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EVALUATION OF FLOW BOILING PRESSURE DROP MODELS FOR HFE-7200 IN MULTI-MICROCHANNELS

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ABSTRACT

Flow boiling pressure drop in a microchannel heat sink was studied using HFE-7200. The multi-microchannel heat sink had 44 channels, of width 0.36 mm, height 0.7 mm, hydraulic diameter 0.475 mm and a 0.1 mm thick wall between the channels. The test section inlet pressure was between 1 – 2 bar, while the mass flux and wall heat flux was varied from 200-400 kg/m^{2}s and 24.8 -234.3 kW/m^2 respectively. The effect of inlet subcooling, ranging from 5 to 20 K, was also assessed. The two-phase pressure drop in the channels increased with heat flux and mass flux and decreased with increasing system pressure. It also decreased at the higher subcooled inlet conditions. The results were compared with past pressure drop correlations.

1 INTRODUCTION

Reliable design tools to predict flow boiling behaviour in microchannel heat exchangers are required for system integration and optimisation for industry to adopt microchannel two-phase technology for cooling high heat fluxes. Accurate prediction methods for microchannel flow boiling pressure drop are important for pump sizing and estimation of power consumption. The ability to capture experimental trends corresponding to changes in operating conditions are also crucial in establishing a safe range of operation where coolant delivery and the effectiveness of the thermal management system are not compromised. However, universally accepted pressure drop correlations are yet to be established and this fact contributes to the slow uptake of microchannel two-phase technology in industry [1]. Two-phase pressure drop in microchannels typically increase with heat flux, vapour quality and mass velocity, while changes in fluid properties, typically result in lower two-phase pressure drop at higher pressures. As reviewed in [2], studies have reported contradictory effects with regards to inlet subcooling. The study found that the two-phase pressure drop of HFE-7200 in a multi-microchannel heat sink at a given operating condition decreased with increasing degree of subcooling between 5 to 20 K. The magnitude of two-phase pressure drop may also be closely related to the dominant flow patterns in the channels and prevailing flow instabilities, especially in parallel microchannel configurations.

1.1 TWO-PHASE PRESSURE DROP MODELS

Flow boiling pressure drop in microchannels is made up of the frictional and acceleration pressure loss component [3] as follows:

$$\Delta P_{fric} = \frac{2\, f_{tp}\, L_{sat}\, G^2\, v_f}{D_h}\left[1 + \left(\frac{x_e}{2}\right)\left(\frac{v_f - v_g}{v_f}\right)\right] \tag{1}$$

$$\Delta P_{acc} = G^2\, v_f\left[\frac{{x_e}^2}{\alpha_v}\,\frac{\rho_f}{\rho_g} + \frac{(1 - x_e)^2}{(1 - \alpha_v)} - 1\right] \tag{2}$$

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Two main approaches, i.e. the homogenous model and the separated flow model, are generally employed to predict two-phase pressure drop, where the main differences are related to the determination of the friction factor and void fraction definitions adopted [3]. The homogenous flow model assumes that the liquid and vapour phases are sufficiently mixed and travel at the same velocity through a channel, i.e. slip ratio = 1. The model is generally applicable for the bubbly flow regime, where the velocities of the dispersed vapour phase and liquid phase do not differ greatly. Two-phase frictional pressure drop is expressed in terms of a two-phase flow friction factor, which is evaluated based on the two-phase Reynolds number and is dependent on the mixture viscosity. The model is relatively sensitive to the two-phase viscosity employed [4], [5]. The separated flow model assumes that the liquid and vapour phase travel with different velocities, i.e. slip ratio ≠ 1, through the channel and considers the flow properties in each phase individually. This model is more applicable to flow boiling in microchannels where, in addition to a first nucleate boiling part, slug flow, churn flow and annular flow prevail. Correlations based on the Lockhart-Martinelli [3] macroscale model express two-phase frictional pressure drop as a function of the single-phase liquid pressure drop and a two-phase multiplier, φ_{tp}^2, defined as the ratio of the pressure gradient of the liquid and gas phase. This can be expressed as a function of the Martinelli parameter, X (see [3] for the definition of X):

$$\varphi_{tp}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{3}$$

Most existing correlations are based on the work of Lockhart-Martinelli and the modification of Chisholm's empirical correlation of the C parameter, which ranges from 5 – 20 based on liquid and gas flow conditions, in Eq. (3) [3]. Mishima and Hibiki [6] included the effect of hydraulic diameter in the expression of C. Qu and Mudawar [7] and Lee and Garimella [8] further correlated C to mass flux. Dimensionless parameters are typically also used to correlate C. Kim and Mudawar [5] proposed C as a function of the liquid-only Weber number, liquid-only Reynolds number, Boiling number and the gas-only Suratman number to account for the different flow structures based on a consolidated database of nine working fluids. Li and Hibiki [4] proposed a correlation for C specifically for multichannel configurations, citing higher frictional losses due to non-uniform flow distribution, based on vapour quality and a two-phase viscosity number, which considers the effect of fluid density, surface tension and mixture viscosity.

In the present work, microscale pressure drop correlations based on the separated flow model are assessed against flow boiling results obtained in a multi-microchannel heat sink (i.e. 44 channels of width 0.36 mm, height 0.7 mm, hydraulic diameter 0.475 mm and a 0.1 mm wall between the channels) using HFE-7200. Experimental data were obtained at inlet pressures of 1 – 2 bar, mass fluxes of 200 – 400 kg/m^{2}s, subcooling degree of 5 – 20 K for wall and base heat fluxes of 24.8 – 234.3 kW/m^2 and 93.7 – 896.3 kW/m^2 respectively. The experimental setup and data reduction method are detailed in [2].

2 RESULTS AND DISCUSSION

Two-phase pressure drop in the channels increased with heat flux and exit vapour quality. Increasing the channel mass flux increased two-phase pressure drop while increasing the system pressure decreased flow boiling pressure drop at a nominal wall heat flux condition. The effect of inlet subcooling on two-phase pressure loss was less significant between ΔT_{sub} = 5 K and 10 K. Increasing the degree of subcooling to ΔT_{sub} = 20 K resulted in a notable reduction in flow boiling pressure drop.

The observed trends of pressure drop may be explained as follows. An increase in wall heat flux increases bubble nucleation activity and consequently the channel void fraction. The increased void fraction accelerates the flow, increasing the momentum pressure loss in the channels. The acceleration of the flow gives a steeper velocity gradient at the channel wall, also resulting in an increase in the frictional pressure drop. Increasing mass flux also results in an acceleration of the flow, as both the frictional and acceleration pressure drop components are related to the term G^2, see Eq. (1) and (2).

Increasing the operating pressure typically increases the vapour density and hence a notable reduction in the liquid-to-vapour density ratio present in the acceleration pressure drop component. The larger vapour density induces a deceleration in the flow, yielding a smaller velocity gradient at the channel wall as well as lower frictional losses in the flow. On the other hand, the reduction of two-phase pressure drop with increasing degree of subcooling, particularly at $\Delta T_{sub} = 20$ K, was attributed to delayed flow regime transitions from bubbly to slug, churn and annular flow in the heat sink.

The prediction accuracy of each correlation was assessed using the mean average deviation, MAE, and percentage of data points captured within a ±30 % error band, θ_{30}:

$$\mathrm{MAE} = \frac{1}{n}\left|\frac{\Delta P_{tp,exp} - \Delta P_{tp,pred}}{\Delta P_{tp,exp}}\right| \times 100\ \% \tag{4}$$

where n is the number of data points and ΔP_{tp} is two-phase pressure drop. In cases where the void fraction, was not specified by the authors, it was calculated based on the Lockhart-Martinelli void fraction model [3]. The results are summarised in Table 1.

Table 1: Flow boiling pressure drop prediction results.

Correlation	MAE [%]	Θ_{30} [%]
Macroscale		
Homogenous model ($f_{tp} = 0.003$ [7])	43.23	42.31
Lockhart-Martinelli [9]	113.38	17.31
Chisholm [10]	28.38	73.08
Microscale		
Mishima and Hibiki [6]	22.72	78.85
Qu and Mudawar [7]	25.21	78.85
Lee and Garimella [8]	46.97	30.77
Kim and Mudawar [5]	48.14	34.62
Li and Hibiki [4]	54.01	32.69

2.1 MACROSCALE CORRELATIONS

The homogeneous flow model [3] and the separated flow model of Lockhart-Martinelli [9] both tended to overpredict the pressure drop of HFE-7200 in the current study. Interestingly, the homogeneous model, which is generally believed to be appropriate for dispersed flows, performed better compared to the model proposed by Lockhart-Martinelli. The homogeneous model predicted 42.3 % of the experimental data within the ±30 % error band, with a MAE of ±43.2 %, while the Lockhart-Martinelli predicted merely 17.3 % of the data with a much higher MAE of ±113.4 %, see Figure 1. Microscale studies in [1], [5], [8], [11] also found that the Lockhart-Martinelli [9] correlation overpredicted their pressure drop data.

The two-phase friction factor employed in the homogeneous model is $f_{tp} = 0.003$, based on the recommendation of Qu and Mudawar [7]. The homogeneous model was found to be highly dependent on f_{tp}. Evaluating f_{tp} based on the mixture viscosity model of Cicchitti et al. [12] and McAdams et al. [13] result in a much higher MAE of ±127.1 % and ±66.6 % respectively compared to when $f_{tp} = 0.003$ was employed. The sensitivity of the prediction accuracy of the homogeneous model on the two-phase viscosity model was also concluded by Kim and Mudawar [5].

The B-coefficient method of Chisholm [10] performed the best amongst the macroscale correlations assessed in this study, predicting over 70 % of the pressure drop data with a MAE of only ±28.4 %. In fact, the Chisholm [10] model outperformed most microscale correlations despite being proposed for macroscale flows. This could be because the two-phase multiplier is based on exit vapour quality and mass flux rather than the empirically proposed C constant for macroscale two-phase flows in the Lockhart-Martinelli correlation.

2.2 MICROSCALE CORRELATIONS

The correlation of Mishima and Hibiki [6] and Qu and Mudawar [7] captured almost 80 % of the data within a ±30 % error band with a MAE of only ±22.7 % and ±25.2 % respectively, see Figure 2(a) and (b). Relatively high prediction accuracies were also obtained using the Mishima and Hibiki [6] correlation in [1], [7], [8]. The frictional multiplier in both correlations was calculated based on the laminar-liquid and laminar-vapour Martinelli parameter. The Mishima and Hibiki [6] model gives Chisholm's C parameter as a function of the hydraulic diameter, and in this case $C = 3$. Qu and Mudawar [7] considered the additional effect of mass velocity in the channels on C, which ranged from $C = 2.64 – 5.15$ at the highest mass flux condition. The void fraction model of Lockhart-Martinelli [3] was applied in [6] while the Zivi void fraction [3] model was used to estimate acceleration pressure loss in [7]. Nonetheless, the choice of void fraction correlation did not appear to significantly affect the prediction results, i.e. less than ±2 % for the MAE and θ_{30}. This was similarly concluded in [5].

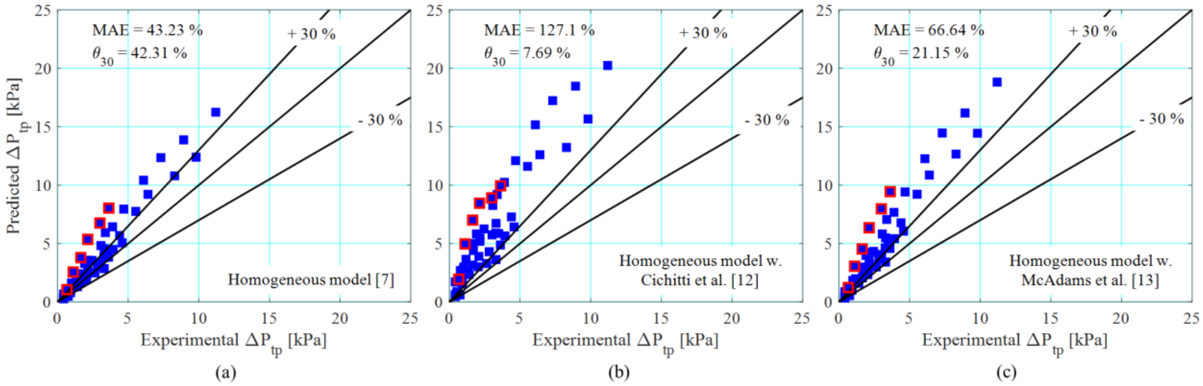
Lee and Garimella [8] generally overestimated two-phase pressure drop, only capturing 30.8 % of the data within the error band, despite the fact that it was developed for flow boiling of water in parallel microchannels. Although the Kim and Mudawar [5] correlation was developed based on a large database involving several working fluids and configurations, the present evaluation found that the model underpredicted pressure drop results at low vapour quality and overpredicted two-phase pressure drop at moderate to high vapour qualities. Li and Hibiki [4], proposed a correlation specifically for multichannel heat sink configurations, which overpredicted most of the data. This may be because the databank included data on micro-pin fins and trapezoidal channels.

Notably, all correlations overpredicted two-phase pressure drop data obtained at the subcooling degree of 20 K. These are indicated by red outlines Figure 1. Pressure drop in the two-phase region ranged from 0.67 kPa to 3.63 kPa at this subcooling condition. The general overprediction of two-phase pressure drop at 20 K could be related to the delayed flow pattern development in the channels [2]. In a related study [2], a tangible relationship between pressure drop and flow patterns was also highlighted.

Studies in [14] and [15] have similarly noted an important dependency of microchannel two-phase pressure drop on flow patterns and subsequently proposed correlations for individual flow regimes. Quibén and Thome [14] found that flow pattern effects, which are particularly important at low mass fluxes and in the high vapour quality region, were not accounted for in most two-phase pressure drop models. The authors segregated their experimental pressure drop data of R134a, R22 and R410A in horizontal tubes according to the Wojtan et al. [16] flow pattern map. Friction factor correlations were proposed for each flow regime based on simplified interfacial flow structures, including bubbly, slug, annular and mist flow regimes. Similarly, Choi and Kim [15] also noted a strong dependency of microchannel two-phase frictional pressure losses on flow patterns. In order to improve the pressure drop prediction of adiabatic two-phase flows in singular rectangular microchannels ($D_h = 0.14 – 0.49$ mm), the authors proposed individual Chisholm's constants for the bubbly, transition and liquid ring flow regime. The above studies show that two-phase pressure drop is intrinsically related to flow regimes, which have a significant effect on the prediction accuracy of two-phase pressure drop.

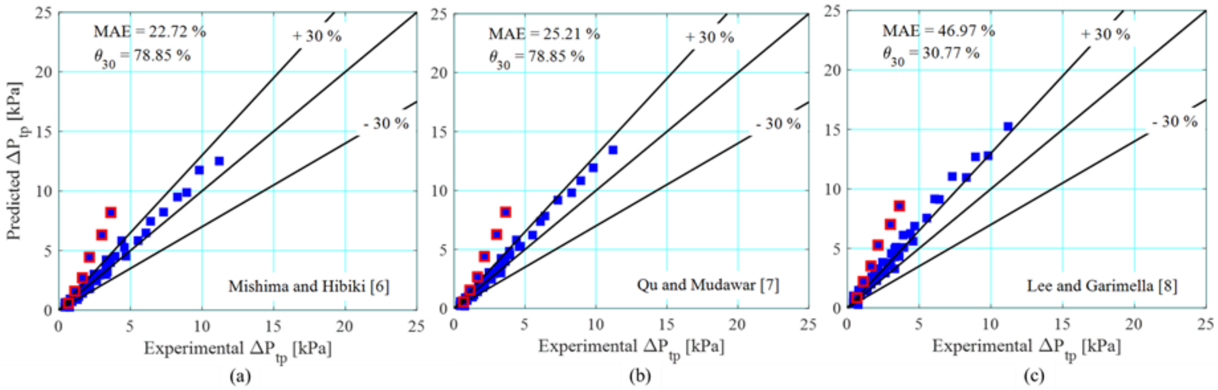
3 CONCLUSIONS

Macroscale and microscale flow boiling pressure drop correlations were assessed using HFE-7200 data obtained in a multi-microchannel heat sink at various operating conditions. The accuracy of the homogenous flow model was highly dependent on two-phase viscosity model employed and assumption of the two-phase friction factor. The classical Lockhart-Martinelli correlation generally overpredicted pressure drop in microchannels, which may be due to the empirically proposed C constant in the two-phase multiplier. The B-coefficient method of Chisholm for macroscale flows accurately predicted over 70 % of the pressure drop data within an error band of ±30 % and outperformed most microscale correlations. The microscale correlation of Mishima and Hibiki, also cited by several other studies for its accurate prediction capability, captured nearly 80 % of the data at 5 – 10 K subcooling with a MAE



(a) (b) (c)

Figure 1:Comparison of flow boiling pressure drop data with the homogeneous model based on (a) f_{tp} = 0.003 [7], (b) the mixture viscosity model of [12] and (c) the mixture viscosity model of [13]. The red squares represent datapoints at 20 K.



(a) (b) (c)

Figure 2: Top three (in order) performing microscale two-phase pressure drop correlations assessed for HFE-7200. The red squares represent datapoints at 20 K.

of 22.7 %. The Qu and Mudawar correlation also performed relatively well. Employment of either the Lockhart-Martinelli or Zivi void fraction model was found to have a negligible effect on the prediction accuracy of microscale models. Pressure drop data obtained at 20 K were generally overpredicted by all correlations. The lower flow boiling pressure drop was attributed to flow regimes in the channel and indicates that the magnitude of two-phase pressure drop is intrinsically related to flow regimes, which could have a significant effect on pressure drop prediction. While exit quality, mass velocity and density ratio appear to be sufficient in capturing the effects of heat flux, mass flux and system pressure, flow pattern-based correlations may be more effective in predicting microscale two-phase pressure drop trends with respect to inlet subcooling. Further work should be conducted to clarify the effect of subcooling on flow patterns, as well as the inter-dependency of dominant flow patterns and flow boiling pressure drop in microchannels.

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NOMENCLATURE

α_v	void fraction, [-]
C	parameter in Eq. (3)
D_h	hydraulic diameter, [m]
f_{tp}	two-phase friction factor, [-]
G	mass flux in the channels, [kg/m^2 s]
L_{sat}	saturated length, [m]
MAE	mean average deviation
n	no. of data points
v_f	specific volume of liquid, [m^3/kg]
v_g	specific volume of gas, [m^3/kg]
X	Martinelli parameter
x_e	exit vapour quality, [-]
ΔT_{sub}	degree of inlet subcooling, [K]
ΔP_{acc}	acceleration pressure drop, [Pa]
ΔP_{fric}	frictional pressure drop, [Pa]
$\Delta P_{tp,exp}$	experimental two-phase pressure drop, [kPa]
$\Delta P_{tp,pred}$	predicted two-phase pressure drop, [kPa]

Greek Letters

Θ_{30}	percentage data points captured within a ±30 % error band, [%]
ρ_f	liquid density, [kg/m^3]
ρ_g	gas density, [kg/m^3]
φ_{tp}	two-phase multiplier, [-]