Pressure drop characteristics of cryogenic mixed refrigerant at macro and micro channel heat exchangers

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Mixed Refrigerant-Joule Thomson (MR-JT) refrigerator is widely applied in various kinds of cryogenic system these days. Temperature glide effect is one of the major features of using mixed refrigerant since a recuperative heat exchanger in MR-JT refrigerator is utilized for mostly two-phase flow. Although pressure drop estimation of multi-phase and multi-component fluid in cryogenic temperature range is necessarily required in MR-JT refrigerator heat exchanger designs, it has been rarely discussed so far. In this paper, macro heat exchanger and micro heat exchanger are compared to investigate the pressure drop characteristics in the experimental MR-JT refrigerator operations. Tube in tube heat exchanger (TTHE) is a well-known macro-channel heat exchanger in MR-JT refrigeration. Printed Circuit Heat Exchanger (PCHE) has been developed as a compact heat exchanger with micro size channels. Several two-phase pressure drop correlations are examined to discuss the experimental pressure measurement results. The result of this paper shows that cryogenic mixed refrigerant pressure drop can be estimated with conventional two-phase pressure drop correlations if appropriate flow conditions are identified.

Key words: Joule Thomson, Mixed refrigerant, heat exchanger, two-phase, pressure drop

INTRODUCTION

A JT (Joule-Thomson) refrigerator is operated as follows. The pressurized refrigerant cools down when it passes through the recuperative heat exchanger, and expanded at the JT valve. The refrigerant reaches low temperature when it expands at almost constant enthalpy condition. Afterwards, the refrigerant of low pressure returns through the recuperative heat exchanger, and the regeneration process is made by transferring the cold source. The cooling effect is intensified by this regeneration process, so that the temperature becomes lower as the refrigerant circulates.

The traditional JT refrigerators are operated in high pressure ratio and have used pure substances for the working fluid such as nitrogen, argon, and nitrous oxides. However, cryogenic JT refrigerators operated with single component refrigerant usually show very low thermodynamic efficiencies [1].

Use of mixed refrigerant (MR) in JT refrigerators enables one to overcome the low exergy efficiency of JT refrigerators. The MR-JT refrigerator operates in mostly two-phase region, which makes temperature glide effect from the dew point to the bubble point in the saturation dome (Figure 1). For this working mechanism of MR-JT refrigerator, the cold-end
temperature is sensitively affected by the thermal performance of heat exchanger as well as its pressure drop characteristics. Therefore, the performance of heat exchanger strongly influences the overall efficiency of the MR-JT refrigerator.

The pressure drop in low pressure channels of the heat exchanger is especially important because the achievable low temperature is directly related to the lowest system pressure.

The heat exchanger design process for the MR-JT is complex, because the MR-JT refrigerator involves the understanding of multi-component, and multi-phase flow characteristics. There have been a few studies regarding to heat transfer and pressure drop correlation for cryogenic mixed refrigerants [2]. However, there are not generalized heat transfer and pressure drop correlations for cryogenic mixed refrigerants.

In this paper, the MR JT refrigerator is operated with two kinds of heat exchanger: the Tubes in Tube Heat Exchanger (TTHE) and Printed Circuit Heat Exchanger (PCHE). The distinctive difference of two heat exchanger is the channel size. The TTHE has 1.6 mm of hydraulic diameter, and the PCHE has 0.026 mm of that. The pressure drop of low pressure fluid is measured and compared to other two-phase pressure drop correlations.

**Table 1 Comparison of two heat exchangers**

<table>
<thead>
<tr>
<th></th>
<th>TTHE</th>
<th>PCHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic diameter (low p. side)</td>
<td>1.58 mm</td>
<td>0.340 mm</td>
</tr>
<tr>
<td>Heat transfer area</td>
<td>0.239 m²</td>
<td>0.202 m²</td>
</tr>
<tr>
<td>Length</td>
<td>6 m</td>
<td>0.55 m</td>
</tr>
<tr>
<td>Volume</td>
<td>0.403 L</td>
<td>0.136 L</td>
</tr>
<tr>
<td>Area density</td>
<td>592 m²/m³</td>
<td>1490 m²/m³</td>
</tr>
</tbody>
</table>

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**MR COMPOSITION**

Mixed refrigerants are selected with two constraints. Firstly, non-flammable gases are selected for safety problem. Secondly, gases are selected with zero ODP (Ozone depletion Portion) values for environmental issue. Finally, Argon, R14, R23, R218, and R134a are selected by constraints and mixed in mole percent of 34%, 22%, 10%, 15%, and 19%, respectively.

![Figure 1. Temperature-Entropy diagram of mixed refrigerant (Ar:R14:R23:R218: R134a=34:22:10:15:19)](image)

![Figure 2. Picture of the TTHE (left) and the PCHE (right)](image)
HEAT EXCHANGERS

The TTHEs have been generally used for JT refrigerators, but its large volume is unfavorable characteristic when the refrigeration system size should be compactly designed. PCHEs are composed with micro-channels, which can increase heat transfer area within the limited volume. PCHE has large area density compared to TTHE, which is beneficial for the compact system design (Figure 2).

The specifications of each heat exchanger are shown in Table 1. The TTHE is composed with the one 3/8 inch outer tube and four 1/8 inch inner tubes. The PCHE is fabricated with etching and diffusion bonding process. The details of two heat exchangers can be found in the preceding studies [3, 4]. The performance of two heat exchangers are investigated in cryogenic temperature range using helium. It can be told that single-phase flow characteristics of heat exchangers are verified with the established correlations.

EXPERIMENTAL SETUP

The MR-JT refrigerator with two kinds of heat exchanger is operated using the test apparatus depicted in Figure 3. The MR is charged from each separate component bottles to the setup. The MR is circulated by a helium compressor (Helix, CTI-8200-air cooled), and passes through the heat exchanger. When the mixed refrigerant passes the JT (Joule Thomson) valve, expansion occurs, which generates cold temperature. The JT valve is made of long thin stainless tube with 1.0 mm inner diameter. After passing through heater, the MR enters the heat exchanger again. The MR from the heat exchanger goes back to compressor to generate constant high pressure.

The mass flow rate of mixed refrigerant was measured by a mass flow meter (Micromotion, CMF025 with 1700 transmitter) which is located between the compressor and the cold out flow of heat exchanger. Five silicon diode thermometers (Lakeshore DT-670SD) are attached to the surface of inlets and outlets tubes of the heat exchanger to measure the flow temperatures with respect to mass flow rates. Four pressure transducers (SENSYS, PSHD 30 bar) are attached to the inlets and outlets of the heat exchanger. Experiments are conducted inside a vacuum chamber in order to eliminate heat ingress from convection during the course of the experiment. All the pipes inside vacuum chamber are soldered to eliminate the leakage of mixed refrigerant in cryogenic temperature.

Temperature data are collected by monitoring device (Lakeshore, Temperature Monitor 218). Mass flow rate and pressures are collected by data acquisition system (NI-USB6210). All collected data are recorded by software from personal computer (National Instrument, Labview 8.2).

EXPERIMENTAL RESULTS

Figure 4 shows temperature variation at typical cool down process of TTHE MR JT refrigerator. The minimum no-load temperature is 125.4 K. The effectiveness of the TTHE is 96.8 %. Figure 5 shows the variations of pressures and the mass flow rate. The pressure drop between inlets and outlets are increased, and the mass flow...
rate is increased as the temperature is lowered. The mass flow rate is increased because of the high density of the partially liquefied refrigerant at low temperature.

Figure 6 and Figure 7 show the temperatures, pressures, and mass flow rate variations at typical cool down process of MR JT equipped with PCHE. PCHE MR-JT reaches the minimum no-load temperature of 138.8 K, and shows effectiveness of 95.2%. It takes 1/3rd of time faster than the TTHE MR-JT system due to the less mass. Pressure drop is also increased during cool down process, which is similar to the that of TTHE MR-JT.

The pressure drops with various mass flow rate is obtained during the cool down process. The pressure drops of low pressure side are calculated with various correlations and compared to experimental results. However, a number of assumptions are needed to calculate the two-phase pressure drop within the specified channel length \( L_{tp} \).

\[
\Delta P = \frac{L_{tp}}{x_2} \int x \frac{2 f_f G^2 (1 - x)^2 v_f \phi_f}{d_h} dx \quad (1)
\]

First of all, the physical properties of the MR are calculated by Aspen HYSYS with Peng-Robinson EOS [5] and applied in the equation (1). The equation (1) needs the inlet quality \( x_1 \) and the outlet quality \( x_2 \). The inlet quality is assumed to be 0.25, which is calculated from T-s diagram with experimental results, and the outlet quality is assumed to be 1. However, the inlet quality is changes from 1 to 0.25 during the cool down process. This assumption is an arbitrary assumption, but it will help to explain qualitative trend. The frictional pressure drops is considered, and gravitational and acceleration pressure drops are neglected for calculations. Single-phase friction factors \( f_f \) of each heat exchangers are validated from previous experiments [3, 4], and applied to the equation (1).

In the present study, four popular macro-channel correlations, four correlations developed specifically for mini/micro- channels, and two correlations for macro channel developed for room temperature mixed refrigerants are examined. The references of correlations are shown in Table 2.

![Figure 4. Temperature variation of MR-JT during typical cool-down period with TTHE](image)

![Figure 5. Pressure and mass flow rate variation of MR-JT during typical cool-down period with TTHE](image)

![Figure 6. Temperature variation of MR-JT during typical cool-down period with PCHE](image)
Figure 7. Pressure and mass flow rate variation of MR-JT during typical cool-down period with PCHE

Table 2 Two-phase pressure drop correlations

<table>
<thead>
<tr>
<th>Reference</th>
<th>Channel Size / Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lockhart Martinelli [6] (Larminar liquid-larminar vapor)</td>
<td>Macro / Pure</td>
</tr>
<tr>
<td>Lockhart Martinelli [6] (Larminar liquid-turbulent vapor)</td>
<td>Macro / Pure</td>
</tr>
<tr>
<td>Chisholm [7]</td>
<td>Macro / Pure</td>
</tr>
<tr>
<td>Fridel [8]</td>
<td>Macro / Pure</td>
</tr>
<tr>
<td>Mishima and Hibiki [9]</td>
<td>Micro / Pure</td>
</tr>
<tr>
<td>Lee and Lee [10]</td>
<td>Micro / Pure</td>
</tr>
<tr>
<td>Qu and Mudawar [12]</td>
<td>Micro / Pure</td>
</tr>
</tbody>
</table>

COMPARISON RESULTS

Figure 8 shows the results of the pressure drop comparisons between calculations and experimental results obtained during the cool down process with TTHE MR-JT. The mean absolute errors (MAE), the equation (2), of each correlations, are provided in also Figure 8.

\[
MAE = \frac{1}{M} \sum \left| \frac{\Delta P_{\text{pred}} - \Delta P_{\text{exp}}}{\Delta P_{\text{exp}}} \right| \times 100\% \tag{2}
\]

Experimental pressure drop results with various mass flux are shown as dots. The data is scattered due to two-phase instabilities. Macro-channel correlations, especially Lockhart-Martinelli with larminar liquid-turbulent vapor model [6] and Sami [13], accurately predict the frictional two-phase flow pressure drop of cryogenic-temperature mixed refrigerant within long tubes. These models are based on the annular flow regime, where high temperature refrigerants are liquid state at walls, and low temperature refrigerants are vapor state. Other correlations, Fridel [8] and Jung & Radermacher [14], are based on separated flow model, nevertheless, they show large MAE with experimental data.

Figure 9 shows the pressure drop comparison results between the correlations and the experimental results obtained during the cool down process with PCHE MR-JT. The correlations developed for
micro-channels [9-12] well predicted the two-phase pressure drop of cryogenic mixed refrigerants. The Chisholm correlation [7], the correlation based on macro-channels, also well predict the pressure drop in PCHE. The best predicted correlation, which is developed by Qu and Mudawar [12], is also based on the annular flow regime in microchannels, and shows 26% of MAE. A portion of the liquid phase flows as a thin film along the channel wall, while the other portion is entrained in the vapor core as liquid droplets. The comparison with the existing correlations and the experimental results indicate that cryogenic mixed refrigerants exhibit annular flow regime in macro and microchannels. It is remarkable for all data with mixed refrigerants to be well correlated with pure fluid two-phase pressure drop correlations.

**SUMMARY**

Recuperative heat exchanger in an MR-JT refrigerator has an important role in the whole system performance. However, it is difficult to design an appropriate heat exchanger for cryogenic MR-JT refrigerator because of complex phenomena of multi component, multi-phase flow. In this paper, well-known two-phase pressure drop correlations are compared to the experimental results obtained during the cool down process of MR-JT. Correlations developed with the annular flow regime assumption predicted pressure drop of two-phase cryogenic mixed refrigerant within 50 % MAE at macro and micro channels. The annular flow regime is expected in cryogenic mixed refrigerant flow. This result suggests that the pressure drop of cryogenic mixed refrigerant can be estimated with pure fluid two-phase pressure drop correlations.

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**REFERENCES**


