PREDICTION OF TWO-PHASE PRESSURE DROP IN HEAT EXCHANGER FOR MIXED REFRIGERANT JOULE-THOMSON CRYOCOOLER

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MOTIVATION

- Recuperative heat exchanger governs the overall performance of mixed refrigerant Joule–Thomson (MR J–T) cryocooler.
- Need of accurate predictive tools for pressure drop to design the heat exchanger for the efficient operation of the cryocooler
- Limited experimental data is available, related to pressure drop of mixed refrigerants of nitrogen-hydrocarbons at cryogenic temperatures.
- There is no generalized correlation for two-phase frictional pressure drop in the literature, which is applicable to a wide range of working fluids, mass velocities, pressures and channel diameters.

OBJECTIVE

- To evaluate the existing empirical correlations for prediction of two-phase frictional pressure drop in the recuperative heat exchanger for MR J-T cryocooler.

TWO-PHASE FRICTIONAL PRESSURE DROP CORRELATIONS

Total pressure drop $\Delta P_{total} = \Delta P_{static} + \Delta P_{mom} + \Delta P_{frict}$

Homogeneous Flow Model (HFM)

Two-phase frictional pressure drop, ΔP_{frict}

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

where f_{tp} is a two-phase friction factor, G is mass velocity, L is length, d_h is hydraulic diameter, and ρ_{tp} is two-phase density.

$$f_{tp} = \frac{16}{\mathrm{Re}_{tp}} \quad : \mathrm{Re}_{tp} \le 2000$$

$$f_{tp} = 0.079\,\mathrm{Re}_{tp}^{-0.25} \quad : \mathrm{Re}_{tp} > 2000$$

Two-phase Reynolds number, Re_{tp}

$$\mathrm{Re}_{tp} = \frac{G d_h}{\mu_{tp}}$$

Two-phase mixture density, ρ_{tp}

$$\frac{1}{\rho_{tp}} = \frac{x}{\rho_g} + \frac{(1-x)}{\rho_f}$$

Two-phase mixture viscosity models in the HFM

Author(s)	Correlation
McAdams et al. [11]	$\frac{1}{\mu_{tp}} = \frac{x}{\mu_g} + \frac{(1-x)}{\mu_f}$
Cicchitti et al. [12]	$\mu_{tp} = x\mu_g + (1-x)\mu_f$
Dukler et al. [13]	$\mu_{tp} = \rho_{tp}\left[\frac{x\mu_g}{\rho_g} + \frac{(1-x)\mu_f}{\rho_f}\right]$

Separated Flow Model (SFM)

Two-phase frictional multiplier, ϕ_f

$$\phi_f^2 = \left(\frac{dp}{dz}\right)_{tp} \Big/ \left(\frac{dp}{dz}\right)_f$$

Lockhart-Martinelli correlation [14]

$$X^2 = \frac{\left(dp/dz\right)_f}{\left(dp/dz\right)_g}$$

where coefficient C varies between 5 to 20 depending on flow regime

$$\phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2}$$

Frictional pressure drop correlations based on SFM

Macro-scale models

Muller-Steinhagen and Heck correlation (1986)

$$\left(\frac{dp}{dz}\right)_F = F(1-x)^{1/3} + \left(\frac{dp}{dz}\right)_{go} x^3$$

$$F = \left(\frac{dp}{dz}\right)_{fo} + 2\left[\left(\frac{dp}{dz}\right)_{go} - \left(\frac{dp}{dz}\right)_{fo}\right] x$$

$$\left(\frac{dp}{dz}\right)_{fo} = f_{fo}\frac{2G^2}{d_h \rho_f} \qquad \left(\frac{dp}{dz}\right)_{go} = f_{go}\frac{2G^2}{d_h \rho_g}$$

Sami and Duong correlation (1992)

$$\phi_{fo}^2 = 8.41(1-x)^{1.764} X_{tt}^{-1.24}$$

Martinelli parameter for turbulent-turbulent flow, X_{tt}

$$X_{tt} = \left(\frac{\mu_f}{\mu_g}\right)^{0.110} \left(\frac{1-x}{x}\right)^{0.882} \left(\frac{\rho_g}{\rho_f}\right)^{0.5}$$

Micro-scale models

Zhang et al. correlation (2010)

$$C = 21\left[1 - \exp(-0.358/La)\right]$$

Laplace number, La

$$La = \frac{\left(\sigma / g(\rho_f - \rho_g)\right)^{0.5}}{d_h}$$

Kim and Mudawar correlation (2012)

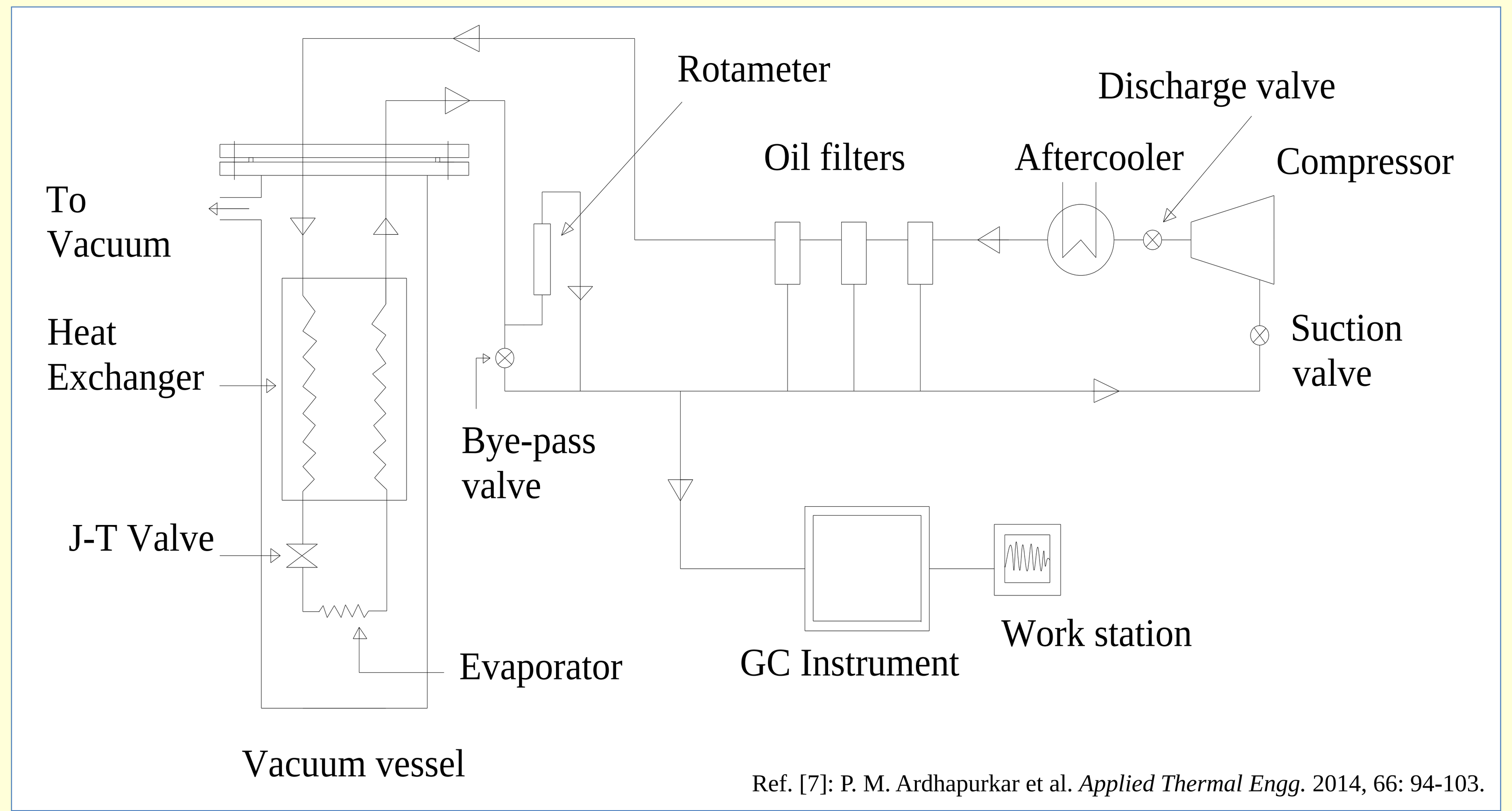
$$\phi_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \qquad X^2 = \left(dp/dz\right)_f \Big/ \left(dp/dz\right)_g$$

$$C_{vt} = 0.0015\,\mathrm{Re}_{fo}^{0.59}\, Su_{go}^{0.19} \left(\rho_f/\rho_g\right)^{0.36}$$

Suratman number, Su_{go}

$$Su_{go} = \frac{\rho_g \sigma d_h}{\mu_g^2}$$

EXPERIMENTAL SET-UP



Ref. [7]: P. M. Ardhapurkar et al. *Applied Thermal Engg.* 2014, 66: 94-103.

Helically coiled tube-in-tube heat exchanger

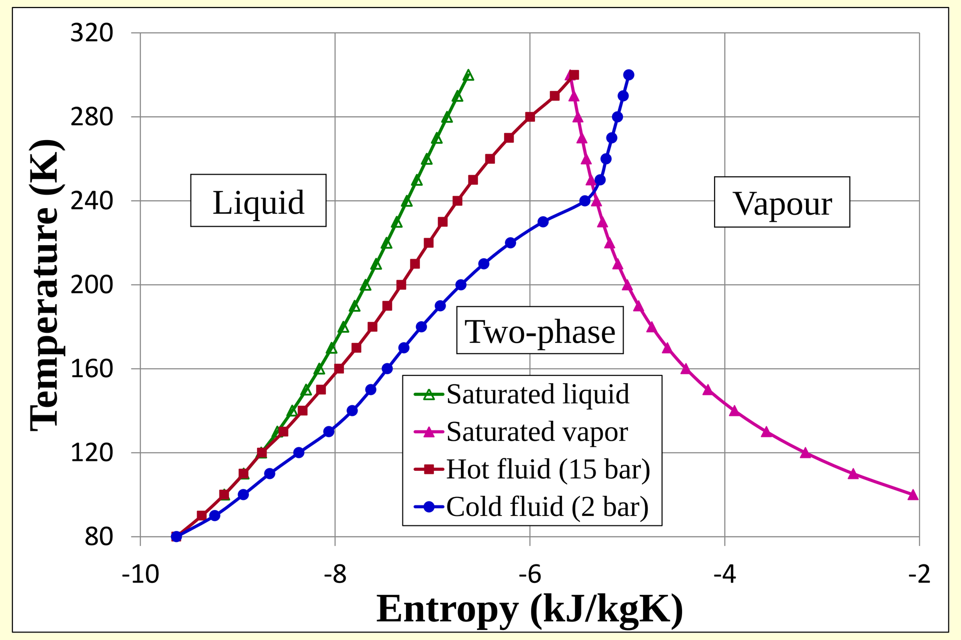
Specifications of Heat Exchanger [7]

Parameter		Value
Inner tube	ID (mm)	4.83
	OD (mm)	6.35
Outer tube	ID (mm)	7.89
	OD (mm)	9.52
Length of heat exchanger (m)		15
Coil diameter (mm)		200

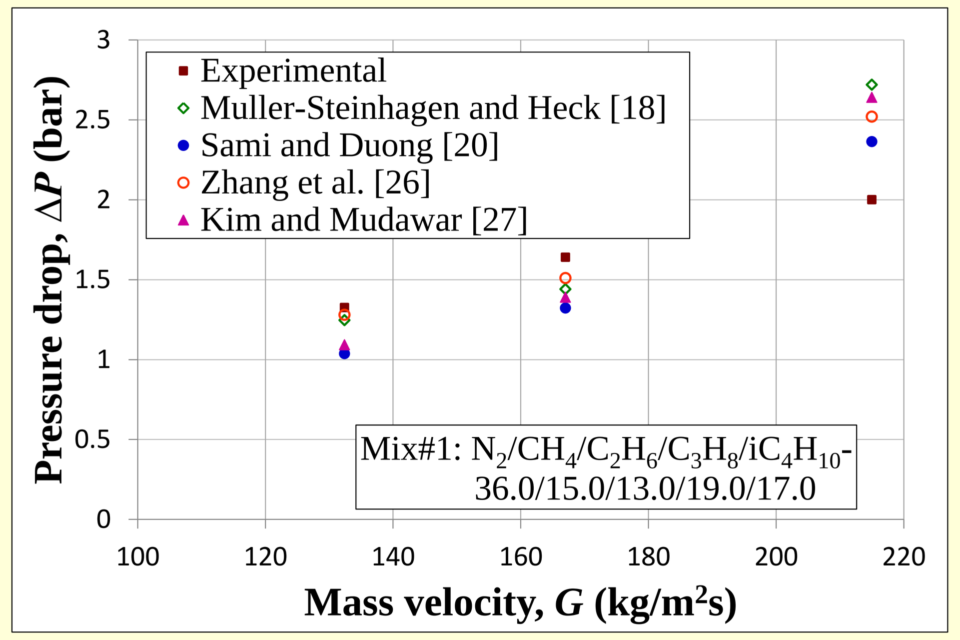
RESULTS AND DISCUSSION

Experimental conditions

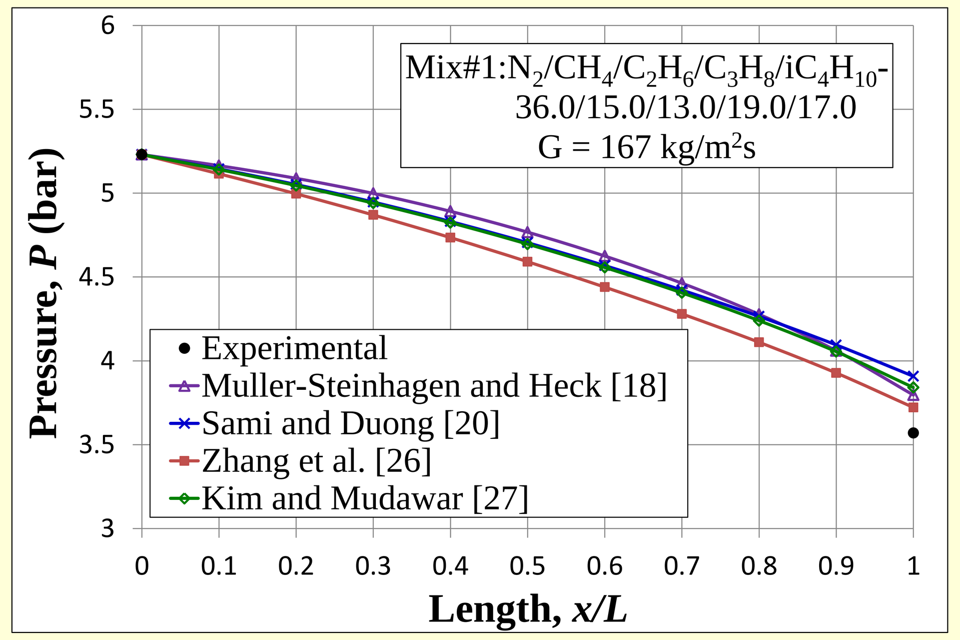
Mixture	Composition	Mass flux, G (kg/m²s)	Temperature, (K) Inlet	Temperature, (K) Outlet	Pressure, (bar) Inlet	Pressure, (bar) Outlet
Mix#1	36.0/15.0/13.0/19.0/17.0	215	100.2	293.5	5.61	2.61
		167	108.8	293.8	5.23	2.41
		132	112.7	294.7	4.25	2.01
Mix#2	15.5/31.0/16.5/21.0/16.0	151	119.1	297.6	5.32	2.31
		146	125.4	300.1	4.94	2.31



Temperature-entropy diagram for Mix#1



Comparison between predicted and experimental two-phase frictional pressure drop



Predicted pressure profiles of the cold fluid in the MR J–T heat exchanger

Assessment of existing two-phase pressure drop correlations

Correlation ↓		Average Absolute Deviation (AAD), (%) Mix#1			Mix#2	
Mass velocity, G (kg/m²s) ⟶		215	167	132	146	151
Homogeneous model (HFM)	McAdams et al. [11]	21.4	44.4	40.2	41.7	48.6
	Cicchitti et al. [12]	126.8	23.1	35.8	10.4	13.2
	Dukler et al.[13]	21.5	44.3	42.0	47.2	52.4
SFM: Macro-scale model	Lockhart-Martinelli [14]	143.2	102.0	116.8	42.2	15.2
	Friedel [16]	62.4	7.9	15.9	8.4	11.1
	Gronnerud [17]	125.4	59.8	82.6	46.8	28.1
	Muller-Steinhagen and Heck [18]	31.6	13.6	6.0	7.2	24.8
	Chisholm [19]	143.6	160.4	143.7	108.6	69.5
	Sami and Duong [20]	14.2	20.4	21.7	34.1	40.5
SFM: Micro-scale model	Mishima and Hibiki [22]	103.5	37.5	46.4	1.8	14.8
	Yu et al. [23]	76.0	82.3	80.8	82.9	84.0
	Lee and Mudawar [24]	135.9	38.7	26.3	11.9	4.3
	Li and Wu [25]	134.7	45.4	55.2	12.1	15.0
	Zhang et al. [26]	22.0	9.2	3.2	27.6	27.6
	Kim and Mudawar [27]	27.5	16.3	17.6	20.8	29.5

CONCLUSIONS

- ✓ Experiments are carried out to measure two-phase pressure drop in the evaporating stream of MR J-T heat exchanger for two different mixture compositions.
- ✓ Extensive evaluation of the existing two-phase frictional pressure drop correlations is presented.
- ✓ The Zhang et al. [26] and Kim and Mudawar [27] correlation which are developed for micro-channels based on SFM give the best predictions of the pressure drop data within 30 % error limit among 15 different correlations assessed.