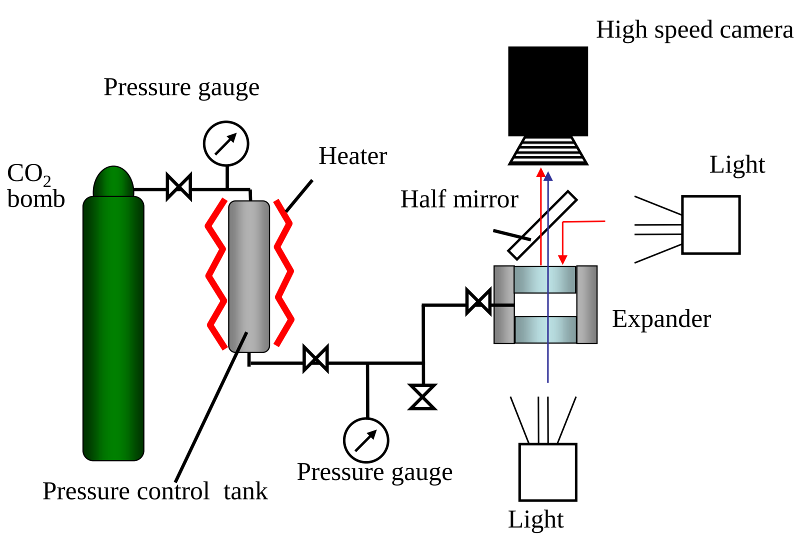

Figure 2: Experimental setup

thermocouple (ϕ=25μm), respectively.

Figure 2 shows an experimental setup. Liquid CO_2 is firstly charged from a CO_2 bomb to a pressure control tank, and the condition in the tank is made to be supercritical by increasing the temperature by an electric heater wrapped around the tank. Secondary, the valve of the expander is opened and the supercritical CO_2 is charged into the expansion chamber. The temperature of the expander body is controlled at the same temperature as the initial temperature and after reaching the thermal equilibrium condition the inlet valve is closed and then the expansion is started. The expansion process is observed by a high speed camera at a frame rate of 4000 fps with either the transmitted light or reflected light. When the inside of the expansion chamber is observed by the reflected light, a half mirror is used to throw the light inside the chamber and a black and white stripe sheet is attached on a backside of the glass to make the inside clear. In the experiment, the initial pressure is 9.1MPa [abs] and the initial temperature is from 10 to 45°C. The expansion speed is controlled by regulating the rotational speed of the eccentric cam. Since the expander is not connected to a refrigeration cycle, the experiment can be done with and without an oil contamination.

2.2 Measurement of heat transfer coefficient

Heat transfer during the expansion process is important factor which influence not only the expander performance but also quality of CO2 at an exit of the expander. The heat transfer coefficient is needed to take the heat transfer into account in a design of the expander. The heat transfer coefficient in the expansion process on an inside wall of the expansion chamber is calculated by the following equation.

$$\alpha = \frac{m\Delta h / \Delta t}{A \cdot \left(T_{body} - T_{fluid}\right)} \tag{1}$$

where, m is CO_2 mass in the expansion chamber, A is surface area in the expansion chamber, T_{boby} is the temperature of the expander body, T_{fluid} is the temperature of CO_2 in the chamber, and Δh is enthalpy difference between those under an isentropic expansion and the experimental one during a small time step Δt. Since the thermocouple hardly detects the transient temperature in the expansion chamber, T_{fluid} is obtained based on the instantaneous pressure and density by using Refprop (Lemmon, 2010). Since heat capacity of the expander is much larger than the heat transfer from the body to CO_2, the body temperature is assumed to be constant. The heat transfer coefficient is also estimated by Adair's correlation developed for reciprocating compressors (Adair, 1972)

$$\alpha = 0.053\left(\frac{\lambda}{D_h}\right)\left\{\frac{D_h V}{\nu}\right\}^{0.8} \mathrm{Pr}^{0.6} \tag{2}$$

The representative length D_h is defined as 6×(cylinder volume)/(surface area). Although vortex velocity was used in Adair's correlation to define the representative velocity V, the piston speed is used in this study for simplicity.

3. RESULTS AND DISCUSSIONS

3.1 Transcritical Expansion Process

Figure 3 shows the transcritical expansion process with a *P-h* diagram, quality and void fraction change, and photographs observed by the transmitted light and the reflected light when the initial temperature is 40°C. In this case, PAG oil is slightly put on the O-ring. The expansion process takes 34 msec and it corresponds to a rotational speed of 1764 rpm if the expansion process is occurs in one revolution. In the *P-h* diagram, solid line shows enthalpy change calculated from the pressure and the density in the expansion chamber, whereas dash line shows isentropic change. The experimental enthalpy shows larger value than the isentropic one by the heat transfer from the expander body. The quality and the void fraction changes in two phase region are plotted against the pressure. Since the process enters the two phase region near the critical point when the initial temperature is 40°C as shown in the *P-h* diagram, the quality becomes around 0.5 at the moment the process enters the two phase region. With decreasing the pressure, the CO_2 gas phase expands and the void fraction increases to 0.9. Photographs shown in right of Figure 3 are taken by the high speed camera. Labels from A to D correspond to points shown in the *P-h* diagram, and the point B is the point where the expansion process enters the two phase region. As shown in the photographs taken by the transmitted light, a blackout phenomenon occurs at point B instantaneously (almost the same as an interval of the frame=0.25 msec) and it continues until the end of the expansion (point D). With looking at the photograph taken by the reflected light, it can be seen that fine mist appears entirely in the expansion chamber at point B and it remains until point D. When the expansion process enters the two phase region, therefore, the liquid phase generated in the two phase region forms the fine mist and the blackout phenomenon is caused by light scattering by the fine mist. The expansion process when the initial temperature is 45°C is almost the same as 40°C, although the expansion process passes across the saturated gas line.

Figure 4 shows the expansion process when the initial temperature is 30°C with the *P-h* diagram and the photographs observed by the transmitted light. It takes 47 msec and the corresponding rotational speed is 1276 rpm. At point B before entering the two phase region, the inside of the expansion chamber becomes slightly fogged. The enthalpy slightly decreases until point C after entering the two phase region. It is caused by a delay of flash, i.e. evaporation of the liquid phase occurs with a certain time-delay and CO_2 remains in the liquid condition.

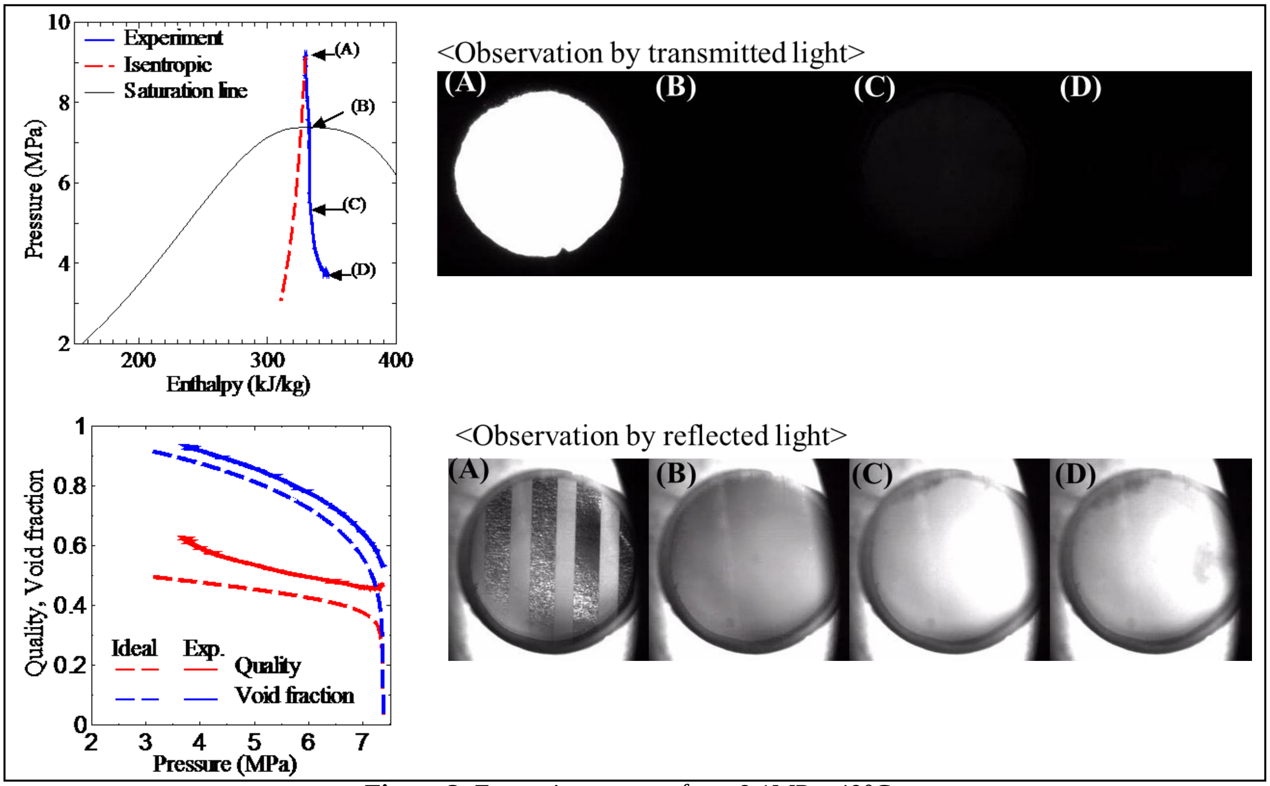

Figure 3: Expansion process from 9.1MPa, 40°C

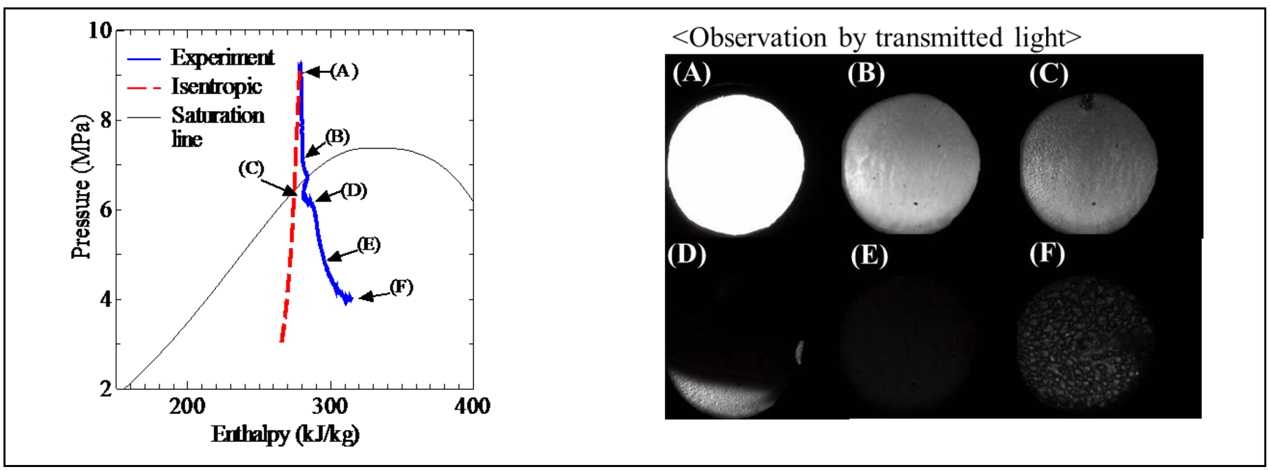

Figure 4: Expansion process from 9.1MPa, 30°C

Consequently, the density of the two phase mixture of CO_2 becomes large and the condition of CO_2 is plotted leftward on the *P-h* diagram. From point C to D, the delay of flash is resolved and the inside of the expansion chamber becomes black. The transition from point C to D takes 4 msec and relatively longer than that in the case of the initial temperature of 40°C. At the end of expansion (point F), the liquid phase is recognized clearly.

The expansion process with the initial temperature of 20°C is shown in Figure 5. It takes 42 msec and the corresponding rotational speed is 1428 rpm. When the expansion process reaches the saturated liquid line at point B on the *P-h* diagram, the delay of flash is seen and the expansion process goes along the saturated liquid line. From point C to D, the delay of flash is resolved and small bubbles appear in the expansion chamber. The inside of the expansion chamber becomes dark at point E by scattering the light by the bubbles. In this case, the delay of flash is larger than that shown in Figure 4. Figure 6 shows the expansion process when the initial temperature is 10°C. In this case, the evaporation does not occur from point B to C. When the evaporation starts, the pressure increases to point D and a part of the delay of flash is resolved. The bubble generation from a valve port located at the top of the expansion chamber is observed at point D and the bubbles spread in the chamber.

The same experiments are done without the oil contamination. There is almost no influence of the oil existence in the expansion chamber on the transcritical expansion process.

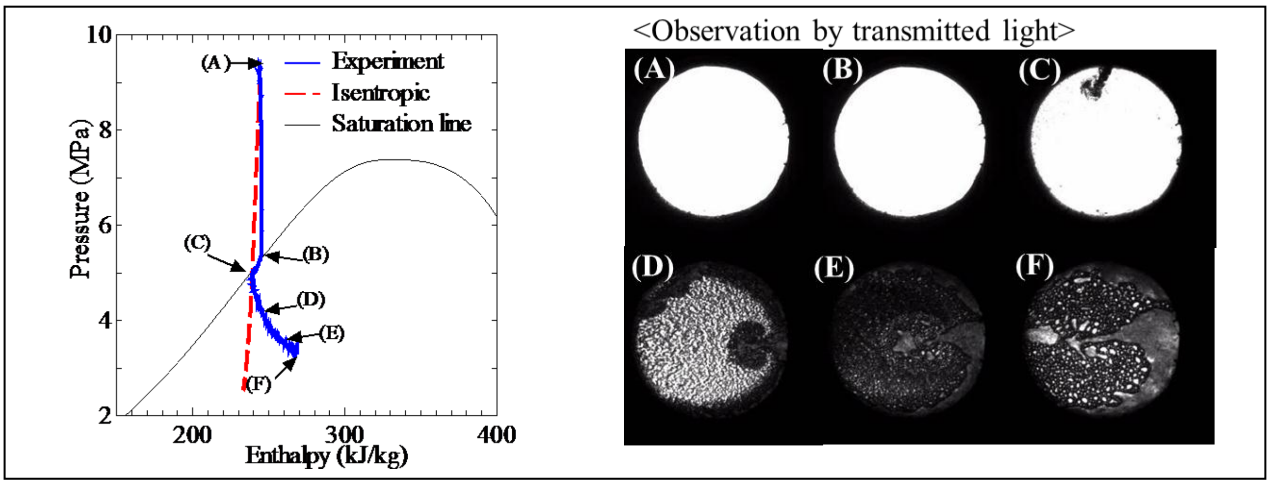

Figure 5: Expansion process from 9.1MPa, 20°C

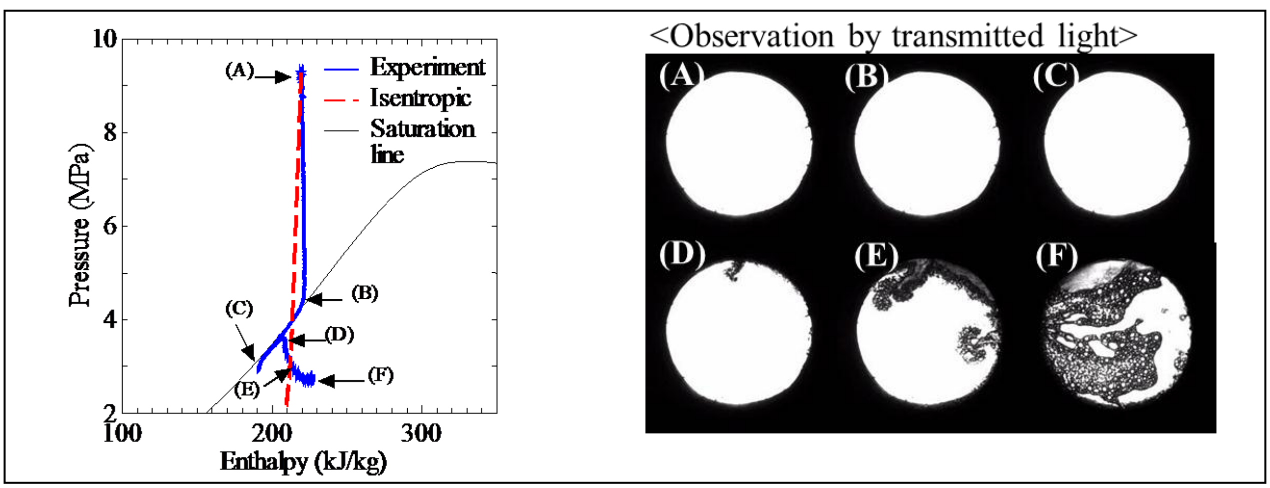

Figure 6: Expansion process from 9.1MPa, 10°C

3.2 Delay of Flash and Underpressure

It is generally reported that the inception of flash hardly occurs at the saturation pressure in a capillary tube, and there exists the single phase metastable region (Chen, 1990). The pressure difference between the saturation pressure and the pressure at which the flash of refrigerant occurs is designated as underpressure. In this study, two kinds of the underpressure are defined as shown in Figure 7. UP_1 in Figure 7 is defined as the pressure difference between the saturation pressure and the minimum pressure in the single phase metastable region due to the delay of flash, whereas UP_2 is that between the saturation pressure and the pressure at which the delay of flash is resolved and the condition becomes two phase. The underpressures are shown in Figure 8 versus the equivalent rotational speed, i.e. the inverse of expansion time, with taking the initial temperature as a parameter. The UP_1 is 0.8 – 1.6 MPa and it is observed only when the initial temperature is less than 20°C. The

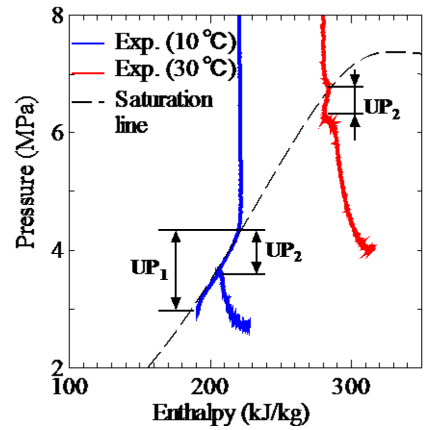

Figure 7: Definition of underpressure

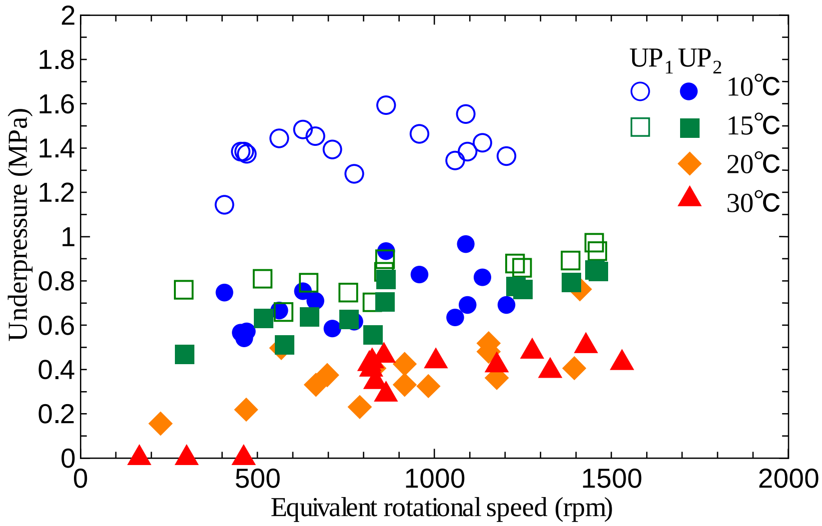

Figure 8: Underpressure

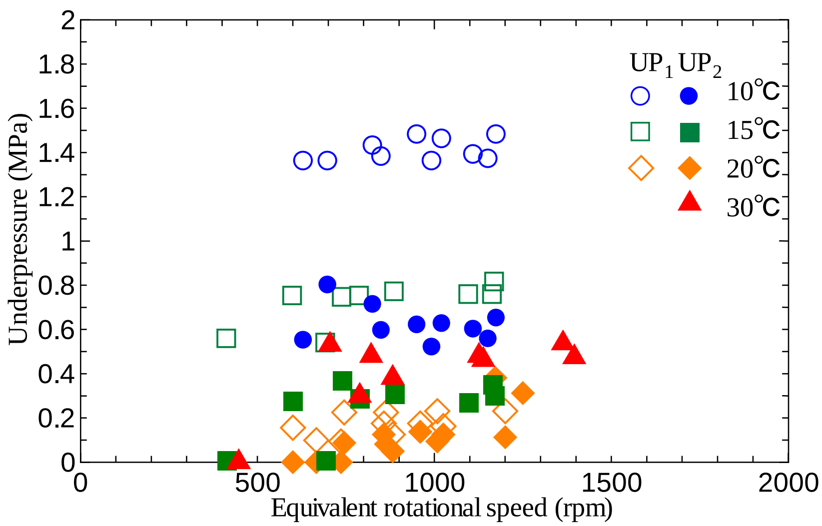

Figure 9: Underpressure under no-oil condition

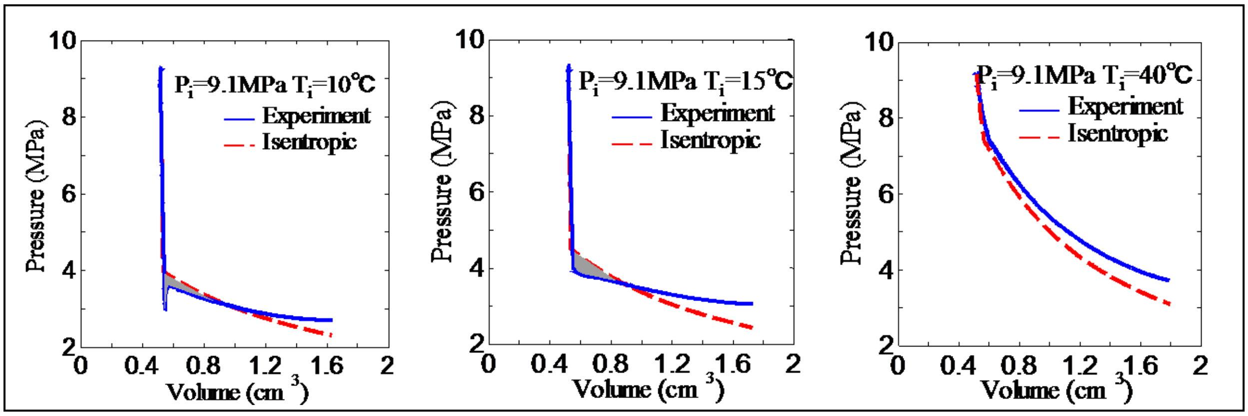

Figure 10: Influence of delay of flash on *PV* expansion work

UP_2 is 0.4 – 0.9 MPa and increases with decreasing the initial temperature. The variation in the underpressure shows that the delay of flash is extremely unstable phenomenon. The underpressure seems to increase slightly with the rotational speed. Figure 9 shows the underpressure when the experiment is done with removing the oil. The underpressure under the no-oil condition has slightly smaller value than that under the contaminated condition with the oil.

When the delay of flash occurs in the expansion process, pressure in the expansion chamber decreases more for the increase of the chamber volume than that of the isentropic expansion, and *PV* work recovered by the expander decreases. Figure 10 shows the *PV* diagram of the expansion process with several initial temperatures. A solid line shows the experimental pressure change and a broken line shows the isentropic one. The gray portion in the *PV* diagram shows a loss work due to the delay of flash. Although the delay of flash at the low initial temperature is larger, the decrease of the *PV* work is a few % because the recovery work in the two phase region is smaller as compared to the recovery work in the supercritical region when the initial temperature is low. However, it is needed to note that the pressure reduction in the two phase region is smaller than that of the isentropic one due to the heat transfer since the expander used in this study has larger heat transfer area than an actual expander. The influence of the delay of flash in the actual expander with less heat transfer may become large than that in the expander used in this study.

3.3 Heat Transfer Coefficient

The heat transfer inside the expander influences not only the expansion process but also an inlet enthalpy at an evaporator and it is needed to take the heat transfer into account when the performance of the expander is evaluated. The heat transfer coefficient in the two phase region is obtained by Equation (1) and shown in Figure 11. There are three graphs depending on a range of the equivalent rotational speed. The heat transfer coefficient is plotted against quality at the instant. The heat transfer coefficient is about 2 - 7 kW/(m^2K), and shows larger value in the quality range of 0.1 – 0.3. In the quality range less than 0.1, the heat transfer coefficient decreases with decreasing the quality. This is due to the fact that the expansion speed in this region is slow because the piston displacement is controlled by the eccentric cam and the piston speed just after starting the expansion is slow. The heat transfer coefficient at the high rotational speed is slightly larger than that at the low rotational speed. When the initial temperature is 30°C and the quality is about 0.1 – 0.2, the heat transfer coefficient has higher value. This is because the heat transfer at this point is calculated based on the enthalpy change when the metastable condition due to the delay of flash is resolved. Comparison of the heat transfer coefficient estimated by Equation (2) with the experimental one is shown in Figure 12. The estimated heat transfer coefficient shows about the same order. Since Prandtl number becomes large near the critical point, the heat transfer coefficient estimated by Equation (2) shows large value when the initial temperature is 40°C and the quality is about 0.5. The heat transfer coefficient when the oil is removed from the expansion chamber is shown in Figure 13. In this case, the heat transfer coefficient shows larger value as compared to that with oil contamination shown in Figure 11. This tendency coincides with the result of a study on the heat transfer coefficient in an evaporator (Dang, 2006).

6. CONCLUSIONS

In this study, a CO_2 transcritical expansion process was investigated experimentally by an expansion chamber having glass windows. The results obtained in this study are summarized as follows.

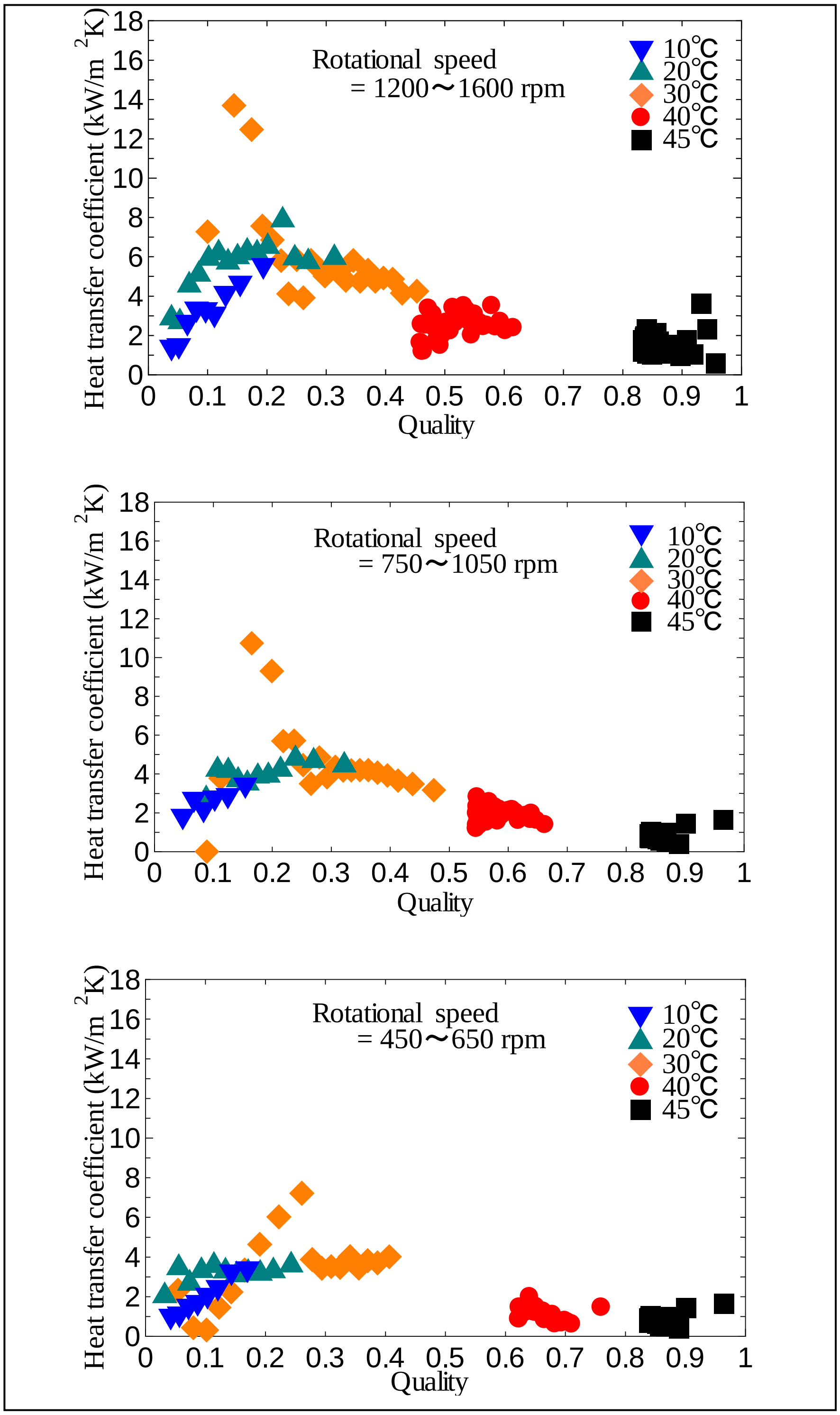

Figure 11: Heat transfer coefficient in two phase region

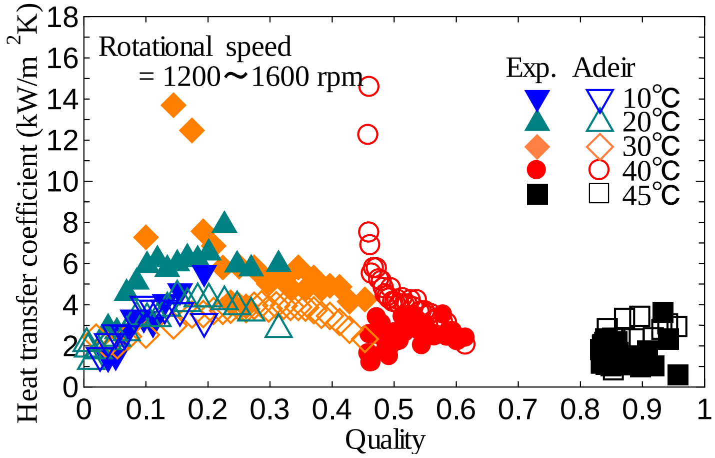

Figure 12: Heat transfer coefficient estimated by correlation

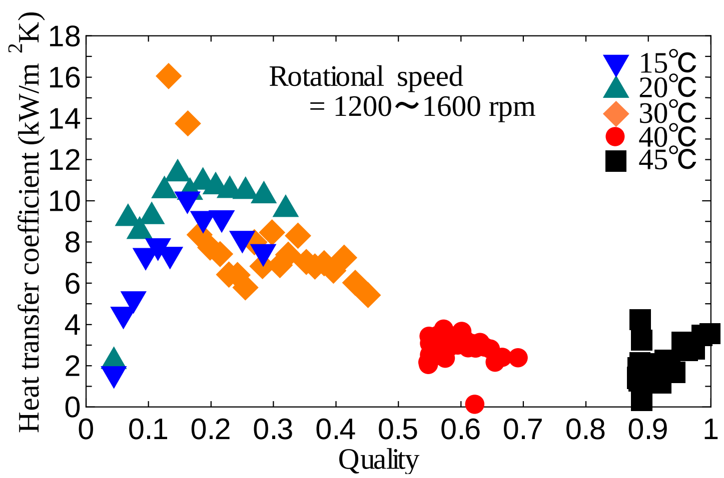

Figure 13: Heat transfer coefficient under no-oil condition

- A blackout phenomenon occurs at the instant that the CO_2 enters the two-phase region. This phenomenon is caused by light scattering by fine mist of liquid phase. When an initial temperature is low, small bubbles are generated and the inside of the expansion chamber becomes dark by the light scattering by the bubbles.
- The transcritical expansion process is accompanied by delay of flash when an initial temperature of the expansion process is low. Underpressure increases with decreasing the initial temperature and slightly increases with a rotational speed. Although *PV* work recovered by the expander reduces by the delay of flash, the influence is a few %.
- The heat transfer coefficient in the expansion chamber is about 2 - 7 kW/(m^{2}K) in the two phase region. The heat transfer coefficient increases with the rotational speed. It can be roughly estimated by a correlation equation developed for reciprocating compressors.
- There is almost no influence of oil existence on the expansion process. When the expansion occurs under no-oil condition, the underpressure slightly decreases and the heat transfer coefficient increases.

REFERENCES

Adair, R.P., 1972, Instantaneous heat flow through the cylinder walls of reciprocating compressors, Purdue University M. S. Thesis.

An, Q., et.al., 2008, Analysis on expansion and phase change process of CO_2 expander, *8th IIR Gustav Lorentzen Conference on Natural Working Fluids*: T4-03.

Chen, Z.H., et.al., 1990, Correlation for metastable flow of refrigerant 12 through capillary tubes, *ASHRAE Trans.*, Vol.96, No.1: pp.550-554.

Dang, C., et.al., 2006, Effect of lubricating oil on boiling heat transfer of carbon dioxide, *7th IIR Gustav Lorentzen Conference on Natural Working Fluids*: #079.

Lemmon, E.W., et.al., 2010, NIST Standard Reference Database 23, Version 9.0.

Lorentzen, G., 1995, The use of natural refrigerants: a complete solution for the CFC/HCFC predicament, *Int. J. Refrig.*, Vol.28, No.8: pp.190-197.

Fukuta, M., et.al., 2009, Performance of Vane-type CO_2 Expander and Characteristics of Transcritical Expansion process, *Int. J. of HVAC&R Research*, Vol. 15, No. 4: pp.711-727.

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