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Experimental Observation of CO₂ Dry-ice Behavior in an Evaporator/Sublimator

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Abstract

In the evaporator/sublimator process of CO₂ (R744) ultra-low temperature cascade heat pump system, it is known, as a problem, that dry-ice blockage makes the system operation fail. The design of an expanding channel for the evaporation/sublimation process is one solution to solve the problem. In this study, a swirl promoter is newly designed and tested by means of experimental observation. In order to give better understanding to heat transfer process in the refrigeration system, particular attention is focused for CO₂ dry-ice solid-gas two-phase flow to obtain the effectivity of heat transfer and to verify the flow-phenomena where a visualization test apparatus is placed horizontally. As results, by installing the swirl promoter in the inlet flow channel, it is found that the dry-ice particles uniformly dispersed in whole pipe cross-section with swirling flow, which induces an increase of heat absorption in CO₂ solid-gas two-phase flow. In the case without a swirl promoter, a dry-ice ball shows lower heat transfer characteristic for higher inlet pressures, and resultantly leading to a possible down-stream blockage of the channel.

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1. Introduction

From the viewpoint of protecting the ozone layer, HCFC and HFCs have been used as refrigerant for heat pump systems since the late 1980s. However, in recent years much problems have been pointed out in term of global warming, for which the global warm potential of HCFC and HFCs is in fact more than 150~10000 higher than CO₂ and the amount of the emission will be increased by 4-5 times during the period from 2000 to 2020 [1]. For the reasons mentioned above, the interest in CO₂ itself used as a refrigerant for heat pump systems has increased substantially because it has properties of zero ozone depletion potential (ODP) with a unit global warm potential (GWP). Also, CO₂ has great potential of effective heat transfer owing to the superior thermodynamic and transport properties. Based on the above advantage, a CO₂ ultra-low temperature cascade refrigeration system has been proposed [2~3]. The refrigeration system can achieve a cryogenic refrigeration below the CO₂ triple point

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temperature of $-56.6\text{ }^{\circ}\text{C}$ at 0.518 MPa by expanding the liquid CO_2 into the cryogenic solid-gas two-phase flow (formation of dry-ice). However, in the evaporator process, it was pointed out that dry-ice blockage in evaporator/sublimator pipe has been found to makes the system operation fail [4]. Taking into account this fact, it is thus important to develop a high-performance refrigeration system with a new functional evaporator/sublimator without the dry-ice blockage. In order to investigate the dry-ice solid-gas two-phase flow behavior in evaporation/sublimation process, a dry-ice observation system with visualization channels modelling the evaporator/sublimator has been designed and tested previously [5]. It has been found that the dry-ice sedimentation phenomena are strongly influenced by the shape of the expansion channel, yielding the fact that a tapered channel at the inlet of the expansion channel substantially eased the sedimentation phenomena of dry-ice. Based on these researches, in the present study, in order to improve heat transfer characteristics in the evaporator/sublimator, a tapered channel of the evaporator/sublimator is newly designed, in which the swirling flow in CO_2 solid-gas two phase state is designed to be induced, and with which the dry-ice behavior and heat transfer affected by the swirling flow is investigated in the present study.

2. Experiment

In the present study, in order to verify the phenomena, which is taking place in the sedimentation/sublimation process, a horizontally placed observation system is designed and manufactured as depicted in Fig. 1. The observation set-up mainly consists of CO_2 cylinder, a pressure control valve, a nozzle, inlet flow channel with swirl promoter, an expanding channel, a visualization section and heating cycle. In order to investigate the effect of a swirling flow, the swirl promoter is installed at the inlet flow channel as depicted in Fig. 2. The swirl promoter is stainless thin wire (of 1 mm diameter) bonded along the inner wall of the inlet flow channel. The visualization section is an acrylic circular concentric pipe. In order to realize sublimation/sedimentation of the dry-ice solid-gas two-phase flow with heat transfer, heat input to dry-ice two-phase flow through the inner pipe is achieved by circulating heated water through the outer pipe gap space of the concentric pipe. The observation section (with heat transfer) was made sufficiently long, 5 m length, so that required phenomena can be observed and recorded for at downstream, where the exit of the inner pipe is opened to the atmosphere. A pipe connected with the CO_2 cylinder is made of stainless steel with an inner diameter of 4.6 mm and the length of 20 mm . The diameter of the orifice nozzle is set as 0.51 mm . The pressure at the inlet of the orifice nozzle is set to 0.8 , 1.0 and 1.5 MPa by the pressure control valve, with which the pressure is controlled to the same condition for the evaporator/sublimator of the actual cascade heat pump system [6]. Through the orifice nozzle, the liquid CO_2 expands, and dry ice particles are produced by Joule-Thomson effect. The mass flow rate of CO_2 is measured by the gravimeter set under the CO_2 cylinder. Heat transferred to the CO_2 solid-gas two-phase flow through the inner pipe is measured by measuring the temperature difference between water at inlet and outlet of the outer pipe as well as the water mass flow. It is noted here that sufficient large amount of (cooling) water is circulated through the annular passage of the observation (and heat transfer) section, keeping the temperature difference of cooling water measurable unit with smallest possible temperature difference, ($\Delta T_{\text{water}} = 0.1\text{ }^{\circ}\text{C}$), so that constant heat flux through the inner pipe wall can be achieved with good accuracy. In the present experiment (heat pump system), the representative heat flux through the inner pipe is for example, $q_{i\text{-wall}} = 10\text{ kW/m}^2$, with $\Delta T_{\text{water}} = 20\text{ }^{\circ}\text{C}$.

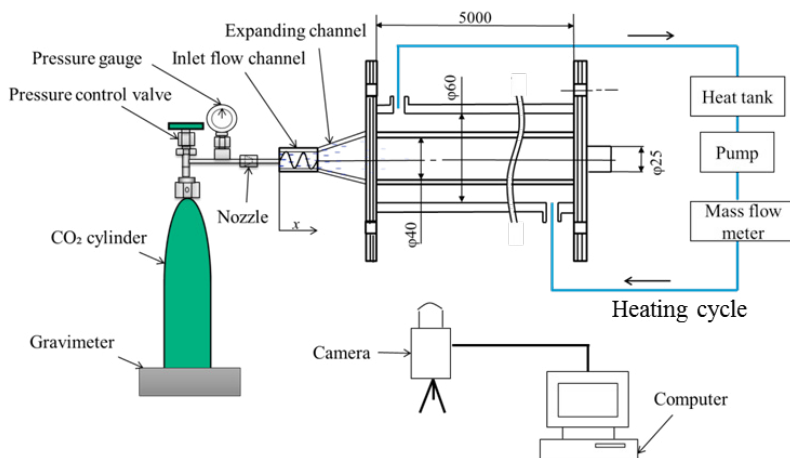


Fig. 1 Schematic diagram of visualization test.

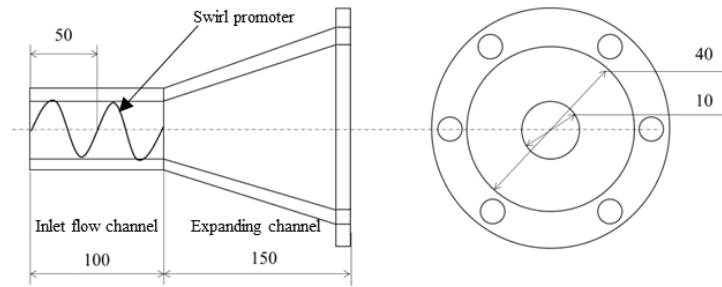


Fig. 2 Detail view of the inlet flow channel and expanding channel.

3. Results and Discussion

Heat transfer characteristics are examined simultaneously in the visualization test section for dry-ice two-phase flow, using the newly adopted and designed experimental apparatus (Fig. 1 and Fig. 2).

As mentioned earlier, for a sake of solving the blockage problem of dry-ice particles and promoting good heat transfer characteristics for dry-ice solid gas two phase flow (which is expected to occur in the actual ultra-low temperature heat pump system), channels with the swirl promoter and one without swirl promoter are examined, also by altering inlet pressure to the inlet flow channel. In both cases (i.e. with swirl promoter and without it), the inlet condition to the inlet flow channel is meticulously controlled by the pressure control valve to unify the both tests. Fig. 3 shows the heat transferred (the heat absorbed) from the water to the sublimating dry-ice in the visualization section, which is circulating in the annular passage in the outer pipe. It is mentioned that the pressure control valve is set to values between 0.8 MPa to 1.5 MPa, and yields the identical condition for both tests, creating the same amount of dry-ice particles through the nozzle installed before entering the inlet flow channel. As shown in Fig. 3, the heat absorbed increase with the increase of the upstream pressure in both cases. The temperature of dry-ice solid-gas two-phase flow decreases, depending on Joule-Thomson effect, when the pressure difference before and after the nozzle increases. Since the outlet of the visualization section is kept at atmospheric pressure, the system condition is merely controlled by the pressure control valve, setting higher value of the pressure gauge makes lower temperature of dry-ice and creating larger amount of dry-ice particles at the inlet flow channel. As shown in Fig. 3, by decreasing the temperature of dry-ice solid-gas two-phase flow, the heat absorbed increased. The heat absorbed in the case without swirl promoter is larger than the result in the case with swirl promoter when the upstream gauge pressure is lower, between 0.8 MPa to 1.2 MPa. In order to explain the reason of the difference, the visualization was carried out in the visualization section and the results are displayed in Fig. 4.

In viewing Fig. 4, it is mentioned that the white color region indicates dry-ice particles. As shown in Fig. 4(a) and (b), in the case without the swirl promoter (Fig. 4 (b)), the volume concentration of dry-ice particles is found to be higher further downstream than closer to the valve, as shown in Fig. 4 (a). Since the swirl flow induced by the swirl promoter increases the momentum of dry-ice particles toward the radial direction of the pipe, the volume concentration of dry-ice particles at the inlet of the visualization section should be increased after the expanding channel, compared with the case without the swirl promoter. As the volume concentration of dry-ice particles increases, the heat absorbed is strongly increased. The phenomena are evident, when the pressure is 0.8 MPa, although, the dry-ice particles do not reach the last half part of the visualization section in the case with the swirl promoter (see in Fig. 4 (c) and (d)), since majority dry-ice particles are sublimated along the inlet part of the visualization section and the last end part of the section is evidently of the gaseous phase and stopped large agglomeration at bottom wall, leading the lesser heat transfer as whole visualization section. On the conversely, without the swirl promoter, dry-ice particles flow with slow speed toward the outlet direction, occupying bottom part of the pipe. It was observed with the case that there are same minor sedimentation and local agglomeration. Thus, with the slow sublimation through the whole visualization section, the overall heat transfer through the pipe is larger than that of with swirl promoter due to occupation of solid-gas two phase in the large part of the pipe.

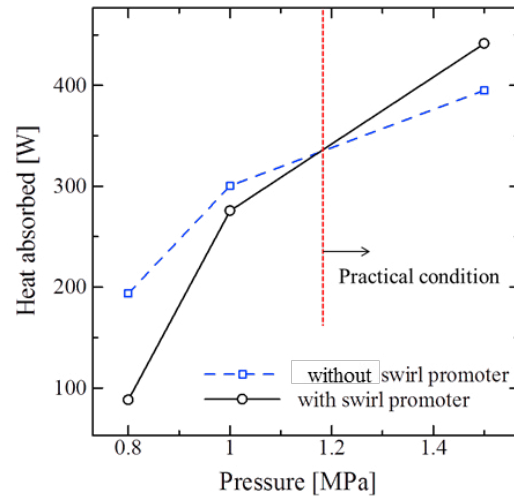


Fig. 3 the heat absorbed at various pressure conditions.

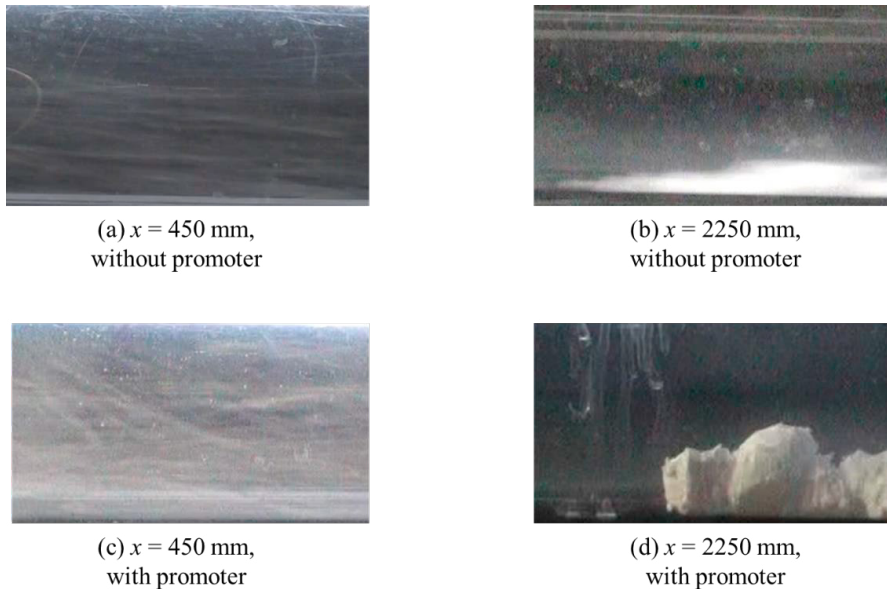


Fig. 4 Visualization results of dry-ice solid-gas two-phase flow in visualization part at upstream pressure of 0.8 MPa.

When the pressure at the nozzle inlet (controlling pressure for the control valve) is increased to 1.0 MPa, the heat absorbed becomes close to the same value for both cases as shown in Fig. 3. The visualization results of dry-ice particles at pressure of 1.0 MPa are similarly displayed in Fig. 5. As shown in Fig. 5(a) and (d) for $x = 450$ mm from the inlet of the visualization section, in the case without the swirl promoter (Fig. 5 (a)), it is found that the volume concentration of dry-ice particles is still higher than that of Fig. 5 (d). Then as the dry-ice particles travel toward downstream at $x = 2250$ mm (Fig. 5 (b)), it is observed that a cluster region alike an elongated dry-ice ball is formed and the dry-ice ball is flown away toward the downstream. In order to explain the phenomena, the generation process of dry-ice ball formation (as shown in Fig. 5 (b)) is schematically explained in Fig. 6. At initial stage of generating an elongated dry-ice ball, there is strong sedimentation of dry-ice particles at bottom wall of the visualization section as shown in Fig. 6 (a). The sedimentation occurs by settling down of large-size dry-ice particles formed and coalesced from small-size dry-ice particles. Then in a second stage, the sedimentary dry-ice ball rotates and rolls in the flow direction as shown in Fig. 6 (b). This is caused by strong up lift force from gaseous phase flow, which passes above the elongated dry-ice ball with combination of stream-wise motion. It is noted that the sliding motion of the dry-ice ball is rather small in comparison with the rotation.

Further down-stream of the visualization section, at $x = 3250$ mm, the shape of the dry-ice ball becomes more and more spherical as shown in Fig. 5(c), yielding strong rotation motion, of which is displayed the detail in Fig. 6(c). The generation of the dry-ice ball has been discussed in Fig. 6(a) \rightarrow (c) together with Fig. 5(a) \rightarrow (c). It suggests the main cause of blockage of evaporator/sublimator [7] further down-stream of visualization section. The dry-ice balls are accumulated and generates agglomeration cluster which often halt the operation of the heat pump system, chocking the passage of the evaporator/sublimator.

In contrast, with the swirl promoter, no such a dry-ice ball formation as in the case of without swirl promoter, are observed, showing clear swirl flow of fine dry-ice particles, expanding in the radial direction of the visualization section and the flow extending towards the end of the visualization section. As shown in Fig. 5(d) \rightarrow (f), it is seen from the visual observation result that it is sublimating in a homogenous flow of dry-ice particles. The strong swirl motion does indeed enhance the heat transfer, as the upstream pressure (controlled by the pressure control valve (Fig. 1)) is increased from 1.0 MPa to 1.5 MPa as shown in Fig. 3, yielding better heat transfer in comparison with the case without swirl promoter. This is entirely due to the fact that dry-ice particles are pushed strongly toward the heat transfer wall by the radial motion, causing high degree of sublimation for each individual particle. In the case without swirl promoter, the heat transfer tends to occur at the bottom side of the visualization section (the pipe) due to the formation of the dry-ice ball (as described previously). The visualization results of dry-ice particles at pressure of 1.5 MPa with and without swirl promoter are shown in Fig. 7. At $x = 2250$ mm, the dry-ice particles can be observed on the bottom side of test section for both cases (Fig. 7(a) and (b)). While at $x = 3250$ mm, in case of using swirl promoter, dry-ice particle cannot be seen (Fig. 7(d)) compared with the case without swirl promoter (Fig. 7(b)).

The basic phenomenological study conducted in the present study supports the fact that in practical operation of the heat pump with a pressure difference of 1.2 MPa (which apply the scale of Fig. 3) to the evaporator/sublimator the heat absorbed is approximately 10 % higher than the case without swirl promoter

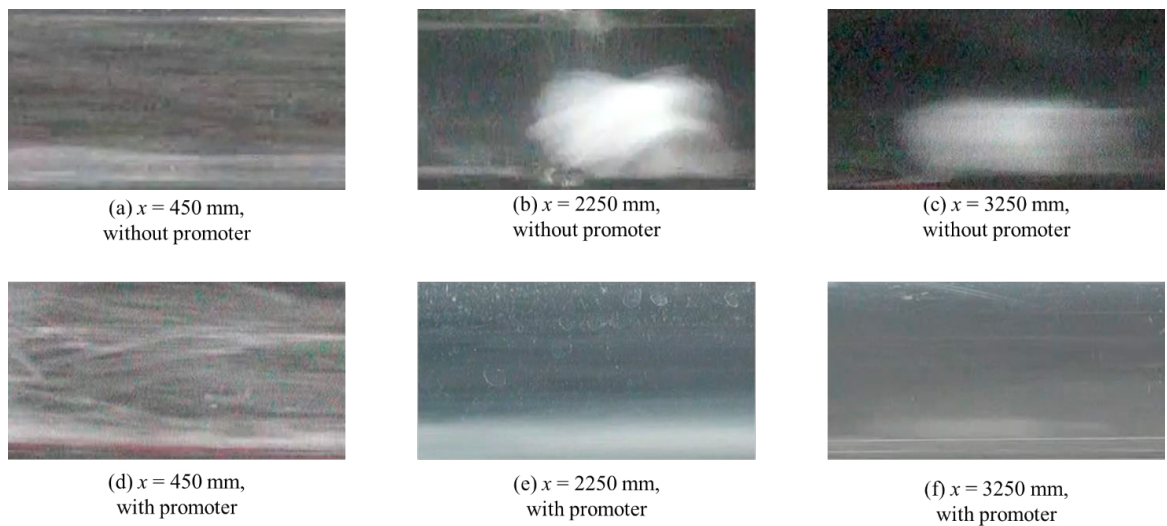


Fig. 5 Visualization results of dry-ice solid-gas two-phase flow in visualization part at pressure of 1.0 MPa.

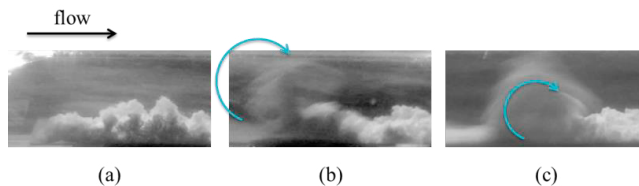


Fig. 6 Generation process of dry-ice ball with time progress ((a) \rightarrow (b) \rightarrow (c)).

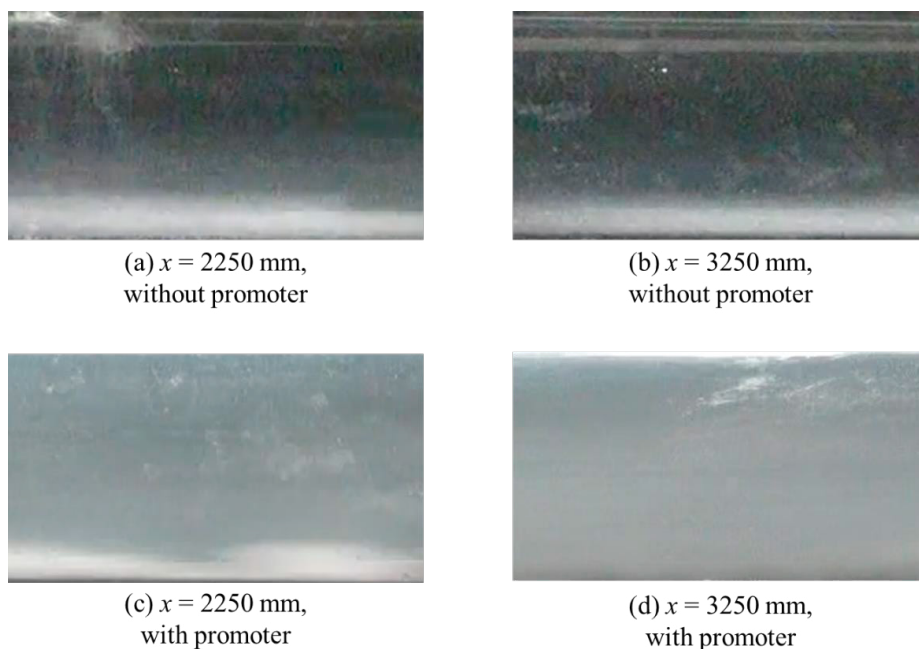


Fig. 7 Visualization results of dry-ice solid-gas two-phase flow in visualization part at pressure of 1.5 MPa

4. Conclusion

Dry-ice behavior and heat transfer in the tested evaporator/sublimator with and without a swirl promoter are simultaneously investigated experimentally. By installing the swirl promoter in the inlet flow channel, it is found that the dry-ice particles are uniformly dispersed in whole pipe with swirling flow, which induced an increase of heat absorbed of CO₂ solid-gas two-phase flow. It is also found that the generation process of dry-ice ball induces the decrease of the heat absorbed of CO₂ solid-gas two-phase flow.

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References

- [1] Montzka, Stephen A., Edward J. Dlugokencky, and James H. Butler. "Non-CO₂ greenhouse gases and climate change." *Nature* 476, no. 7358 (2011): 43-50.
- [2] Giroto, Sergio, Silvia Minetto, and Petter Nekså. "Commercial refrigeration system using CO₂ as the refrigerant." *International journal of refrigeration* 27, no. 7 (2004): 717-723.
- [3] Yamaguchi, Hiroshi, and Xin-Rong Zhang. "A novel CO₂ refrigeration system achieved by CO₂ solid-gas two-phase fluid and its basic study on system performance." *International Journal of Refrigeration* 32, no. 7 (2009): 1683-1693.
- [4] Zhang, Xin-Rong, and Hiroshi Yamaguchi. "An experimental study on heat transfer of CO₂ solid-gas two phase flow with dry ice sublimation." *International Journal of Thermal Sciences* 50, no. 11 (2011): 2228-2234.
- [5] Yamaguchi, H., Iwamoto, Y., Ozaki, S. and Nekså, P. "Experimental observation of sedimentation phenomena of CO₂ dry ice in model channel." *Proceedings of the 11th IIR-Gustav Lorentzen Conference on Natural Refrigerants GL2014*, 2014-3 (2014).
- [6] Sarkar, Jahar. "Ejector enhanced vapor compression refrigeration and heat pump systems—A review." *Renewable and Sustainable Energy Reviews* 16, no. 9 (2012): 6647-6659.
- [7] Yamaguchi, Hiroshi, Xiao-Dong Niu, Kenichi Sekimoto, and Petter Nekså. "Investigation of dry ice blockage in an ultra-low temperature cascade refrigeration system using CO₂ as a working fluid." *international journal of refrigeration* 34, no. 2 (2011): 466-475.