Experimental investigation of 2 K JT (Joule-Thomson) cooling system using “distributed JT effect heat exchanger”

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Abstract. The simplest cooling method to achieve 2 K is to use a subatmospheric cooling system of liquid helium, which may have high efficiency benefited from a counterflow heat exchanger. This paper describes the design and fabrication a specific heat exchanger with significant pressure drop using a capillary tube. It is called a “distributed JT (Joule-Thomson) effect heat exchanger”. The hot and cold stream specifications of the heat exchanger are as follows; 0.4 mm ID (inner diameter), 0.64 mm OD (outer diameter) and 1.7 m length; 2.4 mm ID, 4 mm OD and 1.1 m length. The heat exchanger was operated using liquid helium as the working fluid at a pressure range of 100 kPa to 3 kPa, and a temperature range of 4.2 K to 2 K. Performance of the heat exchanger is analysed by Fanning friction factor and Colburn J-factor. The experimental investigation presents the characteristic of the distributed JT effect heat exchanger using liquid helium for the first time in the world.

1. Introduction

1.1. 2 K JT (Joule-Thomson) cooling system

2 K JT (Joule-Thomson) cooling systems consist of a heat exchanger and a JT expansion system. Knudsen et al. designed and fabricated the a 2 K JT refrigerator with two expansion systems and two heat exchangers [1]. The end of the hot stream of the heat exchanger in Knudsen’s system reached the specific enthalpy of 3.19 J/g at 2 K. The value is the lowest specific enthalpy by 2 K JT cooling system using liquid helium ever. Since the specific enthalpy of liquid helium becomes larger when its pressure is lower, the heat exchange of liquid helium at lower pressure can reach lower specific enthalpy than heat exchange at higher helium pressure. Therefore, Knudsen et al. suggested that the 2 K JT cooling system, which uses the heat exchanger with continuous pressure drop, may reach the lower specific enthalpy.

1.2 Distributed JT effect

The pressure loss effect in the heat exchanger was studied by Hwang et al. [2]. The specific enthalpy of the hot stream of a heat exchanger can be derived as equation (1).

\[ di = \dot{m}c_p(dT - \mu_{JT}dP) \]  

(1)
The specific enthalpy of the hot stream has to be decreased in the flow direction. In the case of liquid helium, the JT coefficient has a negative value (-0.00025; saturate liquid at 4.2 K). Furthermore, \(dP\) is always a negative value in the flow direction. Therefore, the term of pressure loss effect, \(-\mu_{JT}dP\), has a negative value, and extra enthalpy decrease in the hot stream is expected despite the same temperature decrease. The flow in the hot stream in the heat exchanger with the pressure drop continuously expands through the stream line. It means the JT expansion is distributed to the entire hot stream, and it is called “distributed JT effect” [3].

This paper describes design and manufacturing of the distributed JT effect heat exchanger. Performance validation of the heat exchanger is also carried out by experiment with liquid helium.

2. Design and manufacturing of the distributed JT effect heat exchanger

The distributed JT effect heat exchanger is designed by considering not only heat transfer performance but also pressure drop effect. Tube-in-tube type is selected for the heat exchanger as shown in figure 1 (a). The inner tube of the heat exchanger contains the hot stream and made of a capillary tube to create pressure drop. The inner tube is spirally twisted. The outer tube contains the cold stream and covers the inner tube. The geometries of each stream are calculated by pressure drop and heat transfer correlations. We select the goal mass flow rate of the hot stream as 0.05 g/s and calculate the pressure drop and heat transfer. To design the heat exchanger by considering pressure drop effect, we need to find the friction factor. Equation (2) is the friction factor correlation of fluid in a helical type tube, which is suggested by previous research [4].

\[
f_0 = 0.046(1 + 0.35\frac{D_{cap}}{D_{hel.}})Re_{D_{cap}}^{-0.2}
\]

Where \(D_{cap}\) is the inner diameter of the capillary tube, \(D_{hel.}\) is the diameter of helical shape as shown in figure 1 (a).

The pressure drop of a two-phase mixture flow can be obtained using the correlation [5] as shown in equation (3).
\[
\frac{dP}{dz}_{T,p} = \left(1 + x\left(\frac{D_t}{D_v} - 1\right)\right)^{0.25}\left(1 + x\left(\frac{\mu_t}{\mu_v} - 1\right)\right)^{-0.25}\frac{2f_0G^2}{\rho_lD_{cap}}.
\]

(3)

Where \(x\) is the quality of the flow and \(\mu\) is the viscosity. The heat transfer coefficient of each stream of the heat exchanger utilizes the Chilton-Colburn analogy \([4]\), which is the correlation between the friction factor and heat transfer coefficient as shown in equation (4).

\[
h = \frac{f_0}{2}Gc_PPr^{-2/3}
\]

(4)

The heat exchanger geometry is determined, and the specifications of the heat exchanger is indicated in Table 1 \([6]\).

3. Experimental apparatus

The experimental apparatus for performance verification of the distributed JT effect heat exchanger is designed and fabricated as shown in figure 1 (b). A 4 K chamber and a 2 K chamber act as liquid helium reservoirs, and they are connected to with each other by the hot stream of the heat exchanger. The outer tube of the heat exchanger (cold stream) covers the hot stream and is connected to a vacuum pump. A vapor cooled shield, a 40-layer sheet of MLI (multi-layer insulation), and thermal anchoring is used to reduce heat ingress by radiation and conduction. Three temperature sensors are mounted on the bottom plate of the each tank and the outlet of the cold stream to measure the fluid temperature in each tank and the temperature of the cold stream temperature, respectively. Three pressure sensors measure the pressure of the both tanks and of the cold stream outlet. A level sensor in the 4 K chamber and two mass

**Table 1. Designed heat exchanger specifications**

|                | Hot stream | Cold stream |
|----------------|------------|-------------|
| Inner diameter [mm] | 0.4        | 2.4         |
| Outer diameter [mm]  | 0.64       | 4.0         |
| Length [m]           | 1.7        | 1.1         |

**Figure 1.** Schematic of the distributed JT effect heat exchanger (a) and experimental apparatus to verify the heat exchanger (b)
flow meters are also installed to measure the mass flow rate of each stream within 0.5% measurement error.

4. Results and discussion

4.1. Mass and energy balance in the heat exchanger

The liquid helium loss rate in the 4 K chamber is measured by the level sensor. The liquid loss is the sum of natural boil-off rate (BOR) of 4 K chamber and the mass flow rate of the hot stream of the heat exchanger. Then, mass balance can be described as equation (5).

\[
\dot{m}_\text{HP} = \rho_i A L_0 \frac{d(\text{Level}/100)}{dt} - \dot{m}_{4\text{K,BOR}}
\]

(5)

Where \(\dot{m}_{4\text{K,BOR}}\) is the natural boil-off rate (BOR) of the liquid helium in the 4 K chamber. The calculated mass flow rate of the hot stream is 0.063 g/s. The mass flow rate of cold stream is measured data by mass flow meter, and the value is 0.03 g/s as indicated in Table 2. Since the temperature and the pressure of the hot stream inlet, the colds stream inlet, and the cold stream outlet are measured, the specific enthalpy of the fluid at the outlet of the hot stream can be evaluated. Then energy balance can be derived as equation (6).

\[
\dot{m}_\text{HP} (h_{\text{in,HP}} - h_{\text{out,HP}}) = \dot{m}_\text{LP} (h_{\text{out,LP}} - h_{\text{in,LP}})
\]

(6)

All parameters in equation (6) except \(h_{\text{out,HP}}\) are known, then we can obtain the value of \(h_{\text{out,HP}}\) (5.36 J/g). The thermodynamic states of the heat exchanger are listed in Table 2.

Table 2. Thermodynamic properties of the heat exchanger

| Point                | \(P\) [kPa] | \(T\) [K] | \(h\) [J/g] | Mass flow rate [g/s] |
|----------------------|-------------|-----------|-------------|----------------------|
| Hot stream inlet     | 100         | 4.2       | 11.4        | 0.063                |
| Colds stream inlet   | 2.4         | 2.0       | 25.1        |                      |
| Cold stream outlet   | 1.9         | 3.78      | 34.6        | 0.03                 |

Figure 2. Heat transfer process of the heat exchanger on P-h diagram of liquid helium
4.2. Heat exchanger calculation

Inlet and outlet points of each stream are indicated in figure 2. We do not know about the information near the point 2, because sensors cannot be mounted at the end of the capillary tube. Therefore, we calculate the temperature profile, the pressure, and the enthalpy of each stream. The heat exchanger calculation is carried out by the pressure drop and the heat transfer correlations as mentioned previously. Figure 2 shows heat transfer process on the P-h diagram of liquid helium. At near the point 2, the pressure loss is dramatically enhanced because the fluid quality of the hot stream continuously increases. Although the pressure drop is large near the point 2, the hot stream pressure at the point 2 is 7.8 kPa. The heat capacity rates \((\dot{m}c_p)\) of the hot and cold stream are 0.33 W/K and 0.16 W/K, respectively. The imbalance of the heat capacity rate between each stream causes degrade of the performance of the heat exchanger. Since the hot stream has the larger heat capacity rate than the cold stream, the specific enthalpy change of the hot stream during the heat exchange process is less than the specific enthalpy change of the cold stream. As the results, the hot stream reaches 5.36 J/g at the point 2. If the heat capacity rates of each stream are the same, the specific enthalpy at the point 2 can be reached lower value than 5.36 J/g. The pressure loss term in equation (1) is \(-c_p\mu_{JT}dP\), and it causes the distributed JT effect. The calculated specific enthalpy change by the distributed JT effect from the point 1 to 2 is 0.09 J/g. If the pressure loss does not exist in the hot stream, the enthalpy of the end of the hot stream will be 0.09 J/g greater than 5.36 J/g (5.45 J/g, the point 2’ in figure 2). It means the distributed JT effect exists in the heat exchanger. If each stream has the same mass flow rate, respectively, the enthalpy of the hot stream reaches lower enthalpy, and the temperature of the cold stream outlet becomes lower than this experiment results. The ‘lower enthalpy’ of the hot stream outlet means the effective heat exchange process. However, the ‘lower temperature’ of the cold stream outlet means the larger entropy generation. Therefore, higher effectiveness (the ratio between the actual heat transfer rate and the maximum possible heat transfer rate) heat exchanger has to be designed as a future work.

5. Conclusion

This paper designs and manufactures the distributed JT effect heat exchanger for 2 K cooling system for the first time. The mass flow rates performance of heat exchanger are 0.063 g/s at the hot stream with the pressure drop of 97 kPa and 0.030 g/s at the cold stream with the pressure drop with 0.5 kPa. The specific enthalpy of the hot stream reaches 5.36 J/g using distributed JT effect as experiment result. If there is no pressure drop (without distributed JT effect), the specific enthalpy of the hot stream reaches 5.45 J/g. The heat capacity rate unbalance occurs in this paper, so we will carry out a further experiment with mass flow rate control with a heater as a future work. Furthermore, we will design and manufacture the advanced heat exchanger which has higher effectiveness than in this paper.

6. References

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