Experimental study on a CO_2-solid-gas-flow-based ultra-low temperature cascade refrigeration system

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Abstract

CO_2 solid-gas two phase flow is investigated in an ultra-low temperature cascade refrigeration system. Visualization test shows that dry ice sedimentation occurs in low mass flow rate. The sedimentation also occurs at low condensation temperature and low heating power input. Based on the present investigation, it is found that the present ultra-low temperature cascade refrigeration system is better to work at heating power input above 900W and condensation temperature above -20°C. At suitable operating condition, the present ultra-low temperature cascade refrigeration system has been shown the capability of achieving ultra-low temperature -62°C continuously and stably

1. Introduction

With concerns on damage of Ozone-depletion substances to environment increasing, work on CO_2 as an alternative for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in refrigerants has been main interests in past twenty years (Lorentzen 1994; Bredesen et al. 1997; White et al. 2002; Rieberer, 2005; Sakar 2006; Cheng et al. 2008). CO_2 is responsible for over 60% of the greenhouse effect, and hence reducing it plays an important role on relieving the greenhouse effect of the earth. It could be an efficient way by recycling CO_2 as a refrigerant instead of its capture and storage only.

CO_2 is abundant in nature and comes at low cost. As an environmentally benign fluid it has properties of zero Ozone depletion potential (ODE), low global warm potential (GWP), non-toxicity, non-flammability and inertness (ASHRAE Handbook). In addition, the thermodynamic and transport properties of CO_2 is also favorable for its using as a refrigerant in terms of its good heat transfer and large pressure drop at the critical pressure and temperature of CO_2 are 7.38MPa (73.8bar) and 31.1°C respectively (Liao & Zhao, 2002). Because of the above advantages, CO_2 fluid has received much attention in recent years in developing various energy conversion systems (Lorentzen 1990, 1993; Nekså et al. 1998, 2002; Hafner 1998; Liao et al. 2002; Saikawa 2004; Girolto et al. 2004; Cechinato et al. 2005; Rieberer 2005; Stene 2005; Zhang et al. 2005; Kim et al. 2004, 2009).

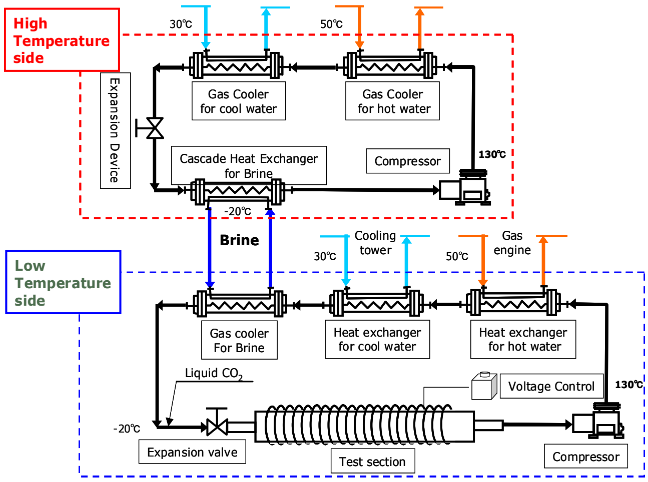


Fig 1. Schematic of the CO_2 cascade refrigeration system

In 2008, a cascade refrigeration system using the CO_2 solid-gas two-phase flow is introduced by Yamaguchi et al. and it has been shown to be able to achieve the ultra-low temperature below the CO_2 triple-point temperature of -56°C. The system is comprised of two CO_2 refrigeration compression cycles (Fig. 1), and the temperature below the triple-point is realized by an expansion process of the liquid CO_2 into the dry ice and gas mixtures in a expansion tube. The reason designing a cascade system is due to a low condensing temperature necessary for dry ice condensation in expanding process. As shown in Fig. 1, this system is composed of a low temperature cycle (LTC) and a high temperature cycle (HTC), respectively. In HPC, CO2 is cooled to below -20°C through a compressor, two condensers, a needle expansion valve and an evaporator. In LTC, one more condenser is used and cooled by the brine from the evaporator of HPC. Through three condensers in HPC, CO2 is cooled to -20°C and then expanded into the expansion tube to achieve the dry ice–gas two phase flow and obtain the ultra-low refrigeration temperature below the triple point. Brine cycle connects the evaporator of HTC and the gas cooler of LTC. The refrigeration principle of that system is illustrated in Fig. 2. The process of 1-2 represents the liquid CO_2 expansion into the two phase flow in the dry ice region, which is below the CO_2 triple point. The ultra-low temperature refrigeration in the system is achieved by the CO_2 dry ice in the expansion tube sublimating and absorbing heat from outside. This process is shown in 2-3 in Fig. 2.

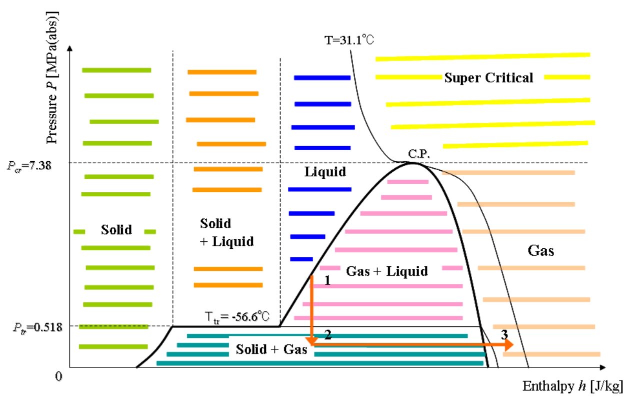


Fig 2. P-h diagram for carbon dioxide

The feasibility study of the ultra-low temperature CO_2 cascade refrigeration system has been performed by Yamaguchi and Zhang (2009). As the dry ice may sediment in the expansion tube and block the CO_2 flow, making the system operation failed, it is very necessary to investigate the dry ice behaviors in the expansion tube for getting the optimized system operation condition. In order to do so, in the present work, the characteristics of liquid CO_2 expanding into horizontal tube through the expansion valve is studied and the dry-ice sedimentation effects on the system performance is investigated.

2. Experiment details

2.1 Visualization test

In order to investigate the dry ice sedimentation in the expansion tube in the CO_2 cascade refrigeration system, a special experimental set-up is built and it is sketched in Fig. 3. The experimental set-up is mainly comprised of CO_2 container, pressure control valve, expansion valve, test section with visualization and heating part and an orifice flow meter. In order to get useful information for the CO_2 cascade refrigeration system (Fig. 1), The test section is made with similar dimensions of the expansion tube in LTC. The visualization part in the test section is a Pyrex circular tube. The heating part in the test section is a SUS316 circular tube rounded by sheath heater for sublimating the CO_2 dray ice particle in it. Although the loop is open one, both the visualization and heating sections are set long enough so that the solid-gas flows with/without CO_2 sublimation can be observed. The visualization and heating tube has dimensions of length 1.93m (Visualization 0.59m and heating 1.34m), thickness 0.0025m and inner diameter 0.04m. In order to keep enough low temperature in the test section, a double cylinder with vacuum thermal insulation structure is installed in the test section to avoid heat transfer between the piping and the ambient.

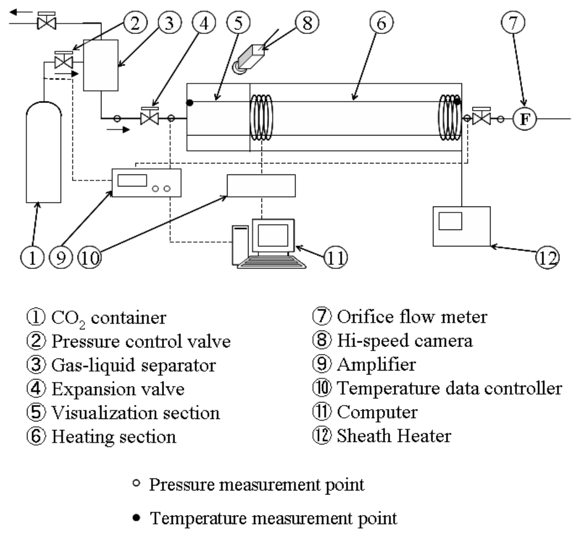


Fig 3. Schematic of experiment set up

In the experiment, Gas-liquid CO_2 in the container is pressurized into the gas-liquid separator through the pressure control valve. In the separator, only liquid fluid is introduced to the expansion valve and the CO_2 gas is recycled to the container. The expansion valve is a needle-type expansion valve with a maximum adjustable diameter of 12.7mm. By the expansion valve, the liquid CO_2 expands, and the dry ice particles are produced by Joule-Thomson effect. In the heating section, the dry ice-gas flow is heated under the constant heat flux condition by the sheath heater so that the dry ice sublimation occurs in the heating tube. After the heating section, the gas CO2 flows through the orifice flow meter and then is discharged outside.

The mass flow rate of the CO_2 flow is controlled by adjusting the expansion valve with maximum adjustable diameter 30mm. The temperature is measured at the inlet the expansion valve and the inlet and outlet of the test section by T-type thermal couples with accuracy of 0.1^{o}C, and denoted as T_{ei}, T_{ti} and T_{to}, respectively. The absolute pressures are measured by pressure transmitters with accuracy of ±0.2% in the inlet of expansion valve, the inlet and outlet of the test section, and orifice outlet, and denoted as P_{ei}, P_{ti}, P_{to} and P_{oo}, respectively. Visualization observation is achieved by using the high-speed video camera. A data acquisition system is used so that real-time data can be recorded with a sampling time period of 5.0 second. All the visulization test is performed at pressure P_{ei} = 1.0MPa and temperature T_{ei} = -45^{o}C.

2.2 System performance test

The performance of the CO_2 cascade refrigeration system based on the visualization results is also carried out. Here we neglect the details of the CO_2 cascade refrigeration system, which can be referred to the work of Yamaguchi and Zhang (2009). The performance study is based on the temperatures and pressures measured at different positions in the system (see Fig. 1). T-type thermocouples with an uncertainty of 0.1^{o}C and pressure transmitter with an uncertainty of 0.2% are used for the measurements. All measured data are transferred into computer through distributor and data logger. The sample data are obtained in every 5s. As the pressure measurement, each two pressures of the CO_2 fluid are obtained at the inlet and outlet of the compressors in HTC and LTC in the system, and for LTC they are denoted as P1 and P2 and for HTC denoted as P1' and P2'. For the temperature measurement, each four temperatures of the CO_2 fluid are obtained respectively for HTC and LTC. In HTC, they are suction temperature T1' at the compressor inlet, discharging temperature T2' at the compressor outlet, condensing temperature T3' at the outlet of the cooling water condenser, and T4' at the evaporator outlet. In LTC, they are suction temperature T1 at the compressor inlet, discharging temperature T2 at the compressor outlet, condensing temperature T3 and sublimation temperature T4 before and after the expansion valve, respectively.

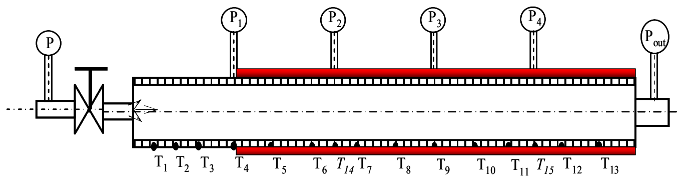


Fig 4. Schematic of test section of expansion tube in LTC

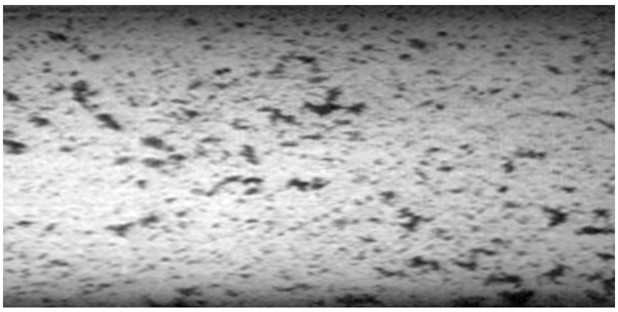
The details of the test section of the expansion tube in LTC with temperature and pressure measuring positions is sketched in Fig. 4. The test section is a copper-made horizontal circular tube, which has an internal diameter of 0.04m and outer diameter of 0.045m. The length of the test section is 5.0 m. The inlet pipe and outlet pipe have a thickness of 0.0015m and an outer diameter of 0.01588m and 0.02222m, respectively. The heater used to heat the tube is silicon gum type heater with good water proof. The heater can be used in a low-temperature environment until -80^{o}C.

In the experiment, HTC is started first and cools the brine of second subsystem. After the brine is fully cooled, the heater rounded in the expansion tube in LTC is started to preheat the tube. When the expansion tube in LTC reaches the prescribed temperature, LTC is started. Then the two machine systems should be made to operate simultaneously. The stable state of the system operation is judged by observing whether T1 and T4 in LTC are converged into a confined range.

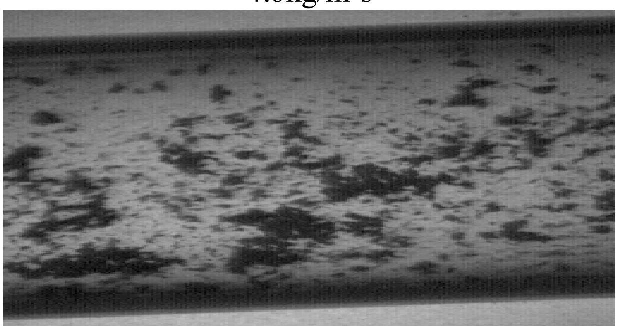
3. Results & Discussions

3.1 Visualization test

The visualization test is carried out at the two mass flow rates of 1.44 and 4.60kg/m^{2}s. Figs. 5 (a) and (b) shows the pictures of the solid-gas two phase fluids taken in the visualization test by the high-speed camera at 13500fps. In Fig. 5. black and white regions represent the dry ice particles and CO_2 gas, respectively. It is seen that the solid-gas fluid flows are successfully achieved by CO_2 liquid expanding process through the needle valve at both mass flow rates. The particle distribution is almost uniform at flow rate of 4.60kg/m^{2}s (Fig. 5 (a)). At this high flow rate, the flow is considered to be turbulent and thus helping the uniform distribution of the dry ice formation the expansion tube. From the visualization results, the diameters of most dry ice particles are estimated about 1.0mm. By taking average of 100 sample particles, the mean particle size is measured to be 1.023mm. When the mass flow rate is reduced to 1.44kg/m^{2}s, as shown in Fig. 5 (b), it is observed that a sedimentation phenomena occurs and larger particles forms in comparison with flow at 4.60kg/m^{2}s. the sedimentation and large particles appeared in low mass flow rate is mainly due to the flow speed is small, and the movement of particles is more difficult to overcome the viscous drag forces inside the fluid and on the tube wall than at high mass flow rate. As a consequence, the particles inside the tube at low mass flow rate collide and stick with each other to form large particles more easily.



(a) CO_2 solid-gas flow at mass flow rate of 4.6kg/m^{2}s



(b) CO_2 solid-gas flow at 1.44kg/m^{2}s;

Fig 5. Pictures of CO_2 solid-gas two phase flows achieved from liquid CO_2 expansion throughout CO2 triple point. (black region represents dry ice particles and white region represents CO_2 gas phase; pictures are taken at 13500fps by high-speed camera)

3.2 CO_2 Cascade refrigeration system test

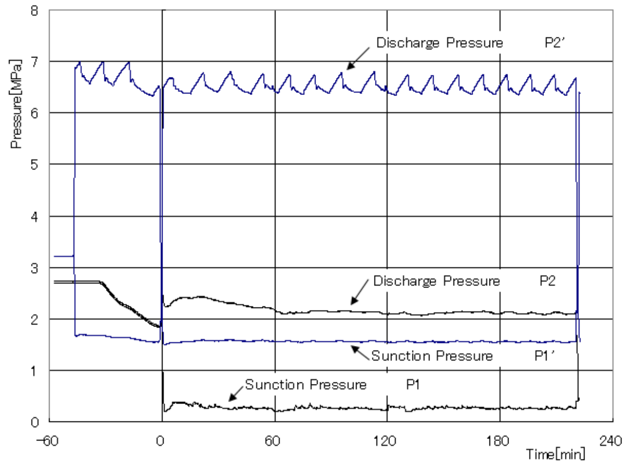
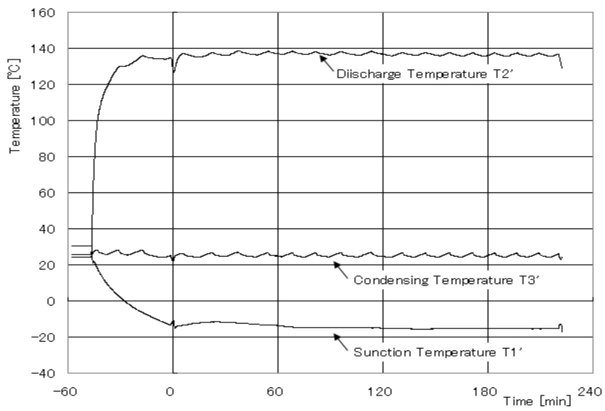
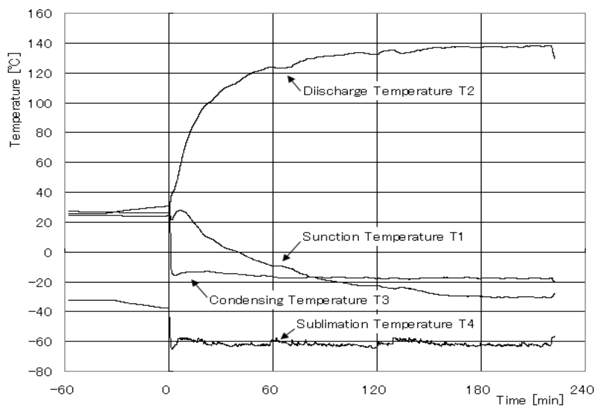


Fig 6. Variations of measured CO_2 pressures of HTC and LTC with time.



(a) Temperature at HTC



(b) Temperature at LTC

Fig 7. Variations of measured temperatures with time.

The behaviors of the cascade system is described in Figs. 6 and 7, which plot the variations of measured CO_2 pressures and temperatures in HTC and LTC with time, respectively. The experimental results are obtained at heating power input is 1000W and the opening of the expansion valve is 15mm. First, the brine is cooled to -20°C by HTC and after that LTC is started to work. 180 minutes later from starting working HTC and LTC, pressure and temperature become steady. After that, average pressure and temperature during 26 minutes are adopted. As shown in Fig. 6 and 7, the measured pressures and temperatures change to a certain value range soon after started, and it takes about 180 min for the inlet and outlet temperatures of the compressor to converge to a certain value range. In HTC, the discharge pressure of the compressor is P2' = 6.60MPa, discharge temperature is T2' = 136 °C, condensation temperature is T3' = 25.1°C, the inlet pressure of the compressor is P1' = 1.65MPa and inlet temperature is T1' = -15°C. The oscillation of the discharge shown in Figs. 6 and 7 is due mainly to the automatic valve opening and closing in cooling tower side, which the temperature variations of cooling water in the heat exchangers. By comparing the p-h diagram shown in Fig. 2, it is certain that the CO2 fluid state in HPC is of gas state at the compressor inlet and outlet, supercritical state at the outlet of the condensers, and liquid–gas two-phase state at the inlet of the evaporator. In LTC, the discharge pressure of the compressor is P2 = 2.20MPa, discharge temperature is T2 = 136°C, condensation temperature is T3 = -17°C, the evaporator outlet temperature is -62°C, and the inlet pressure and temperature of the compressor are P1 = 0.36MPa and T1 = -30°C, respectively. Based on P–h diagram in Fig. 2 again, the CO2 fluid state is confirmed to be of gas state at the compressor inlet and outlet, liquid state at the inlet of the expansion valve and solid–gas two-phase state at the inlet of the test section. Based on Figs. 6 and 7, it is confirmed that the CO2 cascade refrigeration system could continuously and stably realize the dry ice-solid two phase flow and an ultra-low temperature of -62°C in the expansion tube.

The behavior by changing heating power of the heater is seen in Fig.8, which shows the variations of the measured evaporating pressure P1 in LTC with the heating power input at three condensation temperatures T3. It is found that evaporating pressure decreases with decreasing heat input for condensation temperatures of -15°C and -20°C. When heat input is decreased to 900W, evaporating pressure at condensation temperature T3 = -25°C increases, implying the sedimentation of dry ice may occurs to blocking the flow. Fig. 9 shows the behavior characteristic of measured local pressures in test section (see Fig. 5) at conditions of opening of expansion valve 15mm, condensation temperature -25°C, heating power input 1200W. As shown in Fig. 9, the local pressures P_1, P_2, P_3 and P_4 changes drastically with system operation time, suggesting that the blockage or sedimentation of dry ice on the tube wall occurs.

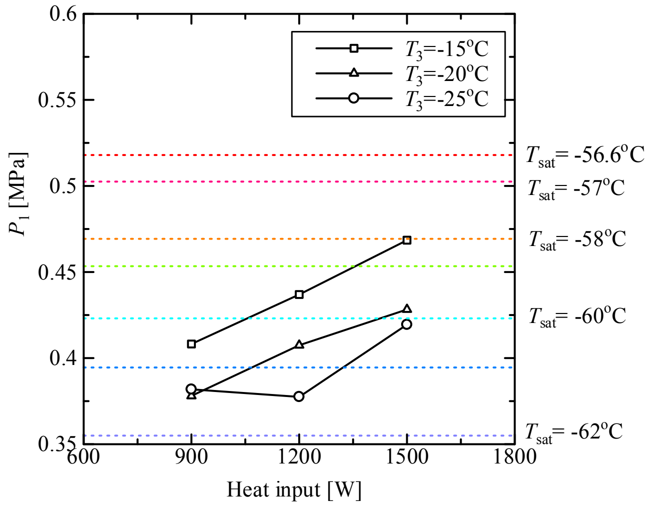


Fig 8. Variations of measured evaporating pressure of LTC with heat input at three condensation temparatures.

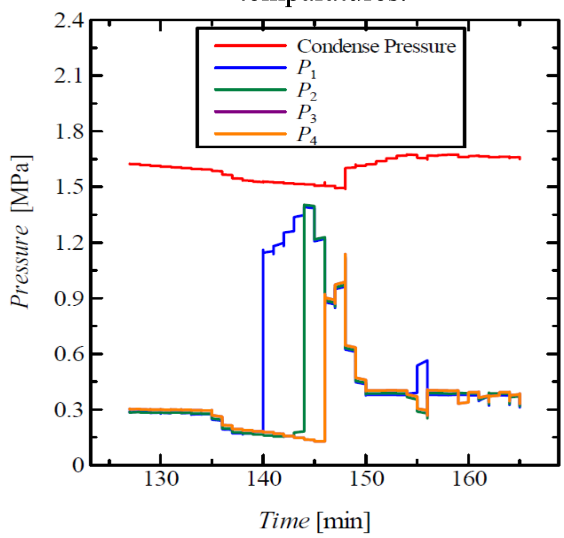


Fig 9. Variation of test section and condensation pressure with time

4. Conclusions

In the present study, dry ice-gas two phase flow is investigated in an ultra-low temperature cascade refrigeration system. Visualization test shows that dry ice sedimentation occurs in low mass flow rate. The sedimentation also occurs at low condensation temperature and low heating power input. Based on the present investigation, it is found that the present ultra-low temperature cascade refrigeration system is better to work at heating power input above 900W and condensation temperature above -20^{o}C. At suitable operating condition, the present ultra-low temperature cascade refrigeration system has been shown the capability of achieving ultra-low temperature -62^{o}C continuously and stably.

Acknowledgement

This study was supported by the Academic Frontier Research Project on 'Next Generation Zero-emission Energy Conversion System' of Ministry of Education, Culture,Sports, Science and Technology., and forms a part of the CREATIV project, performed under the strategic Norwegian research program RENERGI. The author(s) acknowledge the partners: Danfoss, FHL, Hydro Aluminium, John Bean Technology, Norske Skog, REMA1000, Systemair, TINE, and the Research Council of Norway (195182/S60) for their support.

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