Flow Boiling Pressure Drop for R410A and RL32H in Multi-channel Tube

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ABSTRACT

Experimental data for pure R410A, R410A and lubricant RL32H mixture pressure drop in flow boiling for micro-channels is presented and analyzed in this paper. Inlet vapor quality of test section was changing at 0.2, 0.4, 0.6 to 0.8 with 0.2 quality increase along the tube, mass fraction of lubricant was changing from 0%, 0.43%, 2.8% to 4.2%, and mass velocity of the pure and mixture varied from 119 to 556 kg s-1 m-2. The experiments have been conducted for average saturation temperature at 5ºC to 20 ºC. Literatures on two phase flow boiling pressure drop for both pure refrigerant and refrigerant with lubricant are carefully reviewed, popular published correlations are used in this study to evaluate test data. New two phase flow boiling pressure drop correlations for pure refrigerant and mixtures inside multi micro-channel tube are proposed.

1. INTRODUCTION

The implementation of microchannel heat exchangers has increased in automotive and building air conditioning systems during the past few decades, due to smaller volume, compact structure, smaller heat resistance, and smaller refrigerant charge inventory. More and more research has been focusing on heat transfer and pressure drop inside mini and micro-channels especially in two phase flow. With the reducing of channel size, inertia, viscous and surface tension forces play more important role than gravitational in micro-channels.

Due to the flow distribution among the paralleled channels, the investigation on single min/micro-channel tube could be very different with multi-channels. The flow inside single channel is more stable and uniform compare to that of multi-channels. Issues like flow instabilities, back flow, possibly early or delayed critical heat flux, were often found in multichannel study only (Bergles and Kandlikar, 2005; B. Agostini et al., 2008). Therefore, the study in multi micro-channels is necessary to understand the thermal dynamics of flow boiling with interactions among parallel channels. There are many researchers worked in flow boiling pressure drop testing in multiple parallel channels for pure refrigerant (Webb R.L., 1996; Monroe C.A., 2003, Newell T.A., et al. 2003; Qu W., Mudawa I., 2003; Lee J., Mudawa I., 2005; Cavallini A. et al. 2005). There are also many flow boiling pressure drop correlations have been developed (Tran et al., 2000; Li and Wu, 2010). These studies covered different type of fluids as well as micro-channel size. Most recently, Kim and Mudawar (2013) did a critical review on most of the test data and correlations, and then proposed a universal pressure drop model for pure refrigerant in mini/micro channels.

In most of current vapor compression processes, the presence of oil is intrinsic and unavoidable since the oil is required to lubricate the moving part of compressor. The amount of lubricant oil circulating in the system can vary from 0.1% to 8.0% by weight in the refrigerant flow. In the open literature, a large amount of papers are involved in the discussion of impaction of oil in refrigerant system for macro tubes (B. Shen and A. Groll, 2003; Pierre et al. 1964; Choi et al. 2001; Hu et al. 2008; Schlager et al. 1990; Eckels et al. 1994). Although the present of the oil might result in improve heat transfer at a certain oil concentration and deteriorate heat transfer at most of conditions, however, the pressure drop results showed an increased when oil becomes part of the flow fluid. The study for heat transfer and pressure drop with refrigerant and oil mixture flow inside mini and micro channels are very few.

R410A is widely used in air conditioning systems together with RL32H as lubricant in both Chiller and Unitary units. There are very few studies focused on heat transfer and pressure drop of R410A and lubricant flow inside multiple micro-channels. A test facility was set up to evaluate heat transfer and pressure drop for both flow boiling and condensation inside mini and micro-channels. In this study, the flow boiling tests were conduct for pure R410A and R410A with RL32H in multiple rectangular micro-channels. With comparing with existing correlations, new correlations are recommended for both pure refrigerant and refrigerant lubricant mixture to match the test data.

2. EXPERIMENTAL APPARATUS

2.1 Flow loop

The test facility used in this study is shown in Figure 1, which can conduct both flow boiling and condensing test at the same time and no need for any rearrangement of the cycle. The cycle is driven by a refrigerant gear pump, subcooled liquid refrigerant flows through the pre-heater to heat up to a desired quality, and then flows through evaporator with certain quality rise, then enters post-heater to become superheated gas before entering pre-condenser. The refrigerant is pre-cooled to a desired quality at entering of condenser with constant temperature cooling water/glycol bath, reducing around 0.2 quality, refrigerant is then cooled down to subcooled liquid flow by post-condenser before a Coriolis mass flow meter and the pump. The pre-heater, evaporator and post-heater are electronic heaters, and the pre-condenser, condenser and post-condensers are constant temperature water/glycol bath.

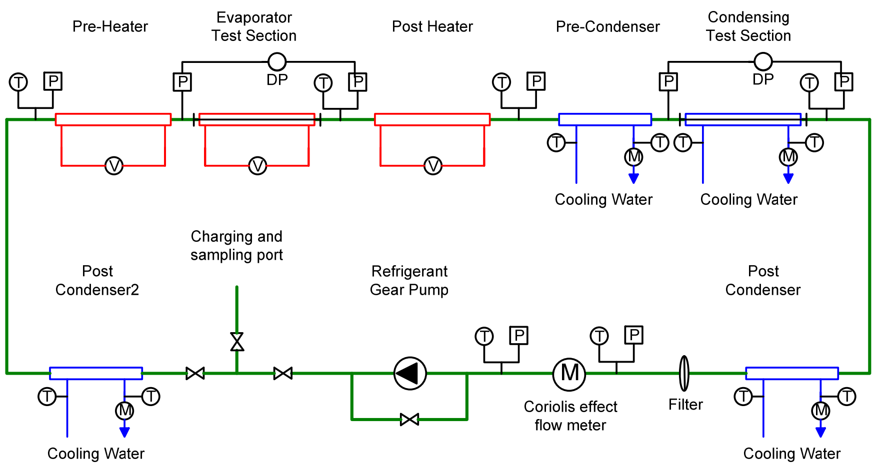


Fig. 1 Schematic of test loop

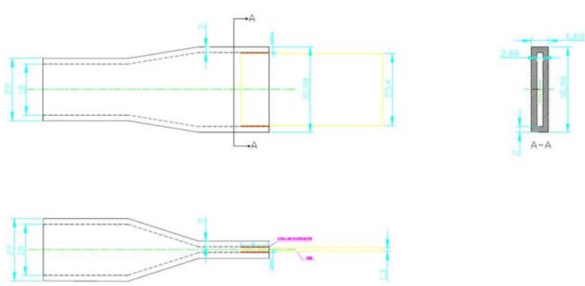


Fig. 2 Transient tube

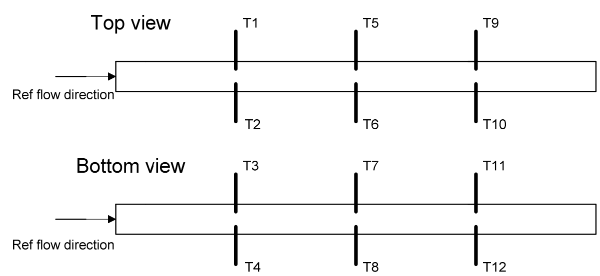


Fig. 3 RTD location on flat tube

2.2 Test section

Fig. 2 shows the detail of the transient connection which is well shaped from round tube to micro-channel tubes. The purpose of the design is to improve the universal flow of the two-phase and control the flow pattern. The pressure drop of the transient connection is also conducted separately in the data reduction process.

There are twelve platinum resistance thermometers attached on the surface of the each test tube as showing in Fig. 3, with six of them on the top of the tube and six on the bottom side. They are used to identify surface temperature for heat transfer coefficient reduction, and also help to observe the distribution of refrigerant flow inside multi-channels. The accuracy of the platinum resistance thermometers is better than 0.1 °C.

Fig. 4 shows the cross section detail geometry information of the 26 ports micro-channel with around 0.6 mm as channel width and 0.7mm as channel height. The length of the test section is 0.43 m.

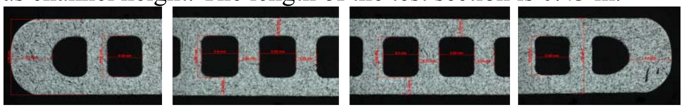


Fig. 4 Enlarged image of the multiple channel rectangular tube

2.3 Operating conditions and measurement accuracy

Heat loss from the overall boiling section including pre-heater, evaporator and post-heater is estimated less than 3%, as well as condensing section. The accuracy of the flow rate was better than 0.5%. The saturated evaporating temperature is within 5°C to 20°C, the mass flux of the fluid is within 100 to 600 kg m-2 s-1, the entering quality of the evaporating test section changes from 0.2, 0.4, 0.6 to 0.8 with a changing quality of 0.2 across test section.
Oil concentrations is measured in the mixture used sample analysis refer to ASHRAE 41.4. The sample is taken between pump and pre-heater which the liquid flow through. The pipe from pre-heater till evaporator is straight pipe and a turbulent was installed ahead of evaporator to pre-mix the refrigerant and lubricant mixture to improve the flow at the entrance of the microchannel tube. The oil mass concentration in the mixture was controlled to be 0.43%, 2.84% and 4.20% in this study.
The pressure sensors are installed in the system before and after each heaters and condensers with error less than ±0.5%, five platinum resistance thermometers type of temperature sensors are inserted into the tubes at: entering pre-heater, leaving evaporator, leaving pre-heater (entering pre-condenser), entering mass flow meter and entering gear pump, the error is smaller than ±0.1°C. The other temperature sensors are attached to the surface of the pipes with error smaller than ±0.5°C. There is also a pressure difference transducer installed across evaporator and condenser section with error smaller than ±206 Pa.

3. RESULTS

3.1 R410A results

Fig. 5 shows the total pressure drop changes with different mass flux and entering quality. The pressure drop increased with increasing of entering quality as well as mass flux. The total pressure drop includes pressure drop of transient section. At higher entering quality, with mass flux increasing, the total pressure drop increases dramatically.

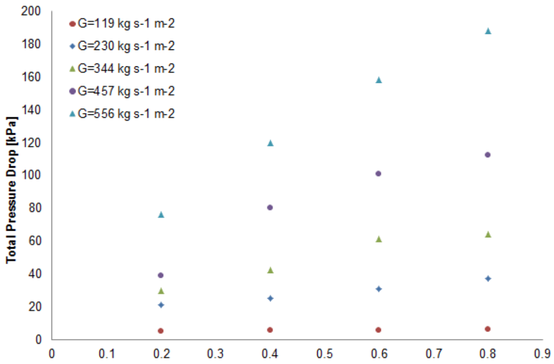
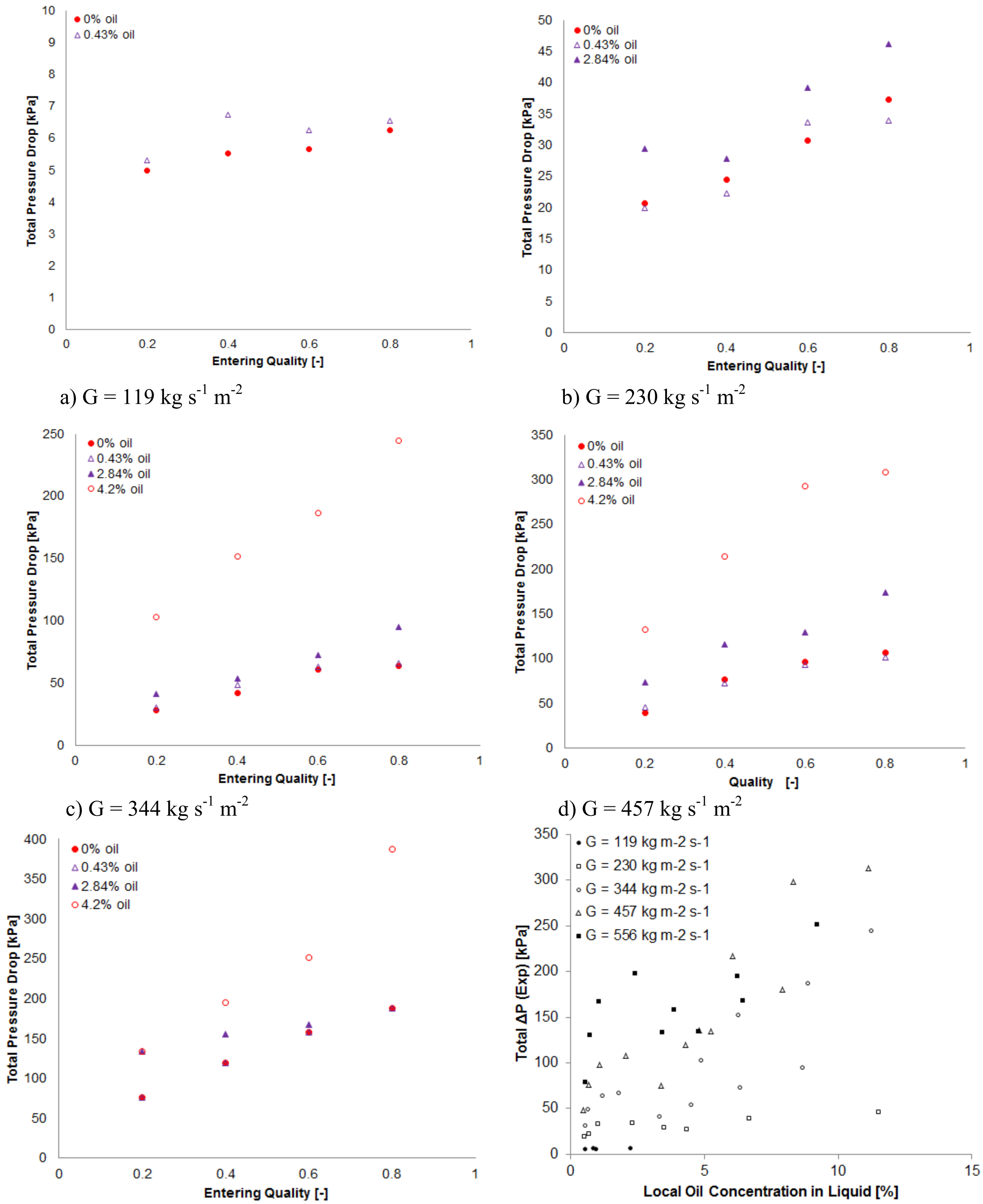


Fig. 5 Pure R410A total pressure drop changing with quality and mass flux

3.2 R410A and RL32H results

Fig. 6 shows the total pressure drop of R410A and RL32H mixture changes with different mass flux and entering quality. The pressure drop increased with increasing of entering quality as well as increasing mass flux. Generally, the present of oil increased total pressure drop, the higher the concentration of the oil in the mixture, the bigger impactions happened on the total pressure drop. The oil mass concentration shown on Fig. 6 (a) to (e) is based on total refrigerant mass, including both refrigerant liquid and vapor. At oil concentration around 0.5%, the total pressure drop is increased slightly across different mass flux. In order to improve the system performance, keep as lower lubricant in refrigerant circulation would be a good idea.
Fig. 6 (f) shows another view of total pressure drops based on local oil concentration, which is calculated in Eq. (1):

$$\omega_{lo} = \frac{\omega_{no}}{\omega_{no}+(1.0-x)(1-\omega_{no})} \quad (1)$$



a) G = 119 kg s^{-1} m^{-2}

b) G = 230 kg s^{-1} m^{-2}

c) G = 344 kg s^{-1} m^{-2}

d) G = 457 kg s^{-1} m^{-2}

e) G = 556 kg s^{-1} m^{-2}

f) Pressure drop based on local oil centration

Fig. 6 R410A with RL32H total pressure drop changing with quality and mass flux

4. DATA REDUCTION AND DISCUSSION

4.1 Pressure drop components

The total pressure drop can be obtained from Eq. (2):

$$\Delta P_T = \Delta P_e + \Delta p_{restr} + \Delta P_{ch} + \Delta P_c \quad (2)$$

The contraction pressure loss at the inlet from copper tube to alumina tube and along the alumina connection is determined from the relations by Eq. (3) from Collier and Thome:

$$\Delta P_c = \frac{G^2 v_f}{2}\left[\left(\frac{1}{C_c} - 1\right)^2 + (1 - \sigma_c^2)\right](1 + \frac{v_{fg} x_{in}}{v_f}) \quad (3)$$

And refer to the same book, the expansion recovery along the alumina connection and outlet from alumina tube to copper tube is determined as Eq. (4):

$$\Delta P_e = G^2 v_f \sigma_c (\sigma_c - 1)(1 + \frac{v_{fg} x_{out}}{v_f}) \quad (4)$$

Here, the contraction coefficient C_c is obtained from a relation by Geiger in Eq. (5).

$$C_c = 1 - \frac{1-\sigma_c}{2.08(1-\sigma_c)+0.5371} \quad (5)$$

The channel mass flux is calculated based on Eq. (6) assuming uniformity of the flow among the channels.

$$G_{ch} = \frac{M}{N W_{ch} H_{ch}} \quad (6)$$

Total two phase pressure drop contains frictional, gravity and acceleration, as shown in Eq. (7)

$$\Delta P_{tp} = \Delta P_{tp,f} + \Delta P_{tp,a} \quad (7)$$

Separated flow model was used and Martinelli void fraction correlation to evaluate acceleration pressure drop:

$$\Delta P_{tp,a} = G^2 v_f \left[\frac{x_{e,out}^2}{\alpha_{out}}\left(\frac{v_g}{v_f}\right) + \frac{(1-x_{out})^2}{1-\alpha_{out}} - 1\right] \quad (8)$$

Here, void fraction model is:

$$\alpha_{out} = \frac{1}{1+\frac{1-x_{out}}{x_{out}}\left(\frac{v_f}{v_g}\right)^{2/3}} \quad (9)$$

The transient pressure drop was reduced by testing for water flow through test section. Using single phase pressure drop correlation in R.K Shah and A.L. London (1978) to calculate pressure drop in channel and then get transient pressure drop Δp_{restr} represented as:

$$\Delta p_{restr} = \frac{G^2}{2\rho_l}\zeta \quad (10)$$

The loss coefficient was determined experimentally by empirical fit based on the computed values of the inlet and outlet losses ratio and it given in Fig 7. The test data does not include the pressure drop in the restriction and the inlet section of micro-channel. For two phase tests, the inlet restriction is used to flash the incoming fluid, which will effectively increase the inlet restriction pressure drop. However, it was not possible to evaluate this parameter in current test facility, but compared to the two phase pressure drop in the microchannel, it is small. The contribution of each pressure drop components changing with mass flux is shown on Fig.8.

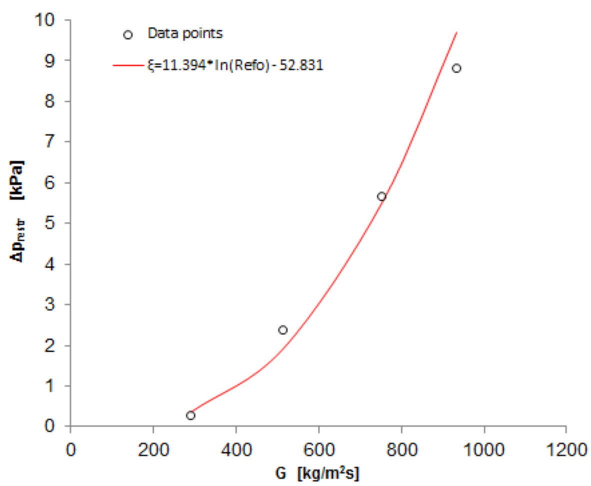


Fig. 7 Curve-fit for inlet loss coefficient pressure drop using test data

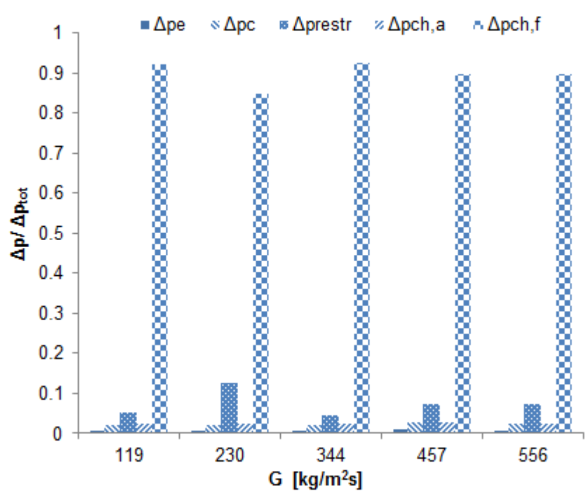


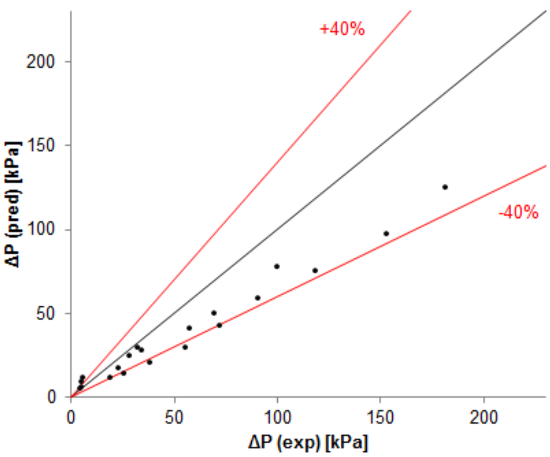
Fig. 8 Contributions of individual components of pressure drop to total pressure drop

4.2 Two phase pressure drop models

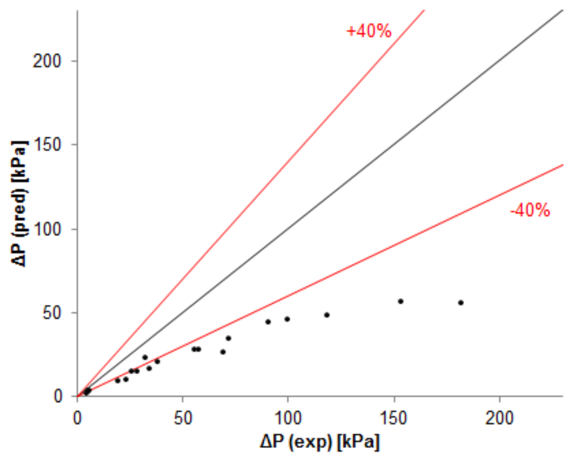
There are two typical types of frictional pressure drop model in two phase flow: the homogeneous model and the separated model. In the homogeneous model, both liquid and vapor phases move at the same velocity (slip ratio = 1). Consequently, it is also called the zero slip model. The homogeneous model considers two phase flow as a single phase flow having average fluid properties depending on mass quality. While in the separated model, two phase flow is considered to be divided into liquid and vapor streams, Hence, it is referred to as the slip flow model. To compare the validity of various existing correlations against the completed database of two phase pressure drop in micro/mini–channels, calculations are made for micro/mini-channels based on the entire channel. Various models are used, which include the homogeneous model with two phase viscosity equation from Beattie and Whalley (1982); and separated models developed by Friedel (1979), Tran et al (2000), Li and Wu (2011) and Kim and Mudawar (2013). However, Friedel (1979) is designed for macro-channels, Tran et al (2000) correlation is based on 2.40-2.93 mm tube with refrigerant flow inside. Li and Wu (2011) is designed based on 0.148-3.25 mm tube and refrigerants flow. Kim and Mudawar (2013) developed a universal model for different fluid and diameter of micro-channel tubes. These 3 flow boiling pressure drop models are used in the study to compare with test data.

4.3 R410A validation results and correlations

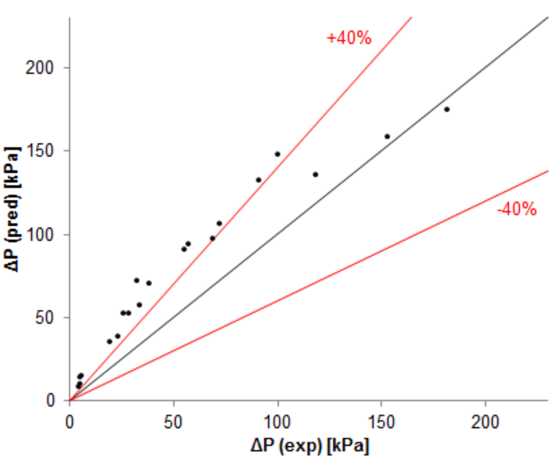
The comparison between test channel frictional pressure drop and three models is show in Fig. 9.



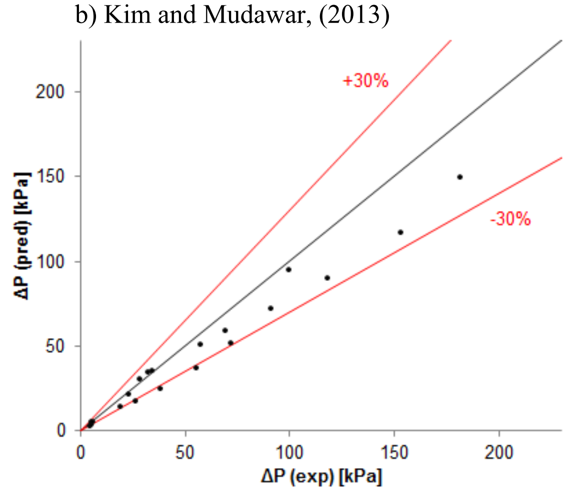
a) Li and Wu, (2010)



b) Kim and Mudawar, (2013)



c) Tran et al., (2000)



d) Proposed correlation

Fig. 9 Comparison of experimental data points with predictions of separate model recommended for micro-channels

Li and Wu (2010) correlation predicts pressure drop well within ±40%, Kim and Mudawar (2013) under predicts the pressure drop and Tran model over predicts the pressure drop. Based on original formulation of Li and Wu, a new correlation was proposed to match the test data better as following to address lower mass flux and also upgrade on the Bd and F2 curve-fit results.

For Bd $\geq$ 0.1 and $BdRe_f^{0.5} \leq 200$, $\mathrm{Bd} = \frac{g(\rho_f-\rho_g)D_h^2}{\sigma}$

For $Re_{fo} \leq 600$

$$\left(\frac{dP}{dz}\right)_F = \left(\frac{dP}{dz}\right)_f \emptyset_f^2, \emptyset_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2}, X^2 = \frac{(dP/dz)_f}{(dP/dz)_g}, C = 5.60Bd^{0.28} \quad (11)$$

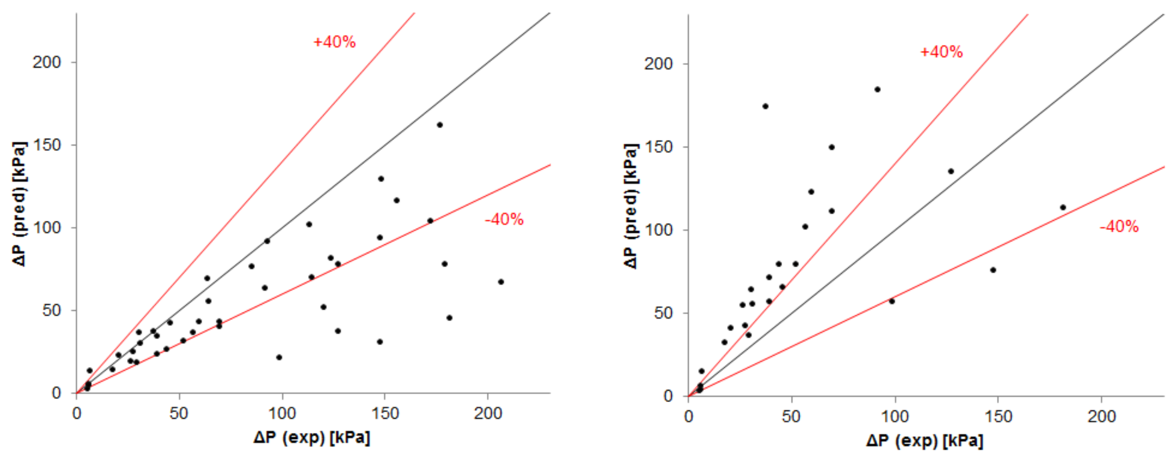
For $Re_{fo} > 600$

$$\left(\frac{dP}{dz}\right)_F = \left(\frac{dP}{dz}\right)_{fo} \emptyset_{fo}^2, \emptyset_{fo}^2 = (1-x)^2 + 2.87x^2P_R^{-1} + 2.1Bd^{0.19}\left(\frac{\rho_f-\rho_g}{\rho_H}\right)^{0.81} \quad (12)$$

The new correlation predicts pressure drop within ±30%, the comparison of test data and proposed correlation is shown in Fig. 9(d).

4.4 R410A and RL32H mixture correlation

There are typical two types of pressure drop enhancement factor for refrigerant and lubricant mixture flow inside tubes: consider the lubricant property impact in the mixture or not. The former pressure drop correlation models (Pierre et al. 1964; Choi et al. 2001; Hu et al. 2008) considered the impaction of mixture property, such as density, viscosity, etc. However, it needs support from mixture properties data, and the errors in the properties would impact the overall accuracy of these models. The later enhancement factor models (Schlager et al. 1990; Eckels et al. 1994) considered impaction of oil concentration and mass flux without property factors, which might loss the capability to extend to general model, but still worth to try without accurate enough mixture properties at very low oil concentration for a specific pair of refrigerant and lubricant mixture. On the other side, most of these factors are developed for macro tubes. The comparison between test data and enhanced factor without consider mixture properties are show in Fig. 10.



a) Shlager et al., (1990) b) Eckels et al., (1994)

Fig. 10 Channel frictional pressure drop on local oil concentration

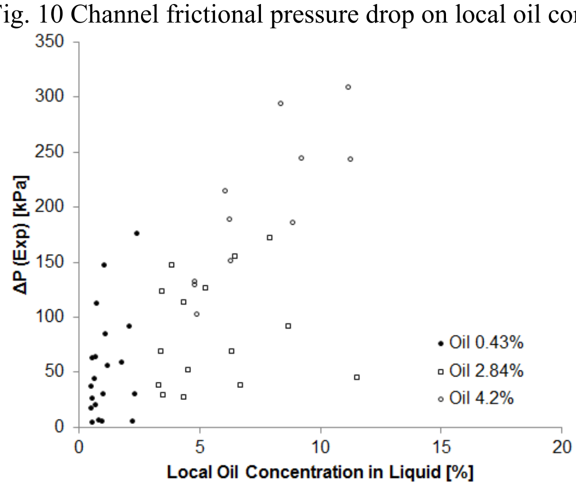


Fig. 11 Channel frictional pressure drop on local oil concentration

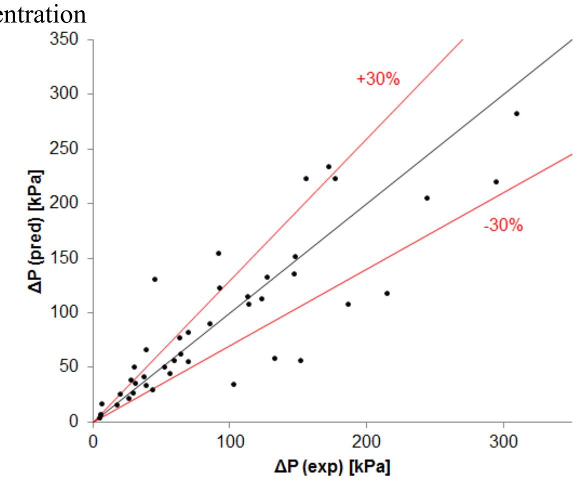


Fig. 12 Comparison with new proposed refrigerant and lubricant correlation

Currently, there is very few studies focus on refrigerant and lubricant mixtures pressure drop models in micro-channel tubes. Based on test data and previous pure refrigerant pressure drop correlation in mini/micro channel tubes, a new pressure drop enhancement factor was developed using the local oil concentration without considering mixture properties.

$$\mathrm{PF} = 1.2344e^{0.1048\omega_{lo}} \quad (13)$$

$$\left(\frac{dP}{dz}\right)_{Fo} = \left(\frac{dP}{dz}\right)_{F} \times PF \quad (14)$$

The channel frictional pressure drop with local oil concentration is shown in Fig. 11. New proposed refrigerant and lubricant correlation comparison is shown in Fig. 12, most of the predict error are within ±30%.

5. CONCLUSION

This study sets up a test facility on refrigerant heat transfer and pressure drop in mini/micro-channels for both flow boiling and condensation. Focusing on flow boiling pressure drop, both pure refrigerant and mixture with lubricant are tested. The total pressure drop measured between the inlet and outlet plenums was compared to predictions of previous models based on separated flow models. Key findings from this study are as follows:

- The total pressure drop increases with increasing oil concentration in the mixture due to the viscosity of the liquid part increased.
- A complete model was constructed for total pressure drop between the inlet and outlet plenums. To calculate the two phase frictional pressure drop portion of the total pressure drop, different separated models were tested.
- New pressure drop correlation is proposed for pure refrigerant with predict error within ±30% compare to test data.
- New pressure drop enhancement factor is proposed for refrigerant and lubricant mixture based on local oil concentration with error within ±30% compare to test data. With the improvement of mixture property at lower oil concentration, enhancement factor could consider mixture properties in pressure drop correlations later.

NOMENCLATURE

Bd	Bond number	(-)
Bo	Boiling number	(-)
C	parameter in Lockhart-Martinelli correlation	(-)
D	tube diameter	(m)
D_h	hydraulic diameter	(m)
f	Fanning friction factor	(-)
g	gravitational acceleration	(m/s^2)
G	mass velocity	(kg/m^2-s)
h_{fg}	latent heat of vaporization	(J/kg)
N_{conf}	confinement number	(-)
P	pressure	(Pa)
P_{crit}	pressure	(Pa)
P_R	reduced pressure	(-)
ΔP	Pressure drop	(Pa)
q''_H	heat flux based on heated perimeter of channel	(-)
Re	Reynolds number	(-)
Re_f	superficial liquid Reynolds number, $Re_f = G(1-x)\,D_h/\mu_f$	(-)
Re_{fo}	liquid only Reynolds number, $Re_{fo} = G\,D_h/\mu_f$	(-)
Re_g	superficial vapor Reynolds number, $Re_g = Gx\,D_h/\mu_g$	(-)
v	specific volume	(m^3/kg)
v_{fg}	specific volume difference between saturated vapor and saturated liquid	(m^3/kg)
Su	Suratman number	(-)
We	Weber number	(-)

X	Lockhart-Martinelli parameter	(-)
x	thermodynamic equilibrium quality	(-)

Greek symbols

α	void fraction	(-)
σ	surface tension	(N/m)
ρ	density	(kg/m^3)
μ	dynamic viscosity	(Pa s)
ζ	pressure loss coefficient	(-)
$\emptyset$	two phase multiplier	(-)
ω	mass concentration	(-)

Subscript

a	acceleration
c	contraction
ch	channel
e	entrance
F	frictional
f	fluid, frictional
g	vapor
in	entering
k	liquid (f) or vapor (g)
lo	local
no	norminal
out	leaving condition
restr	restrictor
T	total
tp	two phase
tt	turbulent liquid-turbulent vapor
tv	turbulent liquid-laminar vapor
vt	laminar liquid-turbulent vapor
vv	laminar liquid- laminar vapor

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