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Technical Note

An experimental investigation on pressure drop of steam condensing in silicon microchannels

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ABSTRACT

Experiments are carried out to study the two-phase pressure drop for water vapor condensation in four smooth trapezoidal silicon microchannels having hydraulic diameters of 109 μm, 142 μm, 151 μm, and 259 μm, respectively. It is found that two-phase frictional pressure drops in the microchannels are greatly influenced by the hydraulic diameter, mass flux and vapor quality. The two-phase pressure drop data in microchannels are compared with existing correlations for macro- and mini-channels based on the homogenous model and the separated flow model to determine their applicability to condensing flows in microchannels. A modified correlation for the Matinelli–Chisholm constant, taking into consideration of surface tension and diameter effects, is developed in the form of the Lockhart–Martinelli correlation for the pressure drop in steam condensation in microchannels. The resulting condensation pressure drop correlation equation is within ±15% of the experimental data.

1. Introduction

Recently, condensation in microchannels has received a great deal of attention because of its important applications to micro heat exchangers and micro fuel cells [1,2]. Wu and Cheng [3] have observed that mist flow, annular flow, injection flow, and slug/bubble flow exits at different locations of the microchannels depending on the local vapor quality. Most recently, Quan et al. [4] have identified condensation flow regimes in a microchannel based on the vapor quality. Since smaller hydraulic diameter of microchannels will lead to higher pressure drop with corresponding increase in power consumption, it is important to obtain correlation equations for condensation pressure drop in microchannels in order to provide a data base for the design of the micro heat exchangers.

It is known that there are two types of correlations for two-phase pressure drops in macrochannels [5]: the homogeneous flow model and the separated flow model. The homogenous flow model (HFM) is based on the assumptions that the vapor and liquid velocities are equal, and the mixture behaves like a single-phase fluid with mean fluid properties depending on the vapor quality. This model was applied in Refs. [6–9] to correlate experimental data for two-phase pressure drops in macrochannels. These homogenous flow models used the same mixture density given by

$$\frac{1}{\rho_{\mathrm{tp}}} = \frac{x}{\rho_{\mathrm{v}}} + \frac{1-x}{\rho_{\mathrm{l}}} \tag{1}$$

and they differed only in the expressions used for the mixture viscosity (see Table 1).

The separated flow model (SFM) was the other popular model for the correlation of two-phase pressure drops data in macrochannels. This model was first proposed by Lockhart and Martinelli [10], who assumed that the isothermal liquid and gas flowing separately with equal static pressure drops. The two-phase frictional pressure drop was assumed of the form:

$$\left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{tp}} = \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{l}} + C\left[\left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{l}}\left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{v}}\right]^{1/2} + \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{v}} \tag{2}$$

which shows that the two-phase pressure drop is the sum of the liquid-only pressure drop, the phase interaction between the liquid and the gas, and the gas-only pressure drop. Eq. (2) can be rewritten as

$$\phi_{\mathrm{l}}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{3}$$

where ϕ_{l}^2 and X are the two-phase friction multiplier and the Martinelli parameter defined as:

$$\phi_{\mathrm{l}}^2 = \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{tp}} \Big/ \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{l}}, \quad X^2 = \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{l}} \Big/ \left(-\frac{\mathrm{d}p}{\mathrm{d}z}\right)_{\mathrm{v}} \tag{4a, b}$$

The Matinelli–Chisholm constant C, being a measure of the interaction between the phases, has a value of $C = 5$–20 depending on whether it is laminar or turbulent flow in the macrochannel. In the above expressions, the pressure drop for the single-phase flow $(-\mathrm{d}p/\mathrm{d}z)_{\mathrm{l}}$ is obtained from the classical theory [11]. The above

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Table 1
Two-phase mixture viscosity models adopted in the homogeneous flow model

Author(s) [Ref.#]	Two-phase mixture viscosity model	MAE (%)
Ackers [6]	$\mu_{tp} = \frac{\mu_f}{\left[(1-x_e)+x_e\left(\frac{\rho_f}{\rho_g}\right)^{0.5}\right]}$	32.85
McAdams et al. [7]	$\frac{1}{\mu_{tp}} = \frac{x_e}{\mu_g} + \frac{(1-x_e)}{\mu_f}$	96.88
Dukler et al. [8]	$\mu_{tp} = \rho_{tp}[x_e\, \upsilon_g \mu_g + (1-x_e)\upsilon_f \mu_f]$	11.21
Lin et al. [9]	$\mu_{tp} = \frac{\mu_f \mu_g}{[\mu_g + x_e^{1.4}(\mu_f - \mu_g)]}$	163.50

correlation and its modified forms by Friedel [12] and Chisholm [13] have been used to predict the two-phase pressure drop with and without phase changes in macrochannels [5].

Recently, some authors [14–17] have conducted experiments on two-phase flow pressure drops in mini/microchannels. They found that conventional pressure drop correlations for macrochannels cannot predict two-phase pressure drop in mini/microchannels, and presented modified forms of the Lockhart-Martinelli type correlation equations to correlate their experimental data. For example, Mishima and Hibiki [14] correlated their pressure drop data of air and water in small circular tubes with an inner diameter of 1–4 mm, taking into consideration the diameter effect on pressure drop by incorporating hydraulic diameter into the Matinelli–Chisholm constant with $C = 21(1 - e^{-319\,D_h})$. Garimella et al. [18] developed a pressure drop model for intermittent flow of condensing refrigerant R134a in horizontal minitubes with hydraulic diameters from 0.5 to 5 mm.

In this study, the pressure drop data for steam condensing in four microchannels, having hydraulic diameters of 109 μm, 142 μm, 151 μm, and 259 μm, respectively, are presented. The Lockhart–Martinelli type correlation, with the modified constant C taking into consideration of the surface tension and the diameter effects, is applied to the pressure drop data in condensation of steam in microchannels. It is found that the correlation equation is within ±15% of the experimental data.

2. Experimental setup and data reduction

The experimental setup, used for visualization study of condensation in microchannels previously [4], was also used in the present study. However, a water-cooled pre-condenser was added before the test section in order to partially condense steam to the desired quality. The four microchannels used in the experiments were 60 mm long, with different size of trapezoidal cross sections as listed in Table 2. Because the inner diameters of the microchannels were too small, static pressures of the water on the inner wall could not be measured directly. Instead, static pressures on the inner wall of the pipes connected with the test section were measured by pressure transducers. Note that the total pressure measured in the experiment was the sum of the two-phase pressure drop in the microchannels, the decelerated pressure drop, the static pressure drop, the pressure loss due to the contraction at the inlet and expansion at outlet of the microchannel in connection with the pipes, i.e.,

$$\Delta P_{exp} = \Delta P_{tp} + \Delta P_a + \Delta P_s + \Delta P_{in} + \Delta P_{out} \tag{5}$$

Note that the static pressure drop (ΔP_s) in the horizontal microchannel is zero. Due to the slight change in quality of steam between the inlet and outlet of the test section, the decelerated pressure drop (ΔP_a) was calculated by the formula given by Carey [5]. The pressure drop losses (ΔP_{in}, ΔP_{out}) due to sudden contraction at the inlet or the expansion at the outlet could be calculated using the formula given by Hewitt et al. [19]. With the total pressure drop data (ΔP_{exp}), the actual two-phase friction pressure drop (ΔP_{tp}) can be calculated according to the above formulas.

Table 2
Geometric parameters of the microchannels used in this experiments

Channel specifications	D_h (μm)	W_t (μm)	W_b (μm)	H (μm)	Aspect ratio (W_t/H)	Number of channels
N1	151	650	522.6	90	7.222	5
N2	142	480	352.6	90	5.333	5
N3	109	300	193.7	75	4	8
N4	259	500	4.37	350	1.428	3

The vapor quality at the inlet of the test section was equal to that at the outlet of the pre-condenser because the inlet of the test section was connected with the outlet of the pre-condenser. According to the energy balance, the quality (x) at the outlet of the pre-condenser can be calculated by

$$x_{i.test} = 1 - \frac{m_{prec}c_{p.prec}(T_{o.prec} - T_{i.prec})}{m_v h_{fg}} \tag{6a}$$

The steam quality at the outlet of test section is determined from

$$x_{o.test} = x_{i.test} - \frac{m_{testc}c_{p.test}(T_{o.testc} - T_{i.testc})}{m_v h_{fg}} \tag{6b}$$

The average vapor quality in the test section is obtained from

$$x = (x_{i.test} + x_{o.test})/2 \tag{6c}$$

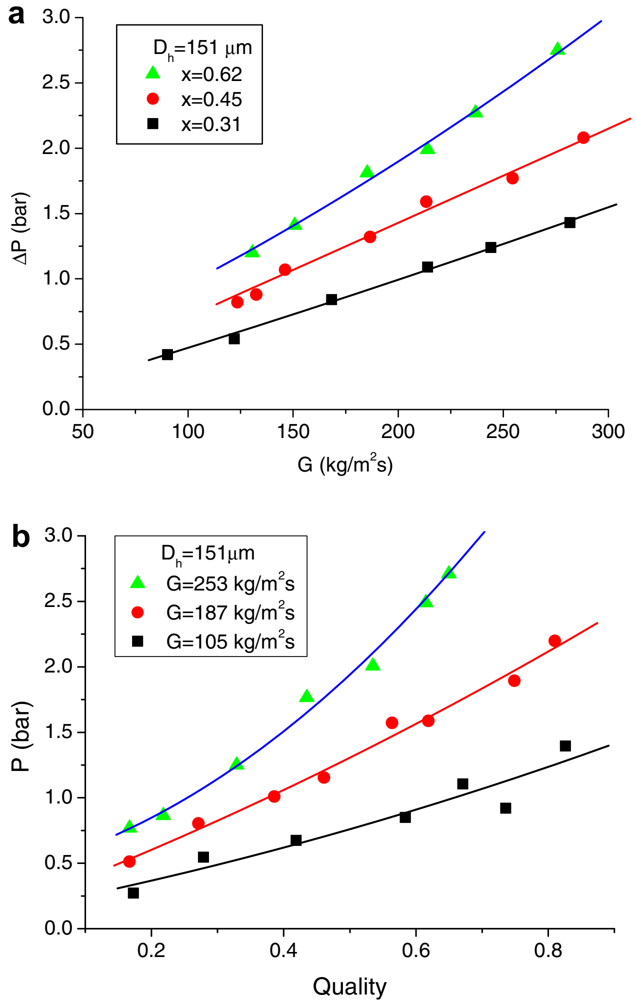

Fig. 1. (a) The effect of mass flux on the pressure drop in N1 microchannels. (b) The effect of vapor quality on the pressure drop in N1 microchannels.

In the above equations, the quantities x, T, C_p, h_{fg} and m represent vapor quality, temperature, specific heat, latent heat and mass flow rate, respectively, and the subscripts "pre", "test", "v", "c", "i" and "o" denote the conditions at the pre-condenser, test section, vapor, coolant, inlet and outlet of microchannels. Because air-cooling was used in the test section where the heat transfer rate was small, the difference between inlet and outlet quality was also small.

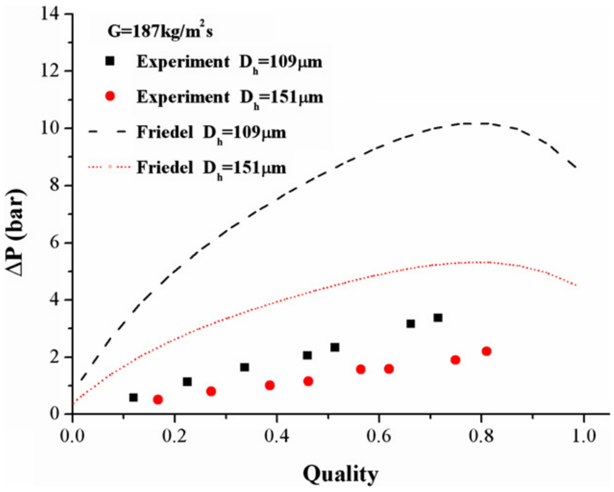

Fig. 2. Effect of microchannel diameter on the pressure drop in N1, N3 microchannels.

3. Results and discussion

3.1. Two-phase flow pressure drop and comparison with existing correlations

The data from the present experiment on two-phase frictional pressure drop as functions of the steam mass flux and quality are presented in Fig. 1a and b. As expected, higher mass flux or higher vapor quality, gave higher two-phase frictional pressure drop. This is because mean density decreases with increase of vapor quality, and thus the average velocity of two-phase fluid increases at constant mass flux, resulting in greater friction force of fluid flow against tube wall.

Fig. 2 shows the comparison of the present two-phase pressure drop data at constant mass flux ($G = 187\ \mathrm{kg/m^2s}$) in two microchannels having hydraulic diameters of 109 μm and 151 μm, respectively. As seen from this figure, the diameter of the microchannels has a strong influence on the two-phase pressure drop. As expected, the larger the diameter, the lower is the two-phase pressure drop. Friedel's [12] correlation of adiabatic two-phase pressure drops for the same hydraulic diameters were computed, and were plotted as solid and dashed lines in the same graph for comparison purpose. It is shown that Friedel's correlation for two-phase pressure drop in macrochannels overestimates the condensation pressure drops in microchannels although the correlation predicts the same trend as the present experimental data.

Fig. 3 is a comparison of the experimental data with the two-phase pressure drop prediction based on the four homogenous flow models given by Ackers [6], Dukler et al. [7], McAdams et al. [8], and Lin et al. [9], respectively. It is found the four homogenous models overestimate the two-phase pressure drop in microchannels. The

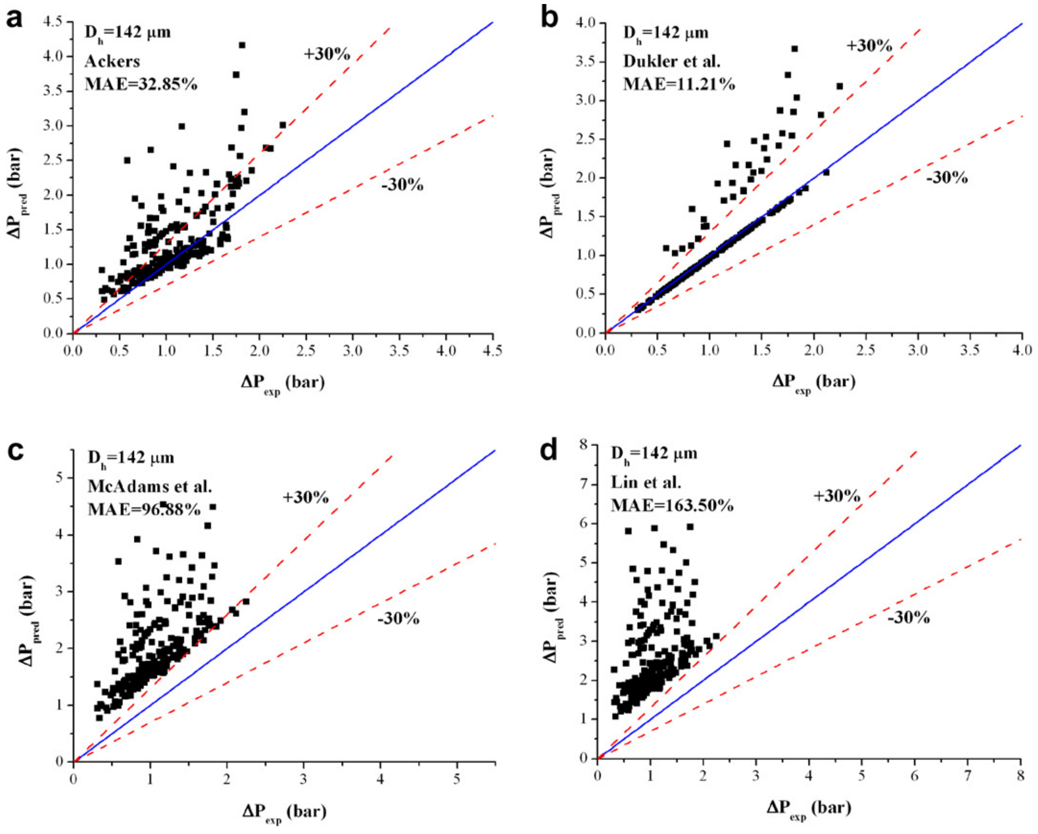

Fig. 3. Experimental data versus predicted pressure drop by homogeneous models of (a) Akers et al. [6], (b) Dukler et al. [7], (c) Mcadams et al. [8], and (d) Lin et al. [9] for N2 microchannels.

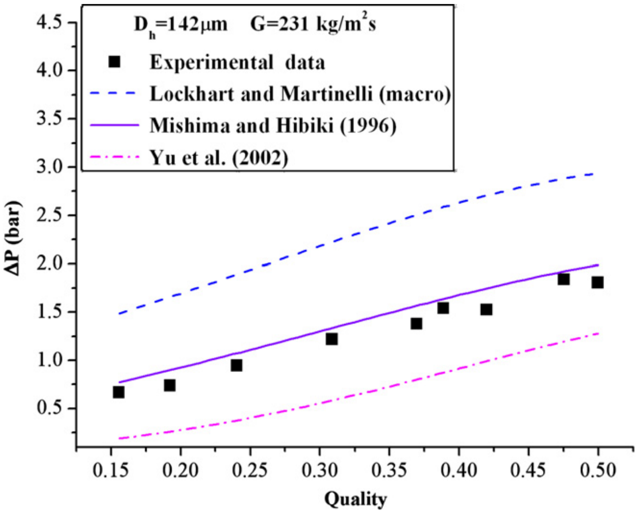

Fig. 4. Comparison of two-phase pressure drop correlations with experimental data at mass flux of 231 kg/m^2 s in N2 microchannels.

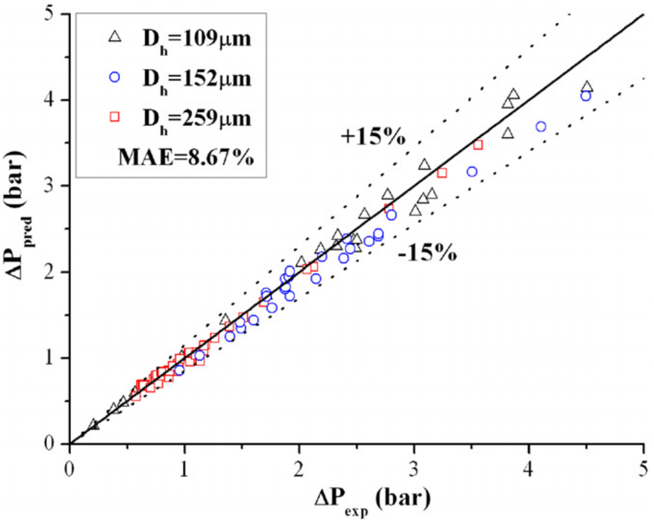

Fig. 6. Comparison of present correlation predictions with pressure drop data in N1, N2, N4 microchannels.

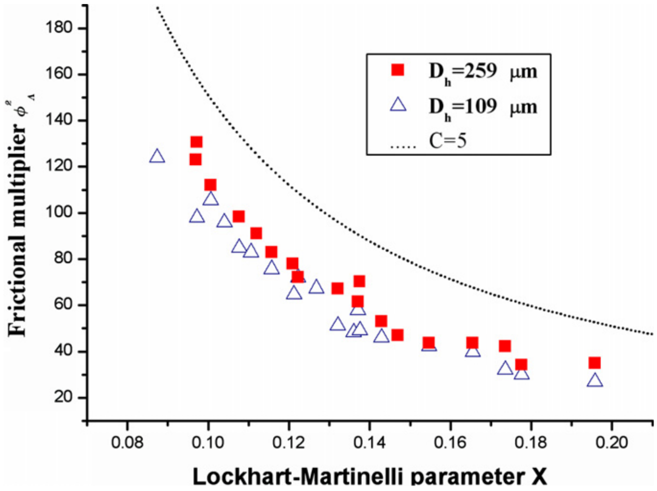

Fig. 5. Variation of ϕ_L^2 versus X in N3 and N4 microchannels.

mean absolute error (MAE) of the pressure drop correlation is defined as

$$\mathrm{MAE} = \frac{1}{N}\sum\left[\frac{|\Delta P_{\exp t} - \Delta P_{\mathrm{Pred}}|}{\Delta P_{\exp t}} \times 100\%\right] \tag{7}$$

Equation (7) was computed for each of the existing correlation, which in indicated in each graph in Fig. 3 and is listed in Table 1.

Fig. 4 is a comparison of two-phase pressure drop predictions of the three separated flow correlations given by Lockhart and Martinelli [10], Mishima and Hibiki [14] and Yu et al. [17] with the present experimental data at constant mass flux of 231 kg/m^{2}s in microchannel. Mishima and Hibiki's correlation [14] overpredicted the present experimental data with the MAE of 10.4%, which is better than the other two correlations because it was developed for air and water in small channels and the properties of air and water are similar to those with steam and water used in this experiment. The Lockhart–Martinelli correlation [10], based on laminar flows of liquid and vapor, consistently overestimates the pressure drop with a MAE of 63.59%. Yu et al. [16] presented a two-phase frictional multiplier correlation given by $\phi_l^2 = X_{vt}^{-1.9}$. However, it is observed from Fig. 4 that this correlation tends to underestimate the present experimental data with a MAE of 55%. This may be due to the fact that their experiments were conducted at lower mass fluxes of 50–200 kg/m^{2}s.

Fig. 5 shows a comparison of two-phase frictional multiplier ϕ_l^2 at G = 143 kg/m^{2}s in two microchannels and the values predicted by the Lockhart–Martinelli correlation with C = 5 (i.e., the minimum value of C). As shown, the present experimental data of the frictional multiplier are smaller than the baseline of C = 5. The data also show that the smaller hydraulic diameter, the smaller the constant C. Similar conclusions were obtained previously by Lee and Lee [15].

3.2. Two-phase flow pressure drop correlation for condensing flow in microchannels

The experimental data in Fig. 1 show that the condensation pressure drop in microchannels is strongly influenced by mass flux, quality and hydraulic diameter. In order to improve the Lockhart–Martinelli type pressure drop correlation for condensation in microchannels, we assume that the Matinelli–Chisholm constant C takes the following form:

$$C = C_0 Re_{Lo}^{m} Bo^{n} Su^{p} \tag{8a}$$

where $Re_{Lo} = GD_h/\mu_l$, $Bo = (\rho_l - \rho_v)gD_h^2/\sigma$ is the Bond number which is a measure of the relative importance of the gravity and surface tension effects, and $Su = Ca/Re = \mu_l^2/(\rho_l D_h \sigma)$ is the Suratman number which may be interpreted as the ratio of the square of the viscous forces to the product of surface tension and inertia forces [15]. After applying a regression analysis of the experimental data to Eq. (8a), we obtained the following correlation for C:

$$C = 0.168 Bo^{0.265} Re_{Lo}^{0.337} Su^{-0.041} \tag{8b}$$

After C is computed from Eq. (8b), the two-phase pressure drop can be computed from Eq. (4) with the single-phase pressure drop in a microchannel with trapezoidal cross section given by

$$\left(\frac{dp}{dz}\right)_l = \frac{2fG^2(1-x)^2}{\rho_l D_h} \tag{9a}$$

where the friction factor f for liquid flowing in a microchannel with trapezoidal cross section is given by Wu and Cheng [20] as

$$fRe = 11.43 + 0.8\exp(2.67W_b/W_t) \tag{9b}$$

with W_b and W_t being the bottom and top widths of the microchannel. The predicted pressure drop determined fromEqs. (4a), (3), (9a), (8b) and (9b) is presented in Fig. 6, which shows that the predicted values are within ±15% of the experimental data with an absolute average deviation of 8.67%.

4. Conclusions

In the present study, the characteristics of two-phase flow pressure drop have been investigated experimentally for condensation of steam in microchannels having a trapezoidal cross section. The measured two-phase pressure drop increases with the increase in mass flux and quality, and with decreasing microchannel diameter. The smaller the microchannel diameter, the lower is the Matinelli–Chisholm constant C, implying smaller liquid and vapor phase interaction in microchannels. The existing correlations for two-phase pressure drop in macrochannels overestimate the present experimental data for condensation pressure drop in microchannels. A modified Matinelli–Chisholm constant, taking into consideration of surface tension and diameter effects, was obtained. The two-phase pressure drop based on the modified Matinelli–Chisholm constant is shown within ±15% of the experimental data.

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