Design of distributed JT (Joule-Thomson) effect heat exchanger for superfluid 2 K cooling device

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Abstract. Superfluid at 2 K or below is readily obtained from liquid helium at 4.2 K by reducing its vapour pressure. For better cooling performance, however, the cold energy of vaporized helium at 2 K chamber can be effectively utilized in a recuperator which is specially designed in this paper for accomplishing so-called the distributed Joule-Thomson (JT) expansion effect. This paper describes the design methodology of distributed JT effect heat exchanger for 2 K JT cooling device. The newly developed heat exchanger allows continuous significant pressure drop at high-pressure part of the recuperative heat exchanger by using a capillary tube. Being different from conventional recuperative heat exchangers, the efficient JT effect HX must consider the pressure drop effect as well as the heat transfer characteristic. The heat exchanger for the distributed JT effect actively utilizes continuous pressure loss at the hot stream of the heat exchanger by using an OD of 0.64 mm and an ID of 0.4 mm capillary tube. The analysis is performed by dividing the heat exchanger into the multiple sub-units of the heat exchange part and JT valve. For more accurate estimation of the pressure drop of spirally wound capillary tube, preliminary experiments are carried out to investigate the friction factor at high Reynolds number. By using the developed pressure drop correlation and the heat transfer correlation, the specification of the heat exchanger with distributed JT effect for 2 K JT refrigerator is determined.

1. Introduction

Cryogenic temperature of 2 K or below is utilized for low-temperature property measurement device, high magnetic field systems such as 45 Tesla hybrid magnet, LHC (Large hadron collider) to observe subatomic matter, NMR (Nuclear magnetic resonance) and various advanced particle accelerators [1-4]. A simple liquid helium system without recuperative heat exchanger can be employed with a vacuum pump to lower the vapour pressure of helium and produce superfluid to provide constant cooling effect. Liquid helium is continuously supplied to sub-atmospheric chamber while experiencing Joule-Thomson (JT) cooling effect. This JT expansion process can be effectively modified for a more efficient cooling device by incorporating a recuperative heat exchanger and an orifice to produce necessary JT cooling effect, which resultantly utilizes the cold energy of the pumped helium vapour. As pointed out by Ganni et al. [5], the sub-atmospheric JT cooling method can be further improved by combining multiple JT expansions and heat exchange processes in between. It is common that the large-size 2 K refrigerator requires very high electric power input in general such as 18 MW to run LHC (20 kW at 1.9 K as cooling capacity) and 5 MW to operate CEBAF (Continuous Electron Beam Accelerator Facility) accelerator (4.8 kW at 2 K as cooling capacity). Tons of liquid helium are also used to cooling such large-scale applications in conjunction with using JT expansions to create 2 K environments. Various studies, therefore, were seriously carried out to improve the efficiency of the 2 K JT refrigeration. Fig. 1 shows...
typical schematic diagrams of these refrigeration systems. In general, 2 K refrigerator is composed of a pre-cooler, a recuperative heat exchanger, a valve and an evaporator or 2 K chamber. The pre-cooler is required primarily to cool down helium from room temperature to approximately 4.5 K. After passing the pre-cooler, helium can be further cooled by a heat exchanger and an expansion valve. JLab (Jefferson laboratory) initially developed a recuperative heat exchanger to be utilized for the 2 K refrigerator in 1980s and SNS (Spallation neutron source) facility improved the efficiency of 2 K refrigeration system by switching the location of the heat exchanger in 2002. Specifically, as the heat in-leak from the environment is intercepted at higher temperature region than the previous system, the entropy generation of the system has been reduced. Knudsen et al. suggested another option using an additional valve and a heat exchanger in 2012, and, the experiment to verify their design was implemented in 2015. [5, 6] It is the most efficient 2 K JT refrigeration cycle up to now although multiple heat exchangers with expansion valves are expected to be more efficient.

![Figure 1. Schematic diagrams of previous 2 K refrigeration systems.](image)

Various papers have dealt with recuperative heat exchangers with the distributed JT effect. Since the heat exchanger with the distributed JT effect actively utilizes the pressure loss effect in the high-pressure stream of the heat exchanger, a capillary tube is usually used to make the heat exchanger. Hwang et al. fabricated triplet heat exchanger by using capillary tubes and investigated the performance in 2009 [7]. Additionally, Hwang et al. referred the relation between the pressure losses in the heat exchanger and the effectiveness in 2010 [8]. Maytal et al. designed and verified the effect of the heat exchanger with the distributed JT effect by using mixed refrigerant in 2014 [9]. Hong et al. used effectiveness-NTU method to predict the effect of the heat exchanger utilizing a capillary tube as a hot stream in 2010 [10]. Damle et al. developed a numerical model to predict transient state of the heat exchanger with the distributed JT effect in 2015 [11]. However, the heat exchanger with the distributed JT effect for 2 K has not been made until now. Additionally, an existence of a JT valve in front of a heat exchanger with the distributed JT effect can regulate the mass flow rate. This paper proposes a 2 K cooling system which uses a JT valve and a distributed JT effect heat exchanger. The design methodology of the distributed JT effect heat exchanger is thoroughly addressed to be used for the efficient 2 K JT refrigerator.

2. Design methodology of recuperative heat exchanger
   The distributed JT heat exchanger not only cools down the high-pressure stream passively by exchanging heat with the low-pressure stream but also allows the high-pressure stream to be cooled actively by its own JT expansion effect.

2.1. Efficiency improvement of 2 K cooling device
The main purpose of 2 K cooling device is to create low temperature environment efficiently by using a high-pressure stream which is usually obtained from near 1 bar saturated liquid helium bath. Fig. 2 represents the overall refrigeration system suggested in this paper. Saturated liquid at 1.4 bar is supplied to the JT valve. After the JT expansion, two phase helium enters the recuperative heat exchanger with the distributed JT effect. At the end of the heat exchanger, the state of helium is to be 2 K of two phase state whose quality is 0.04. In the evaporator section, two phase helium is separated into liquid and vapour. The saturated vapour only returns to the cold stream of the heat exchanger after absorbing heat.

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of 2 K system using heat exchanger with distributed JT effect.

![Figure 3](image3.png)

**Figure 3.** Design method of heat exchanger with distributed JT effect

Table 1 shows the state of each position. The system is ideally 2.4 % more efficient than the process suggested by Knudsen et al. The cooling efficiency is defined as (1).

\[
Efficiency = \frac{\text{refrigeration capacity}}{\text{required power}}
\]  

(1)

The efficiency of the system is usually determined by only the potential refrigeration capacity which is inversely proportional to the enthalpy at the position 3. The continuous pressure drop process for this heat exchanger is simulated and carefully designed as illustrated in Fig. 3.

| Position | Temperature (K) | Pressure (kPa) | Quality (-) |
|----------|----------------|----------------|-------------|
| 1        | 4.6            | 140            | 0 (Saturated liquid) |
| 2        | 4.4            | 120            | 0.06        |
| 3        | 2              | 3.13           | 0.04        |
| 4        | 2              | 3.13           | 1 (Saturated vapor) |
| 5        | 3.8            | 3.13           | Superheated vapor |

Fig.4 shows the ideal pressure-enthalpy diagram of helium passing the high-pressure hot stream of the heat exchanger from 4.5 K to 2 K. The saw-toothed black line starts from 4.5 K and ends near 2 K by following the saturated liquid line closely. The estimated steady state temperature profiles in the heat exchanger are also plotted at Fig. 5. Fig. 5 (a) indicates the temperature profiles of the high-pressure (hot stream) and the low-pressure (cold stream) ones considering the pressure drop effect of the high-pressure stream (Fig. 2 and Fig. 3). Since the heat capacity rates of two streams are different, they are not parallel. Fig. 5 (b) is also depicted for comparison, which is the temperature profiles with no-pressure drop effect, but with two JT valves as shown in Fig. 1 (c). Fig. 5 (a) presents the smaller overall temperature difference between hot and cold streams than that of Fig. 5 (b), which may elucidate the better cooling efficiency of the distributed JT heat exchanger by producing less entropy due to heat.
transfer with finite temperature difference. NTU (Number of transfer unit) needed to this heat exchanger is precisely computed by applying general heat exchanger calculation algorithm for each sub-unit heat exchanger modelled as shown in Fig. 3. The total NTU is the summation of each NTU calculated for each sub-unit heat exchanger. The resultantly computed NTU value is 5.6. The design analysis demonstrates that the recuperative heat exchanger with the distributed JT effect should enable the 2 K refrigerator to maximize its cooling capacity at 2 K by creating near saturated liquid condition at the exit of the heat exchanger. The required pressure drop in the hot stream of the heat exchanger is 117 kPa from 4.5 to 2 K. It is also very crucial that the pressure drop less than 2 kPa is only permitted at the cold stream. The proper pressure drop and heat transfer coefficient correlations are, therefore, very important to design the heat exchanger with the distributed JT effect.

![Figure 4. Pressure-enthalpy diagram of helium passing the heat exchanger with continuous pressure loss.](image)

![Figure 5. Steady state temperature profiles in the heat exchanger.](image)

2.2. Heat exchanger configuration

It is clear that some extraordinary pressure drop in the high-pressure side of the heat exchanger can be deliberately induced so that the continuous J-T effect occurs during normal heat exchange process. The detailed heat exchanger analysis enables one to design a heat exchanger for producing near 2 K high-pressure stream at its cold end to create 2 K helium without further expansion. The physical
configuration of the exemplary heat exchanger is similar to one found in a dilution refrigerator. The high-pressure helium flows through the spirally wound capillary tube to produce the desirable amount of pressure drop and accommodate sufficient heat transfer area. Fig. 6 (a) shows the test capillary tube with inner diameter of 0.4 mm before it is encapsulated by the larger spiral tube whose inner diameter is 2.4 mm. The larger tube holds the low-pressure helium stream for heat exchange. The fabricated heat exchanger is specifically for the mass flow rate of 0.07 g/s and also shown in Fig. 6 (b).

![Capillary tube](image)

(a) Inner capillary tube of heat exchanger  (b) Outer tube of heat exchanger

**Figure 6.** Fabricated spiral type recuperative heat exchanger.

2.3. Pressure drop consideration

The heat exchanger is specifically fabricated to produce precise continuous pressure drop effect as well as the appropriate heat transfer performance at the pre-determined mass flow rate of helium. In general, the empirical correlation to predict pressure drop of helical coil heat exchanger is suggested for capillary tube as written in (2) [12]. This correlation is utilized at various experimental conditions.

\[
\frac{\Delta P}{\Delta L} = \frac{0.092G^2[1+3.5(D_e / D_c)]}{Re^{0.5}D_e \rho}
\]

Since the value of \( \frac{D_h}{D_e} \) in this paper is relatively smaller than the usual cases, a preliminary experiment is carried out to verify and correct the correlation by using high pressure helium at liquid nitrogen temperature which is approximately 77 K. In the case of high Reynolds number range around 30,000 which is needed to design the heat exchanger with distributed JT effect for 2 K refrigerator, the correction factor of 1.46 is determined. When the two-phase flow occurs in the heat exchanger, the equation (3) is applied [13] to calculate the pressure drop.

\[
\phi^2 = \left( \frac{dp}{dx} \right)_{\text{tp}} = \left[ 1 + x \left( \frac{\rho_l}{\rho_v} - 0 \right) \right] \left[ 1 + x \left( \frac{\mu_l}{\mu_v} - 0 \right) \right]^{0.25}
\]

2.4. Heat transfer consideration

The heat transfer requirement is less stringent than that of pressure drop. Using (5), the necessary UA value is computed at each small sub-unit heat exchanger. Convective heat transfer coefficient in the capillary tube is estimated by the following equation (6).

\[
NTU = \frac{UA}{mc_p}
\]
\[ h = 0.023 \text{Re}^{-0.2} \text{Pr}^{-2/3}[1 + 3.5(D_r / D_c)] \]  

(5)

If there is two-phase flow in the capillary tube, the homogeneous model is considered as suggested in the reference [13]. The convective heat transfer coefficient of low-pressure helium in the outer tube is calculated from the well-known Nusselt number relation [14] as shown in equation (11).

\[ Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \]  

(6)

The required UA value at each sub-unit heat exchanger is calculated by the overall thermal resistances as in the following equation (12).

\[ \frac{1}{UA} = \left( \frac{1}{hA^{hp}} + \frac{\ln(D_o / D_c)}{2 \pi kL} + \frac{1}{hA^{lp}} \right) \]  

(7)

3. Summary
The development methodology of distributed JT effect heat exchanger is described for 2 K cooling device. Different from conventional recuperative heat exchangers, the distributed JT effect heat exchanger actively utilizes the pressure loss of high-pressure stream as well as the heat transfer characteristic. For the lab scale application dealing with small mass flow rate such as 0.07 g/s, which can be used in low-temperature property measurement device, the heat exchanger can be accordingly designed and fabricated with two stainless steel 304 tubes and its dimension is precisely determined after performing pressure drop test. One for the high-pressure side is 1.7 m long spirally wound capillary tube of which the inner diameter is 0.4 mm and the outer diameter is 0.64 mm. The other for the low-pressure side is 1.1 m long and 0.8 mm thick tube with 4 mm outside diameter. The designed heat exchanger is expected to enable the 2 K refrigerator to maximize its potential cooling capacity at 2 K.

Acknowledgments
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