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Development of a heat exchanger with distributed Joule–Thomson effect for a closed-cycle cryocooler

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Abstract. The Joule-Thomson (JT) cooling technique is widely used in low temperature application due to its unique characteristics, such as compactness, low vibration, and ability to reach sub-Kelvin temperatures with simple mechanical components. In this study, a counterflow heat exchanger incorporating a distributed Joule-Thomson (JT) effect was developed for use in a JT cryocooler. The heat exchanger has a helical-in-tube-type construction and is installed in a closed-cycle cryocooler. Pressure drops in the helically coiled capillary samples were also measured. The cryocooler uses a Gifford-McMahon refrigerator as a precooler and helium-4 as the working fluid for the JT cooling circuit. The system can achieve temperatures below 1.7 K without a heat load. The cooling power depended on the operational settings of the cryocooler. A typical cooling power value of 0.2 mW was measured at 2.3 K with a circulation rate of 57 μmol/s. The estimated states of helium flowing in the heat exchanger were plotted on an enthalpy-temperature (h-T) diagram. These results demonstrate the effectiveness of the distributed JT effect in enhancing cryocooler performance and provide a foundation for further optimization of JT cooling technique.

1. Introduction

The Joule-Thomson (JT) cooling technique is widely used in various applications, including home appliances, gas liquefiers, superconducting apparatus, cooling for high sensitivity detectors, cryogenic material properties measurements apparatus, and sub-Kelvin cooling refrigerators. JT cryocoolers for cryogenic applications typically consist of a high-pressure working fluid supply, counterflow heat exchangers, and a flow impedance, such as an orifice or a JT valve for working gas expansion. When helium is employed as the working fluid, precooling is necessary because its maximum inversion temperature, approximately 43 K, is well below the room temperature. Therefore, helium must be precooled below this inversion temperature to achieve temperature reduction after expansion. For small-scale JT cooling circuits, mechanical refrigerators are often used to precool the working fluid. Many researchers have experimentally, theoretically, and numerically investigated the JT cooling.

Among these investigations, the distributed JT effect has attracted the interest of researchers as a measure to improve the characteristics of JT cooling circuits and their thermodynamic importance [1]. The distributed JT effect is a continuous expansion caused by the frictional pressure drops along a flow channel, which is typically formed with a narrow and long capillary tube. Hwang and Jeong [2] investigated the distributed JT effect and revealed the conditions for improving the effectiveness of a recuperative heat exchanger. When this effect is properly applied to the counterflow heat exchanger of the JT cooling circuit, the cooling characteristics can be improved. Maytal [3] indicated that the change in the enthalpy of the fluid flowing in a heat exchanger owing to a pressure change cannot be neglected when the frictional pressure drop along the flow channel is significant. The possibility and advantage of eliminating flow impedance, such as a JT valve at the cold end of the high-pressure channel of the heat exchanger, is also pointed out when the distributed JT effect becomes significant. The elimination of the flow impedance can further simplify the construction of the JT cryocooler and increase its robustness to flow-channel plugging. Damle and Atrey [4] developed a transient simulation program to predict the cool-down characteristics of miniature JT cryocoolers. A distributed JT effect was used in the simulations. Jeong et al. [5] developed a distributed JT-effect heat exchanger for 2 K-JT cooling system immersed in a liquid helium dewar. The system utilizes the negative JT coefficient of liquid helium to increase the effectiveness of the heat exchanger. Kim [6] investigated the continuous pressure drop in a tube-in-tube recuperative heat exchanger for 1.8 K-JT cooling system with a liquid helium dewar. They developed a thermal model to investigate the performance of a heat exchanger with the distributed JT effect.

The objective of the present study is to develop a counterflow heat exchanger that leverages the distributed JT effect for use in a JT cryocooler capable of reaching temperatures below 4 K and to investigate the characteristics of the counterflow heat exchanger with the distributed JT effect. Therefore, a helical-in-tube-type counterflow heat exchanger with a distributed JT effect was developed for a small-scale JT cryocoolers. The flow impedance of the helically coiled capillary tube for the high-pressure channel was designed to be sufficiently high to eliminate the need for the flow impedance at the cold-end outlet on the high-pressure channel of the heat exchanger for expansion. The low-pressure channel was formed by the space between the outer surface of the high-pressure channel capillary and the inner wall of the outer tube of the heat exchanger. The characteristics of the developed counterflow heat exchanger were investigated by integrating it into a JT cryocooler. The cryocooler used a two-stage Gifford–McMahon (GM) refrigerator as the precooler. Helium-4 was used as the working fluid in the JT cooling circuit. The minimum temperature reached by the JT cryocooler was below 1.7 K.

Estimating the pressure drop in a flow channel is a key factor in the designing of heat exchangers with a distributed JT effect. Because a helical-in-tube-type structure was selected as the counterflow heat exchanger, the pressure drops in the helically coiled small channel was of primary interest.

2. Apparatus

Two kinds of measurement apparatus were constructed and used in this study. One was the apparatus for the pressure drop measurement in the capillary, and the other was the JT cryocooler for the evaluation of the developed counterflow heat exchanger.

2.1 Apparatus for Pressure drop measurement in helically coiled capillary

Figure 1(a) schematically shows the pressure drop measurement apparatus for a helically coiled capillary. The test gas was supplied from a high-pressure gas bottle via a manually controlled pressure regulator. Condensable impurities in the test gas were removed by the liquid nitrogen cooled cold trap. A helically coiled capillary sample was connected to the test section that was set in a FRP (Fiber Reinforced Plastic) dewar. For the measurement at room temperature, the FRP

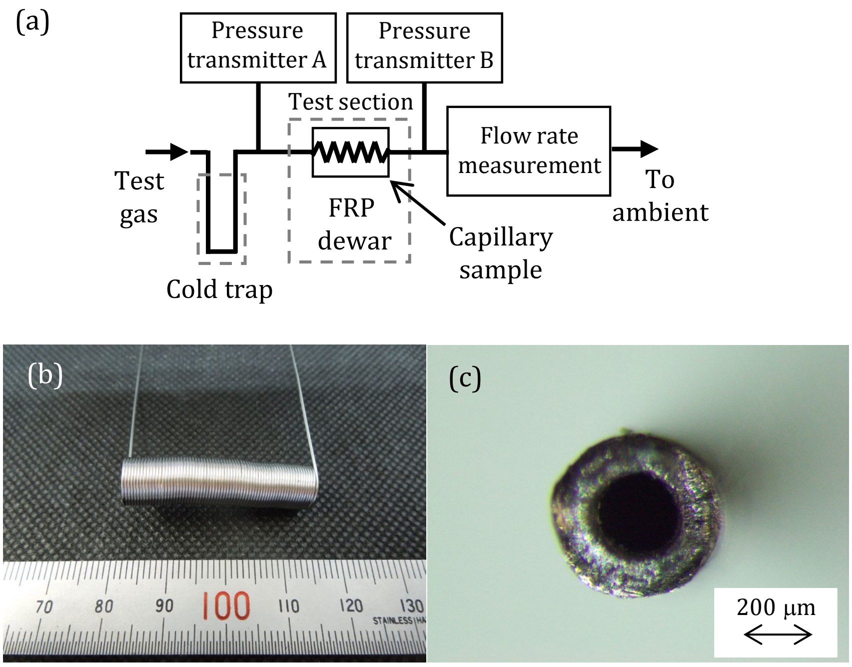

Figure 1. (a) Schematic diagram of the apparatus for the pressure drop measurement in a capillary sample. (b) Example of a capillary sample for the pressure drop measurement. (c) Magnified cross-sectional photo of the capillary with an inner diameter of 0.2 mm.

dewar was kept empty. Nitrogen and helium were used as test gases. For the measurement at the liquid nitrogen temperature, the FRP dewar was filled with liquid nitrogen and the capillary sample was immersed in a liquid nitrogen bath. Helium was used as the test gas. The pressures of the gas flowing before and after the capillary sample were measured with absolute-type pressure transmitters A and B with an accuracy of ±0.25 % of full scale, respectively. The pressure measurement full scale is 0.3 MPa. The volumetric gas flow rate can become as small as a few cm^3/min in this measurement. The flow rate was measured by a positive displacement method. The gas coming out of the outlet was directed through a tube into a graduated cylinder. The graduated cylinder was placed upside down in a water tank and filled with water. As the gas enters the graduated cylinder the water in the cylinder is replaced by the gas and the flow rate can be measured with the uncertainty of less than 3 %.

The capillary samples are made by winding a stainless steel capillary. Figure 1(b) illustrates a typical capillary sample. The capillary tube, which has an inner diameter of 0.2 mm and a length of 2 m, is helically coiled to form the capillary sample. The inner diameter of the coil is approximately 8.3 mm. Figure 1(c) illustrates a cross-sectional view of a capillary with an inner diameter of 0.2 mm. The channel shape was not perfectly circular and the inner surface did not appear to be perfectly smooth. These factors may affect the secondary flow in the channel; however, further investigation is required.

2.2 JT cryocooler with a distributed JT-effect heat exchanger

The developed counterflow heat exchanger was integrated into a JT cryocooler to investigate its characteristics. Figure 2 illustrates an image of the essential cold part of the JT cryocooler. The apparatus was constructed in the available space of an existing GM/JT cryocooler [7]. The closed-

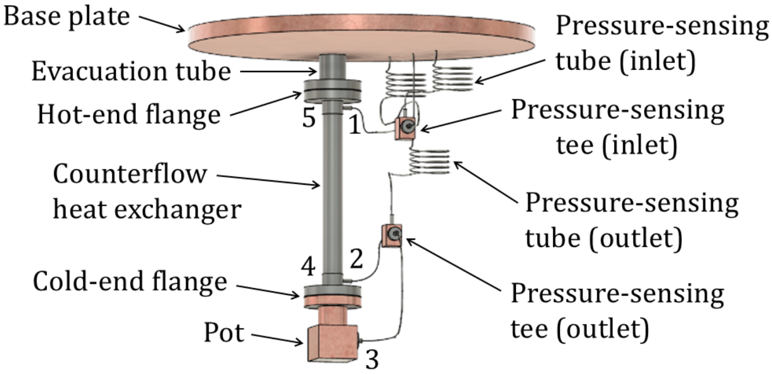

Figure 2. CAD (Computer-aided design) image of the JT cryocooler for the heat exchanger characteristics investigation. Numbers indicate the locations of the counterflow heat exchanger, 1: Inlet of the high-pressure channel, 2: Outlet of the high-pressure channel, 3: Pot, 4: Inlet of the low-pressure channel, 5: Outlet of the low-pressure channel.

cycle gas handling system for the JT circuit is shared with an existing GM/JT cryocooler. The operation and basic construction of the JT circuit are described elsewhere [7, 8]. An evacuation tube, pot made of copper, and temperature and pressure measurement equipment were installed.

The developed counterflow heat exchanger was connected between the bottom of the newly installed evacuation tube and a pot with flanges. All essential cold parts were set inside a vacuum shroud for thermal isolation. A two-stage GM refrigerator was used as a precooler for the JT cooling circuit. The base plate is cooled using the second cold-stage of a GM refrigerator. Helium-4 was used as the working fluid in the JT cooling circuit. The GM refrigerator is not a state-of-the-art model; however, it can cool the base plate and the helium flowing in the JT circuit to approximately 8 K before the helium enters the heat exchanger under the test from the inlet of the high-pressure channel. The pressures and temperatures at the inlet and outlet of the heat exchanger are determined as follows: Copper pressure-sensing tees were placed at the inlet and outlet of the high-pressure channel in the heat exchanger. The pressure-sensing tees were connected to a differential digital pressure manometer with a maximum pressure range of 130 kPa, set outside the vacuum shroud using pressure-sensing tubes. The measured pressure difference corresponded to the pressure drop developed in the high-pressure channel. The length of the pressure-sensing tube made of stainless steel was set sufficiently long to suppress the conductive heat load through it from the room-temperature portion to the pressure-sensing tee at a cryogenic temperature, which was negligibly small. The pressure-sensing tubes were partially coiled to ensure compactness. The supply gas pressure to the high-pressure channel is also monitored by a pressure transducer with a pressure range of 0.5 MPa attached to the room temperature portion of the supply tube.

The temperatures of the helium flowing at the inlet and outlet of the high-pressure channel were measured using thermometers attached to each pressure-sensing tee. The uncertainty of the temperature measurement should be better than ±0.1 mK.

Helium from the outlet of the high-pressure channel enters the pot through the capillary. Subsequently, helium from the pot flows into the low-pressure channel of the counterflow heat exchanger and is evacuated by a vacuum pump set outside the vacuum shroud through an evacuation tube.

Pressure-sensing tubes were not installed in the low-pressure channel because they were not easy to install in the present apparatus. According to preliminary measurements at room temperature before the installation to the JT cryocooler, the maximum pressure drop in the low-pressure channel was estimated to be a few tens of Pa. This maximum pressure drop is estimated to increase up to a few hundred Pa at a cryogenic temperature when liquid helium was condensed in the pot. Although the coiled capillary of the high-pressure channel was inserted into the outer tube of the heat exchanger, the inner diameter of the outer tube (14.4 mm) was still relatively large for the flow channel. Therefore, the pressure drop in the low-pressure channel is ignored in the following analysis.

A pressure transducer attached to the room-temperature portion of the evacuation tube indicated the pressure at the pot minus the pressure difference between the pot and the location at which the pressure transducer was attached.

The helium temperatures at the inlet and outlet of the low-pressure channel were measured using thermometers attached to a copper thermometer block embedded at the hot-end and cold-end flanges.

3. Pressure drop measurement and analysis

As a preparatory test prior to the counterflow heat exchanger design, the pressure drops in the helically coiled capillary samples were measured against the volumetric gas flow rate.

The capillary tubes made of stainless steel with inner diameters of 0.1, 0.2, 0.3, 0.5 mm, and 0.7 mm with a length of 2 m were helically coiled to form the capillary sample. The inner diameter of the coil was set as approximately 8.3 mm.

The Fanning frictional factor, f for a circular cross-sectional channel flow is defined as,

$$f = D_i \Delta P / (2 L \rho v^2) \quad (1)$$

where D_i the channel inner diameter, ΔP the pressure drop, L the channel length, ρ the density of fluid, v the fluid velocity.

A fully developed laminar flow in a straight circular cross-sectional channel has the characteristic parabolic velocity profile of a Hagen-Poiseuille flow. The friction factor, f can be derived analytically as follows:

$$f = 16/Re \quad (2)$$

Various correlations yielding friction factor, f for helically coiled channels have been proposed. Many of these correlations were created for flows under specific conditions at ambient temperature. It is difficult to predict the correlation that is more suitable for specific cryogenic flow estimation without experimental measurements [9]. In this study, three correlations were selected and their applicability to the development of a helical-in-tube-type heat exchanger was experimentally evaluated.

The first correlation was proposed by Schmidt [10]. The second was the correlation proposed by Manlapaz and Churchill [11], and the third was the correlation proposed by Ghobadi [12]. The combination of correlations is not unique and there is no guarantee that the combination is optimal. However, based on the literature search, this combination was deemed reasonable for the current study. The first and second correlations have been used for several decades for flows in helical channels. The third was proposed relatively recently and claims better fitting results than the existing correlations. The thermophysical properties of helium and nitrogen were determined using REFPROP software [13].

Figure 3(a) illustrates the experimentally obtained friction factors, and those calculated with the correlations and the value for laminar flow against the Reynolds number, $Re = (\rho v D_i)/\mu$

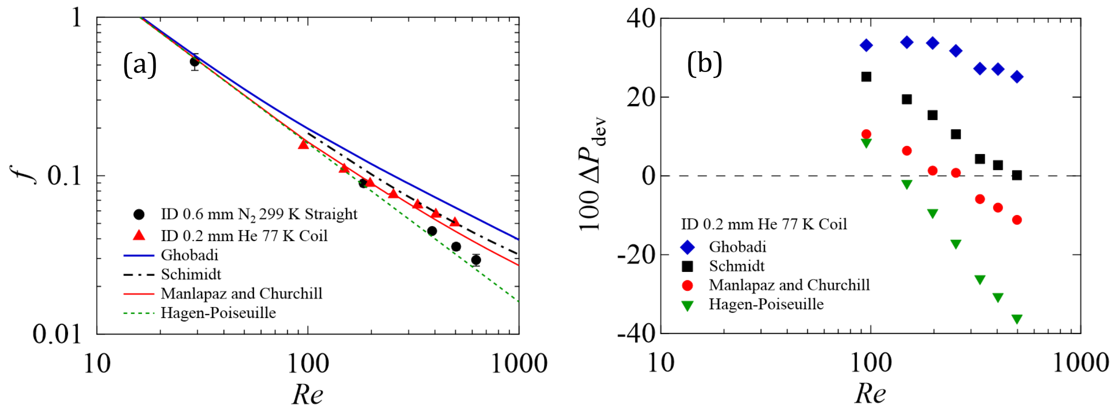

Figure 3. (a) Experimentally obtained and calculated friction factors, f against the Reynolds number, Re. (b) The deviation of the calculated pressure drop, ΔP_{dev} against Re.

where ρ is the density, v is the fluid velocity, D_i is the inner diameter of channel, μ is the dynamic viscosity. The filled circle symbol represents the experimentally obtained value for straight tube with an inner diameter of 0.6 mm and a length of 2 m. The Nitrogen was used as the test gas at 299 K. The error bars show the measurement uncertainty owing to the variations in the pressure and flow rate measurements. The dashed line represents the value for laminar flow in a straight tube (Hagen-Poiseuille flow) using Equation 2. This comparison demonstrates the validity of the pressure-drop measurement apparatus.

The filled triangle symbol represents the measured value in helically coiled capillary sample with an inner diameter of 0.2 mm and a length of 2 m. The thick solid line represents the values calculated using the correlation proposed by Ghobadi. The dashed-dotted line represents the values calculated using the correlation proposed by Schmidt. The value obtained from the correlation proposed by Manlapaz and Churchill is represented by the thin solid line.

Figure 3(b) illustrates the deviation of the calculated pressure drop $\Delta P_{dev} = ((\Delta P_{cal} - \Delta P_{mea})/\Delta P_{mea})$, (where ΔP_{cal} is the calculated value by the correlations, ΔP_{mea} is the measured value) against Reynolds number, Re for capillary of 0.2 mm in inner diameter at 77 K. Figures 3(a) and 3(b) are derived from essentially the same data; however, they are presented in a different way. The observed deviations within the measured Re range varies from -20 % to +35 %. Similar comparison results were obtained for capillary samples with inner diameters other than 0.2 mm. In the preset study, it was found that the deviations in the correlations by Manlapaz and Churchill, and Schmidt were smaller than those by Ghobadi. However, the Ghobadi's correlation was less sensitive to Re variations. This insensitivity can be advantageous in certain applications or handling. The correlations proposed by Manlapaz and Churchill, and Schmidt were used to design the counterflow heat exchangers in this study.

4. Counterflow heat exchanger with the distributed JT effect and analysis

A helical-in-tube-type counterflow heat exchanger for a small-scale JT cryocooler was developed and installed to a small-scale JT cryocooler. Figure 2 illustrates its appearance. It has flanges at both ends. A helically coiled capillary with an inner diameter of 0.1 mm and length of 4 m was inserted into the stainless-steel outer tube with an inner diameter of 14.4 mm and length of 14 cm. The inner diameter and length of the capillary were determined by analysis using the correlations by Manlapaz and Churchill, and Schmidt. The impedance of the helically coiled capillary was estimated to be sufficiently high to eliminate additional flow impedance, such as that of a JT valve for expansion.

Table 1. Measured temperatures and pressures of the helium flowing in the counterflow heat exchanger.

Point no.	Location	Pressure / kPa	Temperature / K
1	Inlet of high-pressure channel	124.2	8.1
2	Outlet of high-pressure channel	6.9	2.3
3	Pot	6.9	2.3
4	Inlet of low-pressure channel	6.9	2.3
5	Outlet of low-pressure channel	6.9	8.0

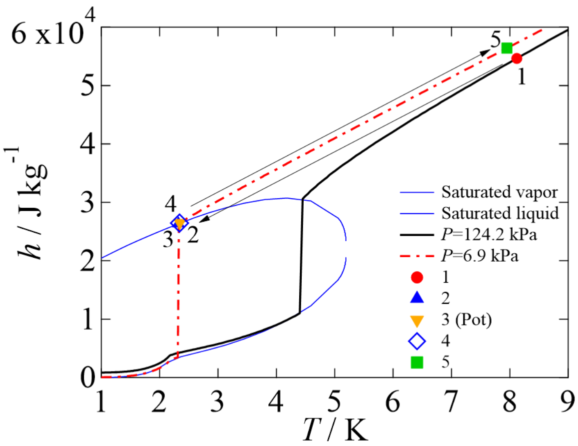

Figure 4. Estimated states of helium flowing in the heat exchanger. Numbers next to the symbols indicate corresponding locations on the heat exchanger. 1: Inlet of the high-pressure channel, 2: Outlet of the high-pressure channel, 3: Pot, 4: Inlet of the low-pressure channel, 5: Outlet of the low-pressure channel. A 0.2 mW of heat load was applied to the pot from a resistive heater attached to the pot in this case. The saturated liquid and vapor lines, and isobars corresponded to the pressures at the numbered locations are plotted.

Table 1 and Figure 4 present examples of the measurement results. A 0.2 mW of heat load was applied to the pot from a resistive heater attached to the pot. The flow rate was 57 μmol/s. The point numbers in Table 1 indicate the corresponding locations on the counterflow heat exchanger, as illustrated in Figure 2. The temperatures and pressures measured at the corresponding locations are listed in table.

Figure 4 illustrates the estimated states of helium flowing in the heat exchanger plotted on an enthalpy-temperature (h-T) diagram. The numbers next to the symbols indicate the corresponding locations on the heat exchanger. The arrows indicate the direction of the process. The thermophysical properties of helium were determined using HePak software [14].

Helium at the inlet of the high-pressure channel of 124.2 kPa and 8.1 K reduced the pressure and temperature down to 6.9 kPa and 2.3 K, respectively at the outlet of the high-pressure channel owing to the impedance of the high-pressure channel and the heat exchange with the flow in the low-pressure channel. The significant pressure drop, and the temperature reduction can be regarded as the result caused by the distributed JT effect of the developed counterflow heat exchanger. The helium from the outlet of the high-pressure channel lies in the two-phase region.

In this case, the temperatures at the points 2 (outlet of the high-pressure channel), 3 (pot), and 4 (inlet of the low-pressure channel) coincided within the uncertainty of the temperature measurement. This is a unique and interesting observation for a counterflow heat exchanger with a distributed JT effect. The minimum helium temperature was obtained at the outlet of the high-pressure channel, because of the significant pressure drops in the high-pressure channel.

However, the temperature at the inlet of the low-pressure channel would be minimum in the conventional counterflow heat exchanger without the distributed JT effect, because the temperature at the JT valve is lower than anywhere in the counterflow heat exchanger. Practically, the temperature at the outlet of the high-pressure channel rarely coincides with that at the inlet of the low-pressure channel in the conventional counterflow heat exchanger.

A temperature at the pot below 1.7 K was achieved without applying a heat load to the pot in the present system.

5. Conclusion

A helical-in-tube-type counterflow heat exchanger utilizing the distributed JT effect was successfully developed for a JT cryocooler. Prior to designing the counterflow heat exchanger, the pressure drops in the helically coiled capillary samples were measured. In this study, the correlations proposed by Manlapaz and Churchill, and Schmidt are used to estimate the pressure drop in a helically coiled capillary. It was also found that the correlation proposed by Ghobadi was less sensitive to Re variations in the present helical coil design.

The developed heat exchanger was integrated into a JT cryocooler, and its characteristics were investigated. The estimated states of helium-4 flowing in the heat exchanger were analyzed using a h-T diagram. It was confirmed that the impedance of the high-pressure channel was sufficiently high to cause significant drops in pressure and temperature in the helium flow. Two-phase helium was obtained without additional flow impedance, as with a JT valve. The measurements will be continued to investigate the temperature distribution around the heat exchanger and the cooling power in more detail.

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