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. On the basis of the present investigation, it is found that the present ultra-low temperature cascade refrigeration system works better at a heating power input above 900 W and condensation temperature above -20°C. Under suitable operating conditions, the present ultra-low temperature cascade refrigeration system has shown the capability of achieving an ultra-low temperature of -62°C continuously and stably.

Keywords: dry ice; two-phase flow; ultra-low temperature cascade refrigeration system

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1 INTRODUCTION

With concerns regarding the damage of Ozone depletion substances to the environment increasing, work on CO_2 as an alternative for chlorofluorocarbons and hydrochlorofluorocarbons in refrigerants has been of great interests in the past 20 years [1–7]. CO_2 is responsible for over 60% of the greenhouse effect, and hence reducing it plays an important role in relieving the greenhouse effect of the earth. Recycling CO_2 as a refrigerant instead of its capture and storage only could be an efficient way.

CO_2 is abundant in nature and comes at low cost. As an environmentally benign fluid it has properties of zero Ozone depletion potential, low global warm potential, non-toxicity, non-flammability and inertness [8]. In addition, the thermodynamic and transport properties of CO_2 are also favorable for its use as a refrigerant in terms of its good heat transfer and large pressure drop at its critical pressure and temperature of 7.38 MPa (73.8 bar) and 31.1°C, respectively [9]. Because of the above advantages, CO_2 fluid has received much attention in recent years in developing various energy conversion systems [9–21].

In 2008, a cascade refrigeration system using the CO_2 solid–gas two-phase flow was introduced by Yamaguchi *et al.* [22] and it has been shown to be able to achieve the ultra-low temperature below the CO_2 triple-point temperature of -56°C by an expansion process of the liquid CO_2 into the dry ice and gas mixtures in an expansion tube. The reason for designing a cascade system is a low condensing temperature necessary for dry ice condensation in the expanding process. As shown in Figure 1, this system is composed of a low-temperature cycle (LTC) and a high-temperature cycle (HTC), respectively. In HPC, CO_2 is cooled to below -25°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, CO_2 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 Figure 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 Figure 2.

The feasibility study of the ultra-low temperature CO_2 cascade refrigeration system has been performed by a recent study [23]. As the dry ice may sediment in the expansion tube and block the CO_2 flow, making the system operation fail, it is very necessary to investigate the dry ice behaviors in the

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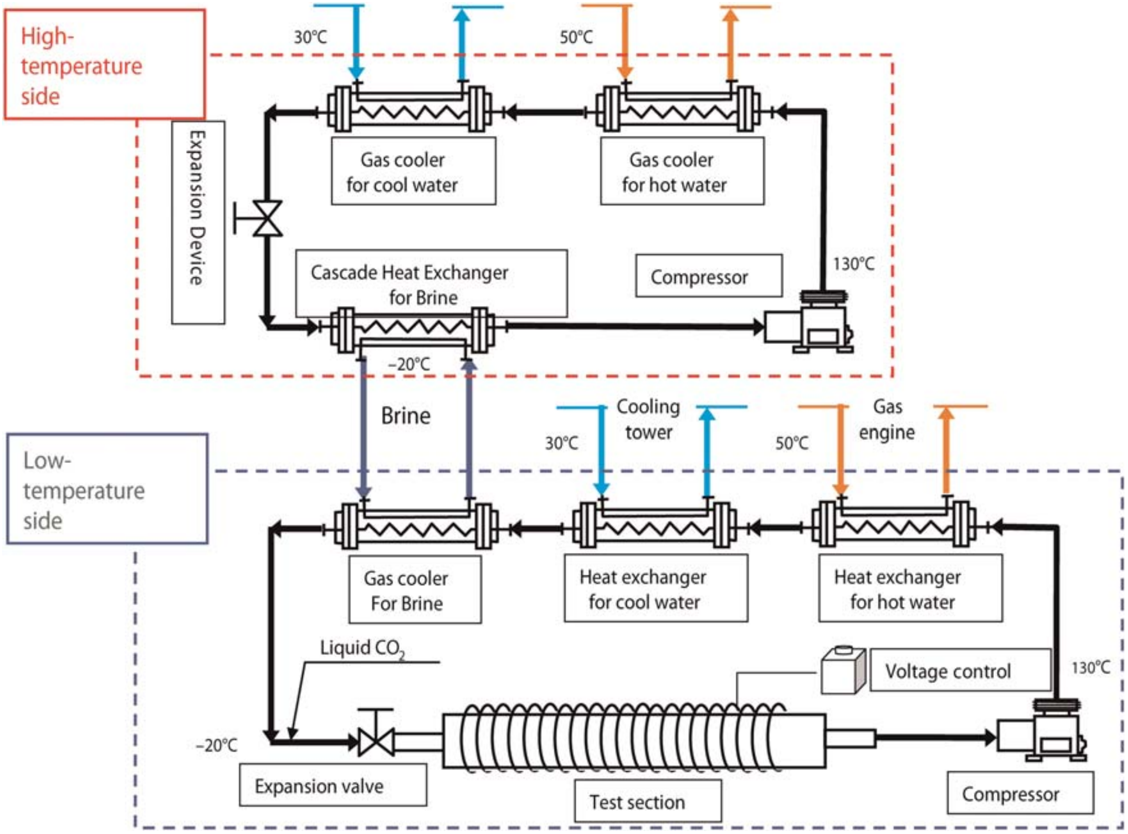

Figure 1. *Schematic of the CO_2 cascade refrigeration system.*

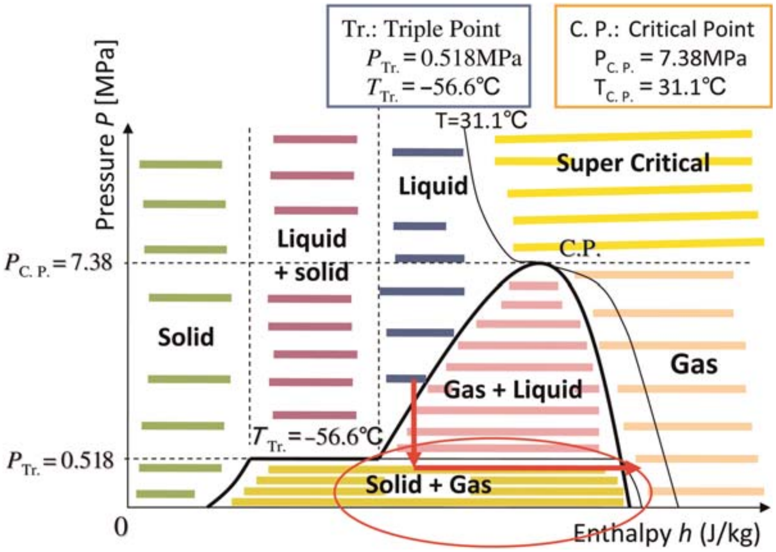

Figure 2. *P–h diagram for carbon dioxide.*

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 a horizontal tube through the expansion valve are studied and the dry ice sedimentation effects on the system performance are 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

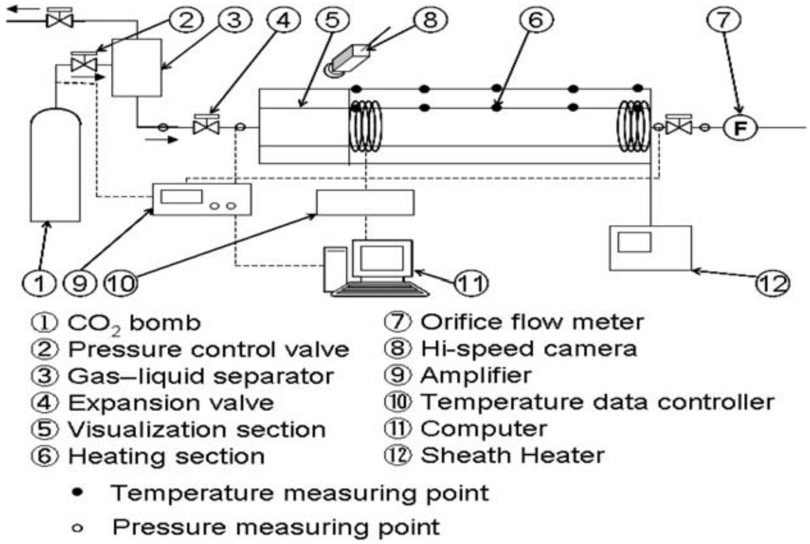

Figure 3. *Schematic of experiment set up.*

experimental set-up is built and is sketched in Figure 3. The experimental set-up mainly comprises a CO_2 container, a pressure control valve, an expansion valve, a test section with visualization and heating parts and an orifice flow meter. In order to get useful information for the CO_2 cascade refrigeration system (Figure 1), the test section is made with similar dimensions of the expansion tube in LTC of the cascade refrigeration system. 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 dry ice particle in it. Although the loop is open, 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 1.93 m (visualization 0.59 m and heating 1.34 m), thickness 0.0025 m and inner diameter 0.04 m. In order to keep a enough low-temperature in the test section, a double cylinder with a vacuum thermal insulation structure is installed in the test section to avoid heat transfer between the piping and the ambient air.

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 diameter of 30 mm. Through the expansion valve, the liquid CO_2 expands, and the dry ice particles are produced by the 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 CO_2 flows through the orifice flow meter and then is discharged outside. Visualization observation is achieved by using the high-speed video camera. All the visualization tests are performed at a pressure of 1.0 MPa and temperature of $-45^{\circ}C$ at the inlet of the tube.

2.2 System performance test

The performance experiment 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, for which work of Yamaguchi and Zhang [23] can be referred. The performance study is based on the temperatures and pressures measured at different positions in the system (Figure 1). T-type thermocouples with an uncertainty of $0.1^{\circ}C$ and a pressure transmitter with an uncertainty of 0.2% are used for the measurements. All measured data are transferred into the computer through a distributor and data logger. The sample data are obtained every 5 s. 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.

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

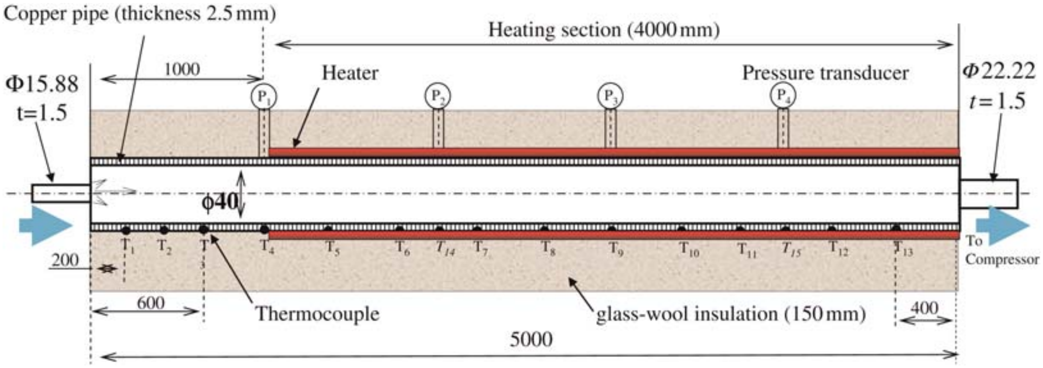

Figure 4. *Schematic of test section of expansion tube in LTC.*

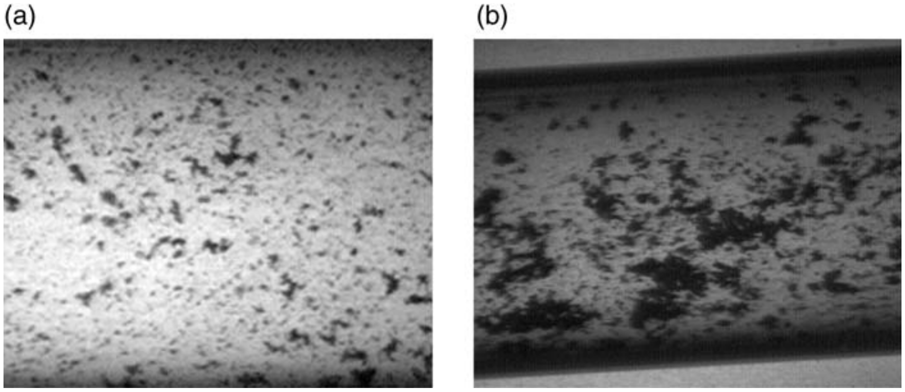

Figure 5. *Pictures of CO_2 solid–gas two-phase flows achieved from liquid CO_2 expansion throughout CO_2 triple point at two opening conditions of expansion valve (black region represents dry ice particles and white region represents CO_2 gas phase; pictures are taken at 13 500 fps by high-speed camera). (a) Co_2 solid–gas flow at mass flow rate of 4.6 kg/m^{2}s, Opening condition at 15 mm and (b) Co_2 solid–gas flow at mass flow rate of 1.44 kg/m^{2}s, opening condition at 10 mm.*

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 AND DISCUSSIONS

3.1 Visualization test

The visualization test is carried out at the two opening conditions of 10 and 15 mm of expansion valve (corresponding low and high mass flow rate, respectively). Figure 5a and b show the pictures of the solid–gas two-phase fluids taken in the visualization test by the high-speed camera at 13 500 fps. In Figure 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 opening conditions. The particle distribution is almost uniform at opening condition of 15 mm (Figure 5a). In this condition, the flow rate of CO_2 is high, and 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 at about 1.0 mm. By taking an average of 100 sample particles, the mean particle size is measured to be 1.023 mm. When the opening condition of the expansion valve is reduced to 10 mm, as shown in Figure 5b, it is observed that a sedimentation phenomena occurs and larger particles forms in comparison with Figure 5a. The sedimentation of large dry ice particles at the low mass flow rate are mainly due to the flow speed being small, and for the movement of particles it 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.

3.2 CO_2 cascade refrigeration system test

The behaviors of the cascade system are described in Figures 6 and 7, which plot the variations of measured CO_2 pressures

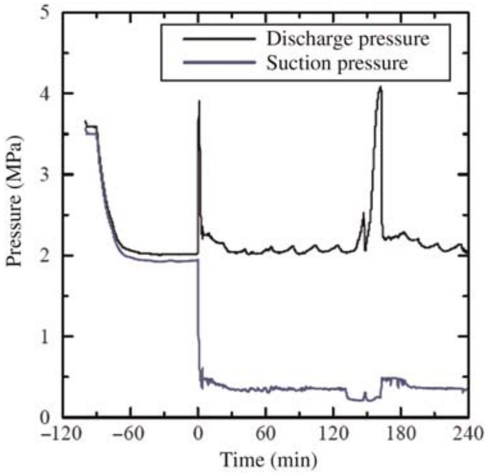

Figure 6. *Variations of measured CO_2 pressures of HTC and LTC with time.*

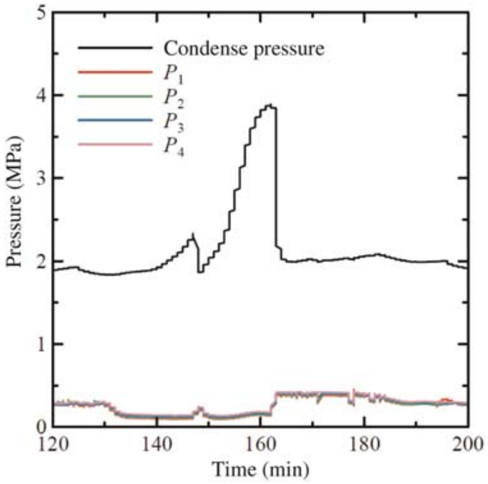

Figure 7. *Variations of measured temperatures with time. (a) Temperature at HTC and (b) temperature at LTC.*

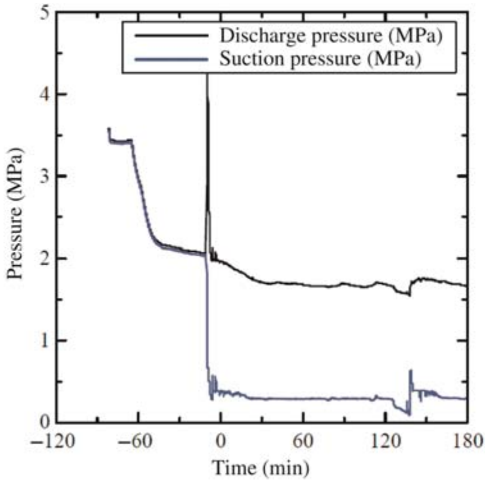

Figure 8. *Variations of measured evaporating pressure of LTC with heat input at three condensation temperatures.*

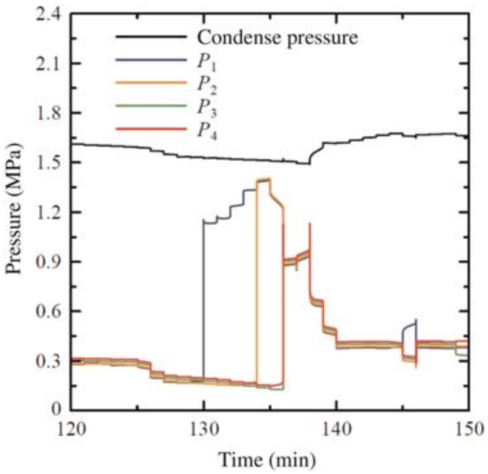

Figure 9. *Variation of test section and condensation pressure with time.*

and temperatures in HTC and LTC with time, respectively. The experimental result obtained at the heating power input is 1000 W and the opening of the expansion valve is 15 mm. The brine is cooled to $-25°C$ by HTC before LTC is started. A total of 180 min after starting working of HTC and LTC, pressure and temperature become steady. After that, average pressure and temperature during 26 min are adopted. As shown in Figures 6 and 7, the measured pressures and temperatures change to a certain value range soon after being 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 $P2' = 6.60$ MPa, discharge temperature is $T2' = 136°C$, condensation temperature is $T3' = 25.1°C$, the inlet pressure of the compressor is $P1' = 1.65$ MPa and inlet temperature is $T1' = -15°C$. The oscillation of the discharge pressure and temperature shown in Figures 6 and 7 is due mainly to the automatic valve opening and closing at the cooling tower side, which the temperature variations of cooling water in the heat exchangers. By comparing the P–h diagram shown in Figure 2, it is confirmed that the CO_2 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 $P2 = 2.20$ MPa, 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 $P1 = 0.36$ MPa and $T1 = -30°C$, respectively. On the basis of P–h diagram in Figure 2 again, the CO_2 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. On the basis of Figures 6 and 7, it is confirmed that the CO_2 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 Figure 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 and −20°C. When heat input is decreased to 900 W, evaporating pressure at condensation temperature T3 = −25°C increases, implying the sedimentation of dry ice may occur to blocking the flow. Figure 9 shows the behavior characteristic of measured local pressures in test section (Figure 5) at conditions of opening of the expansion valve of 15 mm, condensation temperature −25°C, and heating power input 1200 W. As shown in Figure 9, the local pressures P_1, P_2, P_3 and P_4 change drastically with system operation time, suggesting that the blockage or sedimentation of dry ice on the tube wall occurs. On the basis of Figure 8, it is found that the present ultra-low temperature cascade refrigeration system is better to work at heating power input above 900 W and condensation temperature above −20°C.

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. On the basis of the present investigation, it is found that the present ultra-low temperature cascade refrigeration system works better at a heating power input above 900 W and condensation temperature above −20°C. Under suitable operating conditions, the present ultra-low temperature cascade refrigeration system has shown the capability of achieving ultra-low temperature −62°C continuously and stably.

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