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Investigation of Pressure Drop in Capillary Tube for Mixed Refrigerant Joule–Thomson Cryocooler

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Abstract. A capillary tube is commonly used in small capacity refrigeration and air-conditioning systems. It is also a preferred expansion device in mixed refrigerant Joule-Thomson (MR J–T) cryocoolers, since it is inexpensive and simple in configuration. However, the flow inside a capillary tube is complex, since flashing process that occurs in case of refrigeration and air-conditioning systems is metastable. A mixture of refrigerants such as nitrogen, methane, ethane, propane and iso-butane expands below its inversion temperature in the capillary tube of MR J–T cryocooler and reaches cryogenic temperature. The mass flow rate of refrigerant mixture circulating through capillary tube depends on the pressure difference across it. There are many empirical correlations which predict pressure drop across the capillary tube. However, they have not been tested for refrigerant mixtures and for operating conditions of the cryocooler.

The present paper assesses the existing empirical correlations for predicting overall pressure drop across the capillary tube for the MR J–T cryocooler. The empirical correlations refer to homogeneous as well as separated flow models. Experiments are carried out to measure the overall pressure drop across the capillary tube for the cooler. Three different compositions of refrigerant mixture are used to study the pressure drop variations. The predicted overall pressure drop across the capillary tube is compared with the experimentally obtained value. The predictions obtained using homogeneous model show better match with the experimental results compared to separated flow models.

Keywords: Mixed refrigerant, J-T Cryocooler, Capillary tube.
PACS: 07.20 Mc, 51.30. +i

INTRODUCTION

A closed cycle MR J-T cryocooler is comprised of a compressor, an after-cooler, a recuperative counter flow heat exchanger, an expansion device and an evaporator. The compressor compresses the refrigerant which is partially cooled in the after cooler and further cooled inside the tube of heat exchanger by the low pressure, low temperature refrigerant stream flowing through annulus of the heat exchanger. Throttling or expansion of the high pressure refrigerant in the expansion device results in the low pressure, low temperature stream. This low pressure, low temperature stream produces cooling effect at the cold end and then returns to the compressor through the heat exchanger.

Capillary tube is commonly used in small capacity refrigeration and air-conditioning systems. It is also a preferred expansion device in MR J-T cryocoolers since it is inexpensive and simple in configuration. Fixed capilliary type expansion devices eliminate manual or automatic adjustment of orifice opening during cool down from ambient temperature to steady state operation of the cryocooler in the cryogenic range. However, the flow characteristic inside a capillary tube is complex. This is due to the fact that the flashing in the capillary tube does not start immediately at the inlet i.e., at the saturation pressure corresponding to the refrigerant temperature. Consequently, vaporization process gets delayed due to required degree of superheat for vapor bubble nucleation. This results to an existence of liquid region (a non-thermodynamic equilibrium condition) below the saturation pressure which is referred to as a metastable liquid region [1].

The selection of capillary tube is done on the basis of desired refrigeration temperature and cooling capacity to be achieved from the cryocooler. Typically, diameter and length of the capillary tube ranges from 1 to 3 mm and 1 to 4 m, respectively. The pressure difference across the capillary tube is the driving force for the mixture to flow through it. Therefore, mass flow rate through the capillary tube increases with increase in pressure difference across it. The pressure drop across the capillary tube is mainly due to frictional resistance and acceleration of the refrigerant because of flashing of some liquid refrigerant. In order to have same mass flow rate and pressure drop across the

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capillary tube, several combinations of length and diameter are possible. Higher pressure drop in the capillary tube leads to lower saturation pressure in the evaporator and hence, lower refrigeration temperature. Additionally, increase in mass flow rate through the system increases cooling capacity.

There are many experimental studies and models available in the literature on the capillary tube with pure CFC and HCFC refrigerants such as R-12 and R-22 due to their commercial applications in refrigeration industry. Few experimental studies are extended to refrigerant mixtures such as R407C, R410A in capillary tubes. Recently, Khan et al. [2] reviewed the literature on these studies. However, no experimental or theoretical study related to two-phase pressure drop and design of the capillary tube for MR J-T cryocoolers is reported in the literature. The mixture of refrigerants such as nitrogen, methane, ethane, propane and iso-butane expands in the capillary tube of MR J-T cryocooler where the temperatures are in cryogenic range. So far, the existing empirical correlations to predict pressure drop across the capillary tube have not been assessed for such refrigerant mixtures and for the operating conditions of the MR J-T cryocooler.

In view of the above, the present study assesses the existing empirical correlations for prediction of overall pressure drop across the capillary tube for refrigerant mixtures used in MR J-T cryocooler. Experiments are carried out to measure the overall pressure drop across the capillary tube used in the MR J-T cryocooler. The distributions of pressures along the length of the coiled capillary tube is obtained using various well known existing correlations given by Friedel [3], Gronnerud [4], Muller-Steinhagen-Heck [5], and the Homogeneous model. The predicted overall pressure drop across the capillary tube is compared with experimentally obtained results for different compositions.

TWO-PHASE PRESSURE DROP CORRELATIONS

Two-phase pressure drop, ΔP_{total}, is the sum of static pressure drop (elevation head), the momentum pressure drop (acceleration head) and the frictional pressure drop. Pressure loss at the inlet and the exit of the capillary tube due to sudden contraction and sudden enlargement of the area is neglected.

$$\Delta P_{total} = \Delta P_{static} + \Delta P_{mom} + \Delta P_{frict} \tag{1}$$

The static pressure drop, ΔP_{static}, is negligible for horizontal tubes. The pressure drop due to momentum, ΔP_{mom} , is estimated using Eqn. 2 [6].

$$\Delta P_{mom} = G^2 \left\{ \left[\frac{(1-x)^2}{\rho_L (1-\varepsilon)} + \frac{x^2}{\rho_G \varepsilon} \right]_{out} - \left[\frac{(1-x)^2}{\rho_L (1-\varepsilon)} + \frac{x^2}{\rho_G \varepsilon} \right]_{in} \right\} \tag{2}$$

where G is total mass flux of both gas and liquid phase, x is mass flow quality, and ρ_G and ρ_L are the respective densities of gas and liquid phases. The void fraction, ε, is obtained from the drift flux model of Steiner [7] for horizontal tubes as given in Eqn. 3**.**

$$\varepsilon = \frac{x}{\rho_G} \left[\left(1 + 0.12(1-x)\right) \left(\frac{x}{\rho_G} + \frac{1-x}{\rho_L} \right) + \frac{1.18(1-x)\left[g\sigma(\rho_L - \rho_G) \right]^{0.25}}{G^2 \rho_L^{0.5}} \right]^{-1} \tag{3}$$

The correlations commonly used to estimate frictional pressure drop are based on either a homogeneous flow or separated flow models. Homogeneous flow models treat two-phase flow as a single phase fluid flow with averaged properties of the liquid and the vapor phase. It assumes no difference in the velocities of the two phases of the fluid, i.e. slip ratio between the two phases is unity. This approach is typically valid for flow regimes such as mist flow or bubbly flow where one phase is evenly dispersed into the other [6]. Whalley [8] argued that homogeneous model is suitable to calculate frictional pressure drop for the mass velocities greater than 2000 kg/m^{2}s. Triplett *et al.* [9] found that the predictions of the homogeneous model are close to the experimental data during slug flow in circular and semi-triangular cross-section channels with hydraulic diameters ranging from 1.1 to 1.5 mm compared with other flow models. The two-phase frictional pressure drop, ΔP_{frict} , for homogeneous model is given in Eqn. 4.

$$\Delta P_{frict} = 4 f_{tp} \frac{L}{d_i} \frac{G^2}{2 \rho_{tp}} \tag{4}$$

where L and d_i is length and internal diameter of the tube respectively. Two phase friction factor f_{tp}, and two-phase Reynolds number Re_{tp} , are given in Eq. 5 and 6 respectively.

$$f_{tp} = 0.079 \, Re_{tp}^{-0.25} \tag{5}$$

$$Re_{tp} = \frac{G d_i}{\mu_{tp}} \tag{6}$$

where μ_{tp} is two-phase mixture viscosity, which is evaluated using Cicchitti et al. (1960) [10] correlation and is given in Eqn. 7.

$$\mu_{tp} = x \mu_G + (1 - x) \mu_L \tag{7}$$

where μ_G and μ_L is gas phase and liquid phase viscosity respectively. The effective density of two-phases in homogeneous model is given in Eqn. 8.

$$\frac{1}{\rho_{tp}} = \frac{x}{\rho_G} + \frac{(1 - x)}{\rho_L} \tag{8}$$

The separated flow model, on the other hand, considers the flow of the two phases distinctly along with the interaction between them. In the present study, three widely used empirical correlations given by Friedel [3], Gronnerud [4], and Muller-Steinhagen-Heck [5] are used to calculate the frictional pressure drop. These correlations are based on separated flow model which utilizes a two-phase multiplier. The Muller-Steinhagen and Heck correlation [5] is an empirical two-phase extrapolation between all liquid flow and all vapor flow. The details of these correlations are available in the literature [3-5].

EXPERIMENTAL SET-UP

The experimental set-up used in the present work is shown in Figure 1. The details of the experimental set-up are described elsewhere [11]. It mainly consists of a compressor, an after-cooler, oil filters, a heat exchanger, an expansion device, and an evaporator. A capillary tube is used as an expansion device. The length and the inside diameter of the capillary tube are 2.0 m and 1.52 mm respectively. Each side of the capillary tube is welded to copper tubing**.** Figure 2 shows the photograph of the coiled capillary tube. The coiled capillary tube is kept in horizontal position.

A rotameter is installed in the suction line near the compressor to measure the volume flow rate of the refrigerant. The mass flow rate of the refrigerant mixture is calculated using the density of the mixture in circulation at the inlet conditions. The composition of the mixture in circulation is measured at steady state operation of the cryocooler. For every experiment, the composition of the mixture in circulation is obtained using a gas chromatograph (Make: PerkinElmer-Clarus500GC). The gas chromatograph instrument is calibrated with components of known purity and mixtures of known composition. All the thermodynamic properties of the mixture are calculated using aspenONE [12] considering Peng-Robinson equation of state [13]. Refrigerant mixture quality is evaluated on the basis of pressure during isenthalpic expansion.

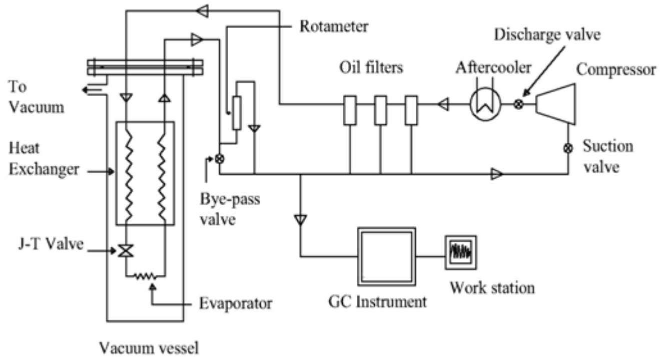

FIGURE 1. Experimental set-up

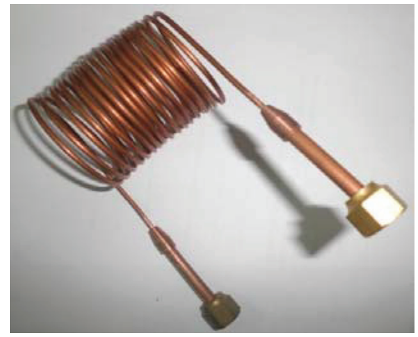

FIGURE 2. Photograph of the coiled capillary tube

Measurement of Pressure Drop

The measurement of pressure drop in the capillary tube for MR J–T cryocooler is crucial since the temperatures at inlet and exit to the capillary tube are in the cryogenic range. The capillary tube, the heat exchanger and the evaporator are placed in a vacuum vessel to minimize the heat losses. In the present work, pressures of the mixed refrigerant at the inlet and the outlet to the capillary tube are measured using gauges which are kept at room temperatures outside the vacuum vessel. For this purpose, two separate capillary tubes are used. The size and length of these capillary tubes are selected such that there is a minimum thermal loss in the cooling capacity of the cryocooler. Pressure gauges with an accuracy of 0.1% full scale (Make: WIKA, Germany) are used for the measurement. The test conducted on each mixture is repeated at least three times to ensure repeatability of the results obtained.

RESULTS AND DISCUSSION

Experiments are carried out for three different mixtures to measure the pressure drop across the capillary tube. Table 1 shows the compositions of nitrogen-hydrocarbon mixtures used in the cryocooler. In MR J-T cryocooler, the performance of the recuperative heat exchanger depends on the mixture composition and the operating conditions of the cryocooler. As a result of this, conditions at the inlet to the capillary tube are different for different mixtures. Table 2 gives experimental conditions such as mass velocity, pressure, temperature and quality at the inlet and the outlet to the capillary tube for all the mixtures. The table suggests that the inlet conditions to the capillary tube are two-phase as the quality is more than zero for all the mixtures.

TABLE 1. Mixture composition

Mixture	Mixture composition, $N_2/CH_4/C_2H_6/C_3H_8/iC_4H_{10}$
Mix#1	5.5/42.5/36.0/5.0/11.0
Mix#2	36.0/15.0/13.0/19.0/17.0
Mix#3	24.0/26.0/15.5/16.0/18.5

TABLE 2. Experimental conditions

Mixture	Mass flux (G), kg/m^2s	Capillary inlet condition			Capillary outlet condition		
		Pressure, bar	Temperature, K	Quality, (x)	Pressure, bar	Temperature, K	Quality, (x)
Mix#1	2095.2	11.41	149.29	0.065	6.11	143.98	0.14
Mix#2	2040.1	13.95	110.53	0.226	5.61	98.62	0.29
Mix#3	2780.0	14.97	118.00	0.13	4.7	106.00	0.22

Figure 3 shows the isenthalpic expansion process for the MRJ-T cryocooler on P-h diagram for Mix#1. Isotherms ranging from 100 K to 303 K are also shown on the P-h chart obtained from the software aspenONE [12]. The processes 1-2 and 3-4 are the heat transfer processes in the heat exchanger, while the process 2-3 is the isenthalpic expansion in the capillary tube. It is evident from the figure that point 2 and 3 lie in the two-phase region. The state of the mixture leaving the expansion device, i.e. point 3, is obtained by intersection of isenthalpic line with the measured pressure of the cold fluid at the outlet to the capillary tube. The temperature of the mixture after expansion corresponding to the point 3, noted from the P-h chart, is found to be around 142 K while actual measured value of the temperature after expansion is noted to be 143.98 K. This confirms the validity of the use of property data obtained from the aspenONE [12] against the experimental results. The mixture at state 4 enters the compressor. The compression process and the heat exchange in the after-cooler are not shown on the P-h chart.

It can also be noted from Fig. 3 that the saturated liquid and vapor lines are close to vertical. Therefore, increase in the quality of the mixture during expansion is not significant. This can be verified from Table 2. The quality at the exit to the capillary tube is lowest (x = 0.14) for Mix#1, while it is maximum (x = 0.29) for Mix#2. The changes in the quality of the mixture affect the two-phase pressure drop in the capillary tube. At the same time, it may be noted that as changes in density of the mixture during expansion are significant, momentum pressure drop has to be considered in addition to frictional pressure drop.

The two-phase pressure drop also depends on viscosity of the mixture which affects the friction factor and Reynolds number of the flow. Therefore, in the present work, the variation in ratio of viscosity, defined as the ratio of the liquid phase to the vapor phase viscosity, (μ_L/μ_G), is studied. Figure 4 shows the variation in viscosity ratio with respect to pressure for the three mixtures. The viscosities of the liquid and the gas phases are obtained at constant enthalpy corresponding to the enthalpy of the mixture at the inlet to the capillary. It is observed that the viscosity ratio increases with decrease in pressure as the mixture gets expanded from higher pressure to lower pressure. The increase in viscosity ratio, μ_L/μ_G, for Mix#1 is lowest, while it is maximum for Mix#2. The values of viscosity ratio at a given pressure are also highest for Mix#2 and lowest for Mix#1.

It is noted from Table 2 that Mix#1 expands at relatively higher temperature i.e. 149 K, while Mix#2 and Mix#3 undergo expansion in the capillary tube at relatively lower temperature. The change in temperature during the expansion for Mix#1 is 5 K, whereas it is 12 K for Mix#2 and Mix#3. It is also observed from Table 2 that the mass velocities for all the mixtures are higher than 2000 kg/m^{2}s. Mix#1 and Mix#2 have nearly same mass velocities, while for Mix#3, it is relatively higher.

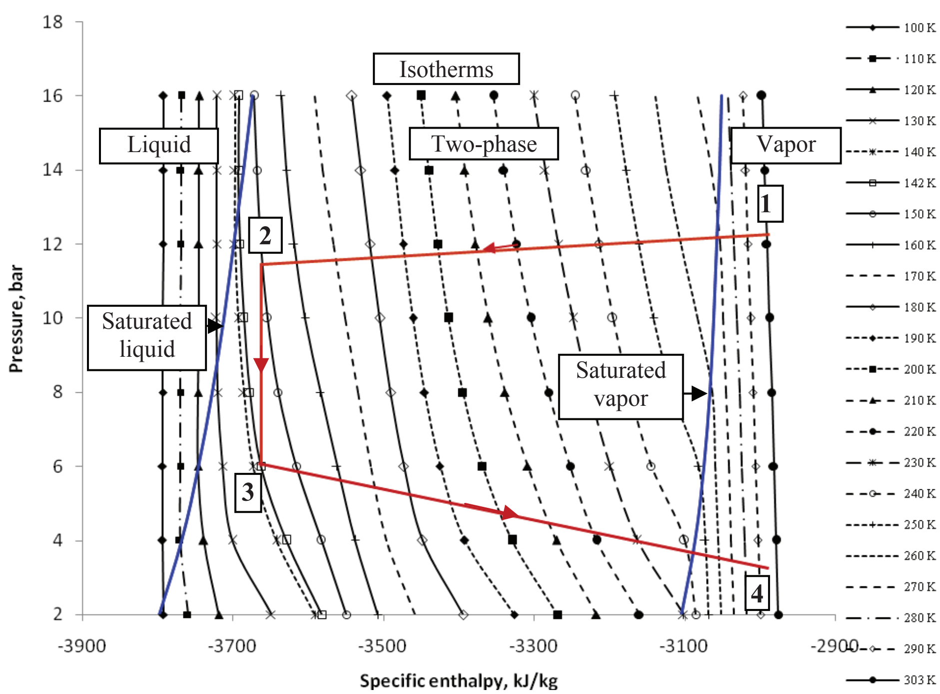

FIGURE 3. P-h diagram for Mix#1

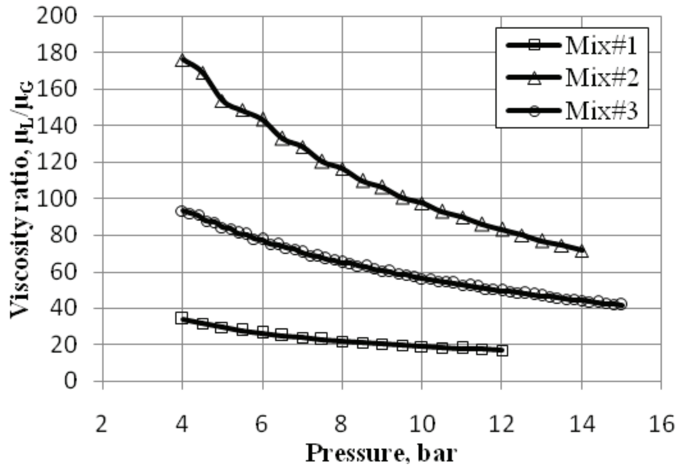

FIGURE 4. Variation in viscosity ratio with pressure during expansion

In the present work, the actual frictional pressure drop is obtained by subtracting the calculated momentum pressure drop from the measured total pressure drop as given in Eqn. 1. The momentum pressure drop is calculated using Eqn. 2. The pressure drop due to gravity is neglected since the orientation of the capillary tube is horizontal in the cryocooler. The ratios of the momentum pressure drop to the frictional pressure drop of the experimental data are 5.76%, 3% and 4.47% for Mix#1, Mix#2 and Mix#3 respectively.

Figures 5-7 show the comparison of pressure drop predicted by the homogeneous model and separated flow models for Mix#1, Mix#2 and Mix#3, respectively. The separated flow model uses Friedel, Gronnerud, Muller-Steinhagen-Heck correlations as indicated in the figures. The experimental values refer to pressures at the inlet and the exit only, where the measurements are carried out. It can be noted from these figures that the homogeneous model predicts the pressure at the exit of the capillary tube closest to the experimental value for all the mixtures.

The two-phase frictional pressure drop calculated using various correlations are compared with the experimentally measured pressure drop as shown in Table 3. It may be noted that the measured pressure drop for Mix#3 is maximum followed by the ones for Mix#2 and Mix#1. The pressure drop for Mix#3 is maximum due to higher mass velocity. The measured pressure drop for Mix#2 is greater than that for Mix#1 even though the mass velocities are nearly same for both the mixtures. The reason for this is that the viscosity ratio for Mix#2 is higher than that for Mix#1, as shown in Fig. 4. The lowest pressure drop for Mix#1 is observed due to lower viscosity ratio,

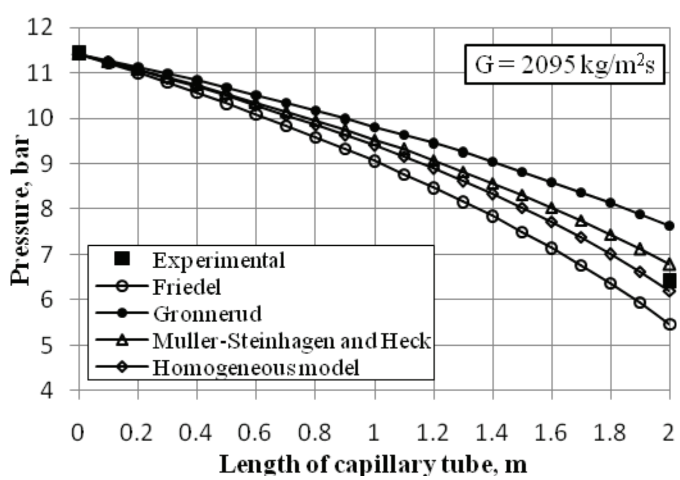

FIGURE 5. Predicted pressure profile for Mix#1

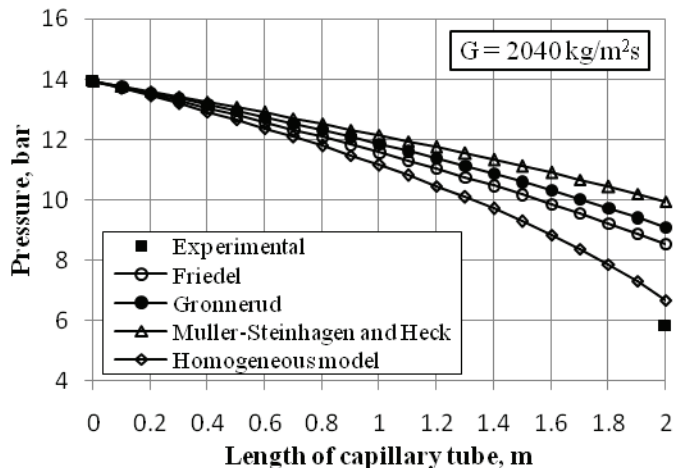

FIGURE 6. Predicted pressure profile for Mix#2

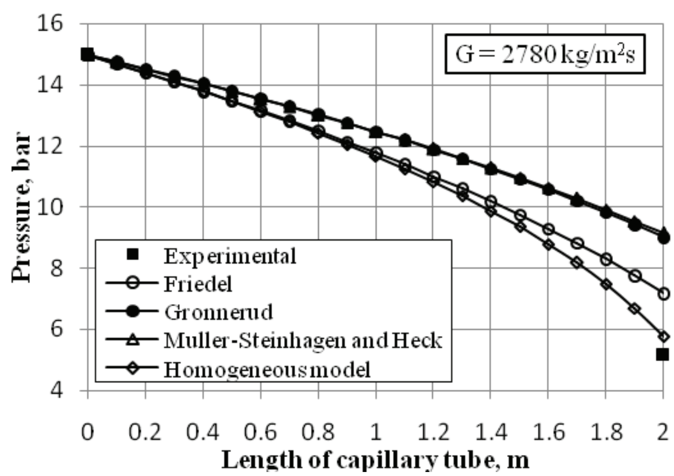

FIGURE 7. Predicted pressure profile for Mix#3

mass velocity and relatively low inlet pressure to the capillary tube. Additionally, for Mix#1, the quality of the mixture at the outlet to the capillary tube is lowest as compared to other two mixtures, which is shown in Table 2. Also, a lower temperature at the inlet to the capillary tube results in a higher pressure drop. This can be explained by the effect of the physical properties on the pressure drop. The density and viscosity of the liquid phase increase while the density and viscosity of the vapor phase decrease as the temperature decreases. This results in a lower liquid velocity and a higher vapor velocity with decrease in temperature for a constant mass flux condition. It is found that the two-phase pressure drop in the capillary tube strongly depends on the mass velocity, properties of the mixture and conditions at the inlet to the capillary tube.

The predicted values of two-phase pressure drop using three different correlations based on separated flow model and using homogeneous model are compared against the experimental data using average absolute deviation (AAD). The AAD is obtained by calculating the normalized percentage difference between the experimental pressure drop and the predicted values. The % AAD obtained for various correlations are presented in Table 4. The % AAD of the pressure drop predicted using homogeneous model is lowest for all the mixtures as compared to those predicted using other correlations. It is 3.79 %, 10.25 % and 6.3 % for Mix#1, Mix#2 and Mix#3 respectively. Friedel correlation found to be better for predicting frictional pressure drop next to Gronnerud and Muller-Steainhagen-Heck correlation. Maximum % AAD for Friedel correlation is 33.33%. It is thus clear from the Table 4 that the homogeneous model can be used to predict the two-phase frictional pressure drop in the capillary tube for MR J-T cryocooler.

TABLE 3. Comparison of predicted frictional pressure drop with experimental values

Mixture	Capillary Inlet press, bar	Pressure drop, (ΔP), bar				
		Expt.	Friedel [3]	Gronnerud [4]	MSH [5]	Homogeneous [10]
Mix#1	11.41	5.01	5.93	3.77	4.63	5.21
Mix#2	13.95	8.1	5.41	4.86	4.0	7.27
Mix#3	14.97	9.83	7.8	5.97	5.84	9.21

TABLE 4. Average absolute deviation of the results

Mixture	Average absolute deviation, (AAD), %			
	Friedel [3]	Gronnerud [4]	MSH [5]	Homogeneous [10]
Mix#1	18.36	24.67	7.58	3.79
Mix#2	33.33	40.0	50.66	10.25
Mix#3	20.65	39.27	40.59	6.3

CONCLUSIONS

It is found that the pressure drop in the capillary tube for MR J-T cryocooler depends on the inlet conditions to the capillary tube such as pressure, temperature and quality of the mixture as well as properties of the mixture.

It can be concluded that the homogeneous flow model is appropriate to calculate the pressure drop of two-phase flow in capillary tubes for MR J-T cryocooler. The results of the work are useful to estimate the pressure drop of the multi-component non-azeotropic mixtures in the range of cryogenic temperatures.

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