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Flow-Regime Based Model for Pressure Drop Predictions in Microchannels

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Void Fraction and Pressure Drop in Microchannels
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Abstract

A flow-regime based pressure drop model is developed to correlate experimental data in the intermittent and annular flow regime. For the intermittent region, an alternative method for microchannel pressure drop predictions based on the average kinetic energy of the mixture is developed. A parameter based in the Weber number, the Lockhart-Martinelli parameter, and the liquid to vapor density ratio is proposed for pressure drop predictions in the annular flow region.

The two correlations were built on experimental data of R410A, R134a, and air-water mixtures with mass fluxes ranging from 50 to 300 kg/(s.m^2), with quality ranging from 0 to 1. 6-port and 14-port aluminum microchannel tubes with hydraulic diameters of 1.54 mm and 1.02 mm, respectively, were used for the two-phase pressure drop experiments.

Entrance/exit pressure drop were directly measured with an additional experiment. The losses due to the entrance/exit zones have been found to exhibit homogeneous flow characteristics, and were correlated to a homogeneous flow parameter based on the kinetic energy of the flow field.

Nomenclature

D	diameter, m or mm
D_h	hydraulic diameter, m or mm
dP/dz	pressure gradient, N/m^3
f	Fanning friction factor
Fr	Froude number
Fr_l	liquid film Froude number
Ft	Froude rate
G	mass flux, kg/(s.m^2)
Ga	Galileo number
N_{conf}	Confinement number
Re	Reynolds Number
We	Weber number
We_v	Weber number for vapor
x	quality
X_{tt}	Lockhart-Martinelli parameter
z	direction of the flow, m
ΔP	pressure drop, N/m^2
Φ	two-phase multiplier
μ	dynamic viscosity, Pa.s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

2ϕ	two-phase flow
a	accelerational
avg	average
f	frictional
g	gravitational
l	liquid
lo	liquid only
v	vapor
vo	vapor only

Introduction

In general, total pressure drop for two-phase flow in tubes can be expressed in terms of a frictional dissipation term, an accelerational head term, and a static term due to gravitation effects.

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\right)_f + \left(\frac{dP}{dz}\right)_a + \left(\frac{dP}{dz}\right)_g \tag{1}$$

Where dP/dz is the gradient of pressure in the direction of the flow (z direction). The accelerational head term is calculated from an analysis of momentum exchange in the pipe, and the static term is the pressure gain or loss that depends on the change in elevation of the section of the tube.

For two-phase flow, the frictional pressure drop is related with the irreversible dissipation of energy due to interactions between the fluid and the wall of the tubes, and interactions between vapor and liquid. There is not an exact theory that predicts pressure losses due to friction. Through many years, investigators have developed semi-empirical correlations based in experimental work to predict two-phase pressure drop. Therefore, the semi-empirical relations are limited to the range of conditions of the experiments at which they are developed.

Two ideal models for frictional pressure drop prediction are the homogeneous and the separated flow models. In the homogeneous model, it is assumed that liquid and vapor velocities of the mixture are equal. Furthermore, the mixture is considered as a homogeneous single-phase fluid with average fluid properties that depends on the quality. On the other hand, the separated flow model considers the liquid and vapor in the mixture flowing separately. In this model, the static pressure drop of the liquid phase and vapor phase are assumed equal. Ideal separated flow assumes no vapor-liquid interactions.

The current investigation compares two-phase pressure drop results in horizontal aluminum microchannels at adiabatic conditions with correlations available in the literature. It will be demonstrated why most of the annular correlations create systematic errors when diameters are in the order of 1mm and below. This study starts with a review of two-phase pressure drop correlations for both large and small tubes. An analysis of the entrance/exit pressure losses is performed in order to isolate the pressure drop of the microchannel tube. The pressure drop experimental results are presented and compared with some of the correlations available in the literature. This investigation proposes new equations for pressure drop predictions depending on the principal flow regime. The analysis of the results and conclusions are based on the experimental work by Niño, Hrnjak, and Newell (2002).

Homogeneous Flow Model

The homogeneous flow model predicts two-phase pressure drop with single-phase pressure drop relations using average properties of the mixture.

$$\left(\frac{\Delta P}{\Delta z}\right)_f = 2f\frac{1}{D_h}\frac{G^2}{\rho_{2\phi}} \tag{2}$$

Where f is the Fanning friction factor, G is the mass flux of the two-phase flow, and D_h is the diameter of the tube. The two-phase density ($\rho_{2\phi}$) is an average density calculated assuming a homogeneous void fraction.

$$\rho_{2\phi} = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l}\right)^{-1} \tag{3}$$

For the homogeneous model, McAdams (1954) suggests friction factor calculations with a Reynolds number that uses an average dynamic viscosity ($\mu_{2\phi}$) of the mixture defined as:

$$\mathrm{Re} = \frac{GD_h}{\mu_{2\phi}} \qquad \text{where} \qquad \mu_{2\phi} = \left(\frac{x}{\mu_v} + \frac{(1-x)}{\mu_l}\right)^{-1} \tag{4}$$

The homogenous flow model is suitable to describe flows where the liquid and vapor phase are moving at the same velocity (for example, plug and slug flow patterns of the intermittent flow regime) by averaging the physical properties of both phases in a segment of a tube.

Separated Flow Model

Most of the available correlations for large and small tubes are based on an annular flow model. Lockhart and Martinelli (1949) performed the most representative investigation that develops the theory of the separated flow model. Their work included an experimental analysis of circular tubes with diameters ranging from 1.48 mm to 25.83 mm, using mixtures of air with benzene, kerosene, water and various oils. Their two-phase pressure drop analysis was based on two basic postulates. The first one states that the static pressure drop for both liquid and vapor phases are the same regardless of the flow pattern, as long as changes of static pressure in the radial direction are not significant (they infer that slug or plug flow are eliminated from consideration). The second postulate states that the sum of volumes occupied by vapor and liquid at any instant are equal to the total volume of the pipe (mass continuity equation).

Based in these postulates and their experimental analysis, Lockhart and Martinelli (1949) developed a new parameter that is used to correlate their experimental results.

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.125} \tag{5}$$

Where X_{tt} is known as the Lockhart-Martinelli parameter, which is equal to the square root of the ratio of the liquid frictional pressure drop to the vapor frictional pressure drop assuming turbulent flow of each phase flowing alone at its superficial velocity. The superficial velocity for liquid and vapor are defined as $V_l=(1-x)G/\rho_l$ and $V_g=xG/\rho_v$, respectively.

Martinelli and Nelson (1948), and Lockhart and Martinelli (1949) defined key multipliers that compares the two-phase flow frictional pressure gradient $(\Delta P/\Delta z)_{2\phi}$ of a particular tube with a single-phase frictional pressure gradient assuming one phase in the same tube.

$$\Phi_{lo}^2 = \frac{\left(\frac{\Delta P}{\Delta z}\right)_{2\phi}}{\left(\frac{\Delta P}{\Delta z}\right)_{lo}},\ \Phi_{vo}^2 = \frac{\left(\frac{\Delta P}{\Delta z}\right)_{2\phi}}{\left(\frac{\Delta P}{\Delta z}\right)_{vo}},\ \Phi_{l}^2 = \frac{\left(\frac{\Delta P}{\Delta z}\right)_{2\phi}}{\left(\frac{\Delta P}{\Delta z}\right)_{l}},\ \text{and}\ \Phi_{v}^2 = \frac{\left(\frac{\Delta P}{\Delta z}\right)_{2\phi}}{\left(\frac{\Delta P}{\Delta z}\right)_{v}} \tag{6}$$

$$\left(\frac{\Delta P}{\Delta z}\right)_{lo} = 2 f_{lo}\frac{1}{D_h}\frac{G^2}{\rho_l}, \qquad \left(\frac{\Delta P}{\Delta z}\right)_{vo} = 2 f_{vo}\frac{1}{D_h}\frac{G^2}{\rho_v},$$

$$\left(\frac{\Delta P}{\Delta z}\right)_{l} = 2 f_{l}\frac{1}{D_h}\frac{[(1-x)G]^2}{\rho_l}, \quad \text{and} \quad \left(\frac{\Delta P}{\Delta z}\right)_{v} = 2 f_{v}\frac{1}{D_h}\frac{(xG)^2}{\rho_v} \tag{7}$$

f_{lo} and f_{vo} are Fanning friction factors assuming that only liquid or only vapor is flowing alone at the same mass flux G of the two-phase flow through the pipe of hydraulic diameter D_h. f_l and f_v are Fanning friction factors assuming that only liquid or only vapor is flowing alone at the same superficial velocity of the phase. The two-phase multipliers measures the irreversible work due to the interactions between the vapor, liquid, and the walls of the pipe, compared with the irreversibilities of only liquid or only vapor flow going through the pipe. Lockhart and Martinelli suggested that all two-phase multipliers could be correlated with the parameter X_{tt}. The most popular two-phase multiplier is Φ_{lo}^2, and several investigators have correlated their experimental pressure drop using Φ_{lo}^2 as a function of X_{tt} and some other parameters.

Large Tube Correlations

Friedel (1979) developed a pressure drop correlation based on the two-phase multiplier Φ_{lo}^2 by conducting experiments for both horizontal and vertical flow, where the smallest diameter was 4 mm. He correlated his experimental data with Φ_{lo}^2 as a function of the Lockhart-Martinelli parameter, Froude number, Weber number, quality, friction factor, as well as physical properties of the mixture.

Jung and Radermarcher (1989) conducted experiments to find a pressure drop correlation during horizontal flow boiling with R22/R114 and R12/R152a mixtures at several compositions as well as pure components. The tube used in these experiments is a circular tube of 9.1 mm ID, and the range of mass fluxes corresponds to 230-720 kg/(s.m^2). Their correlation is based on the two-phase multiplier Φ_{lo}^2 that depends only on the Lockhart-Martinelli parameter and the quality of the mixture.

Souza, Chato, Wattelet and Christoffersen (1993) developed a correlation for two-phase pressure drop for evaporator tubes. R12 and R134a were used as the refrigerants in their test apparatus, and a 10.9 mm ID horizontal smooth copper tube was used in their experiments. The predominant flow pattern for most of the tests is annular flow. Their correlation for the two-phase multiplier Φ_{lo}^2 was based on the Lockhart-Martinelli parameter, Froude Number, and the quality of the mixture.

Small Tube Correlations

Yang and Webb (1996) measured pressure drop in a plain and a micro-fin rectangular 4-port microchannel tubes with hydraulic diameters of 2.64 and 1.56 mm, respectively. The study included single-phase and two-phase data with R12 using mass fluxes ranging from 400 to 1400 kg/(s.m^2). They used a different approach to correlate their experimental data. They defined a friction factor that depends on an equivalent liquid flow that will give the same pressure drop as the two-phase flow. Their correlation uses an equivalent mass flux of liquid proposed by Akers, Deans, and Crosser (1959) for friction factor calculations.

Zhang and Kwon (1999) developed a pressure drop correlation using the two-phase multiplier Φ_{lo}^2, based on experiments with R134a, R22, and R404A through a 6.20 mm and a 3.25 mm copper tube, and a circular 6-port microchannel with a hydraulic diameter of 2.13 mm. Mass fluxes from 200 to 1000 kg/(s.m^2) were used in their experiments. Their correlation describes Φ_{lo}^2 as a function of the quality and reduced pressure of the mixture (ratio between saturation pressure of the mixture and critical pressure of the fluid). It should be noted that there is an inherent relation between reduced pressure and the ratio of physical properties:

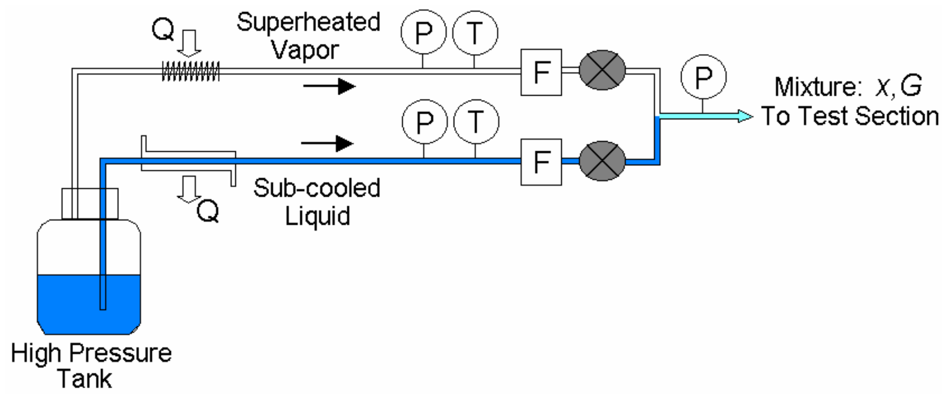
$$C(P_r)^m = C\left(\frac{P_{sat}}{P_c}\right)^m = \left(\frac{\rho_v}{\rho_l}\right)^n \left(\frac{\mu_l}{\mu_v}\right)^o \quad (8)$$

Where P_{sat} is the saturation pressure, P_c is the critical pressure of the refrigerant; the fluid properties (ρ_l, ρ_v, μ_l, μ_v) are at the saturation temperature, and *C*, *m*, *n*, and *o* are constants. For example, Jung and Radermacher (1989) report in their correlation *C*=0.551, *m*=0.492, *n*=0.5 and *o*=0.1 for pure refrigerants.

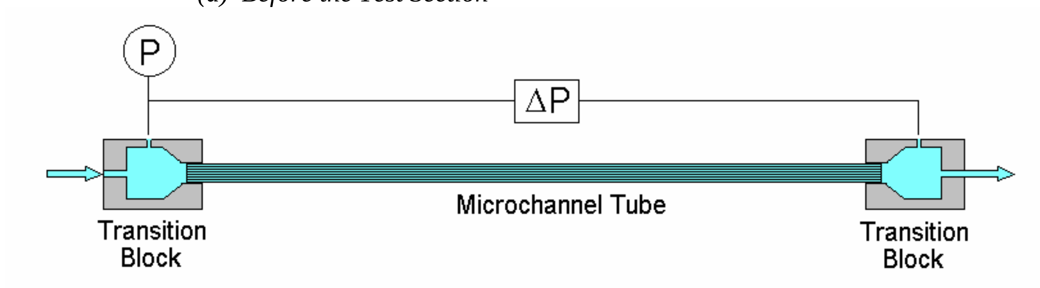
Tran, Chyu, Wambsganss, and France (2000) performed experiments with 2.46mm and 2.92mm circular tubes, and a 4.06mm x 1.7mm rectangular channel during evaporation. Fluids used in the experiments include R134a, R12, and R113 with mass fluxes ranging from 50-800 kg/(s.m^2). They compared their experimental results of the annular region (high mass flux and qualities) with large tube correlations, concluding that most of them under-predict their pressure drop results. They conclude that the additional pressure drop in the annular region of two-phase flow in small tubes is related to an additional friction related to the bubbles that are confined, elongated, and slide over a thin liquid due to the size of the channel, compared with the unrestricted movement of these bubbles in the large tubes. They used Φ_{lo}^2 to correlate experimental pressure drop. Their correlation includes the confinement number Nconf., defined by Cornwell and Kew (1993), which is an expression that represents the ratio between the surface tension to buoyancy forces. Table 1 describes non-dimensional parameters discussed in the first portion of this investigation.

Experimental Facility

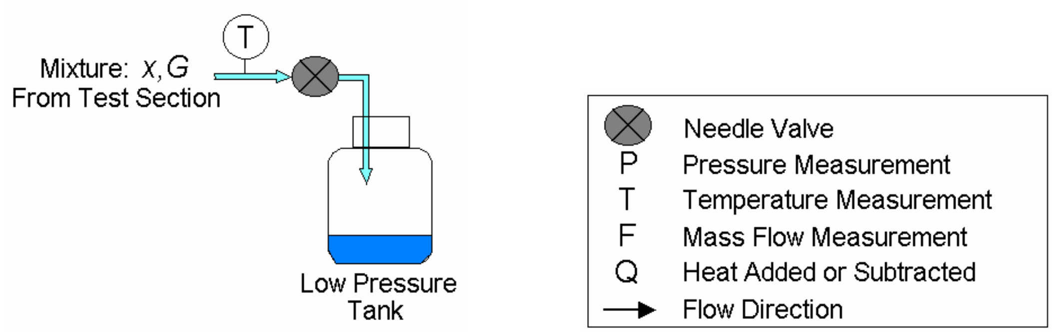
Figure 1 shows a schematic drawing of the microchannel test facility for experimental investigation of pressure drop. The major components of the system are the high and low temperature refrigerant tanks, pressure transducers, thermocouples, mass flow sensors, the transition pieces, and the microchannel test section.



(a) Before the Test Section



b) Microchannel Test Section and Pressure Drop Measurement Arrangement



c) After the Test Section

Figure 1: Schematic Drawing of the Experimental Facility

The refrigerant flows as a "once-through" process with vapor and liquid flowing separately out of a heated reservoir tank (high pressure tank). Heat is added to the saturated vapor flow with an electric resistance heater to superheat the stream. Sub-cooled liquid is achieved by removing heat from the saturated liquid in a heat exchanger with chilled water. After single-phase temperature, pressure, and mass flow rate are measured for each flow, the sub-cooled liquid and the superheated vapor streams are mixed. Conditioning valves are used to control the streams of both flows and set the desired quality and mass flux.

Table 1: Some of the Parameters Used for Pressure Drop Correlations

Parameter	Equation	Meaning
Reynolds Number	$\mathrm{Re} = \frac{GD}{\mu}$	Ratio of Inertial to Viscous Forces
Lockhart-Martinelli Parameter	$X_{tt} = \left(\frac{1-x}{x}\right)^{0.875} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.125}$	Ratio of the liquid frictional pressure drop to the vapor frictional pressure drop (assuming each phase turbulent and flowing alone at the superficial velocity).
Froude Rate	$Ft = \left(\frac{x^3 G^2}{\rho_v^2 g D (1-x)}\right)^{\frac{1}{2}}$	Ratio of Vapor Kinetic Energy to Energy dissipated lifting the Liquid
Froude Number	$\mathrm{Fr} = \frac{G^2}{\rho^2 g D}$	Ratio of Inertial to Gravitational Force
Weber Number	$\mathrm{We} = \frac{G^2 D}{\rho \sigma}$	Ratio of Inertial to surface tension Forces
Confinement Number	$N_{conf.} = \frac{\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{0.5}}{D}$	Numerator corresponds to the ratio of surface to buoyancy forces.

The two-phase blend moves through the microchannel test section. Transition pieces are used to provide a connection between the microchannel and the round copper tube of the flow system. The mixture finally reaches the cooled reservoir (low pressure tank) after passing the test section. A conditioning valve at the end of the test section is used to set the saturation temperature/pressure of the test section.

The experimental facility allowed pressure drop measurement on microchannels with R134a, R410A, and air-water mixtures at mass fluxes ranging from 50 kg/(s.m^2) to 300 kg/(s.m^2), and all ranges of qualities (0% to 100%). All tests were performed under adiabatic conditions, and in a horizontal orientation.

Mass fluxes between 50 kg/(s.m^2) and 350 kg/(s.m^2) are typical for most of the automotive applications using microchannels. Few applications use mass fluxes as high as 750 kg/(s.m^2). However, these ranges are low compared with mass fluxes of other air-conditioning appliances (household heating and air-conditioning, etc.)

Two mass flowmeters are used to measure independently gas and liquid mass flow. The nominal flow range of both flow measurements is from 0-0.022 kg/s with an accuracy of ±0.10% for the liquid flow rate, and ±0.5% for the gas flow rate. Measurement of the absolute pressures is achieved with differential transducers ranging from 0-2068 kPa, and an accuracy of ±0.25% full scale, and a barometric pressure with a precision of ±0.3%. Temperature measurements are carried out with type T thermocouples with an accuracy of 0.25°C. Density of gases and liquids are found with a computer program where thermodynamic properties are obtained from a built-in function call in terms of any other properties. The precision of the quality property is found with a propagation error analysis. It is found that the error decreases (i.e. precision increases) when the quality increases. The error propagation analysis gives the following precision for the quality: $x \pm 0.003x^{-1.193}$. For qualities higher than 40%, the error is less than 1%. Error ranging from 1-4% is found for qualities between 10%-40%.

The transition blocks of Figure 1 are designed to allow pressure measurement, and to provide connection between the microchannel tube and the round copper tube of the experimental facility. Pressure drop is measured with a differential pressure transducer with a range of 0-220kPa and an accuracy of ±0.25% of the reading. Two multi-port aluminum microchannel tubes are used for two-phase flow experimental analysis. A 6-port microchannel has a hydraulic diameter of 1.54±0.02 mm and a cross-sectional area of 16.7±0.1 mm^2. A 14-port microchannel has a hydraulic diameter and a cross-sectional area of 1.02±0.01 mm and 15.0±0.1 mm^2, respectively.

The dimensions of the microchannel were measured using digital image processing. This method analyzes a digital image of a polished cross-section area of the microchannel. The area of each microchannel is determined by counting pixels.

Experimental Pressure Drop Measurements

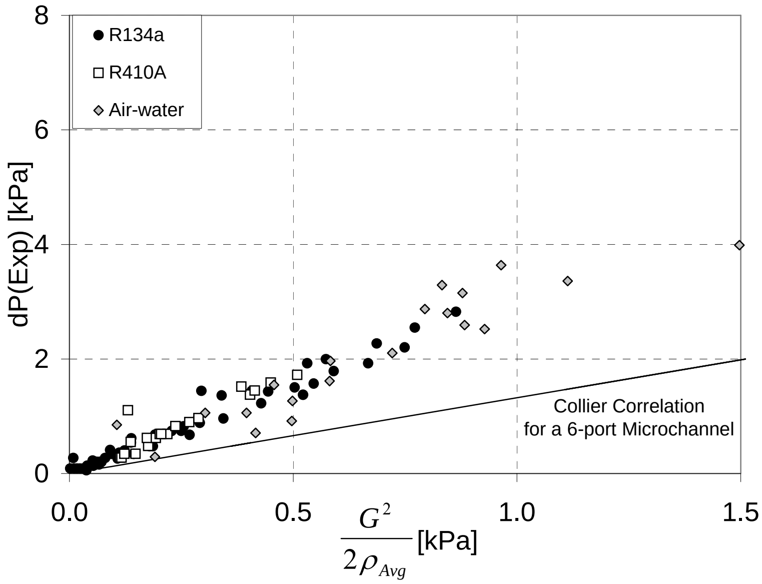
As Figure 1 shows, the principal components of the microchannel test section are the transition blocks and the microchannel tube in between. Therefore, pressure drop measurements include the frictional pressure drop in the microchannel plus an additional entrance/exit pressure drop due to a flow contraction and a following expansion through the transition blocks.

An additional experiment was completed in order to describe quantitatively the pressure losses due to the area change. The transition blocks were placed directly together with a short piece of microchannel tube. In this arrangement, the pressure gradient due to acceleration changes (area change causes acceleration changes) is large compared with pressure losses due to friction.

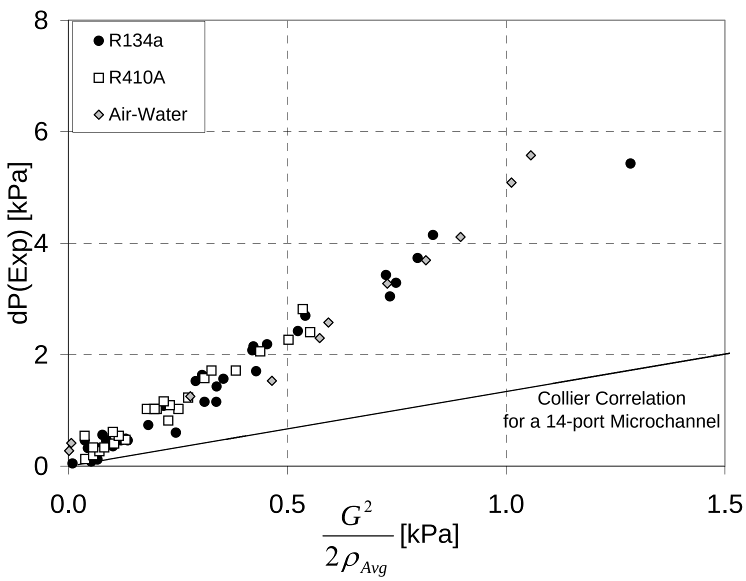
Utilizing a homogeneous flow model analysis for contraction and expansion devices suggested by Collier and Thome (1996), a correlation for the transition section pressure drop for each microchannel tube was developed. In general, the model developed by Collier and Thome (1996) suggests that the total entrance/exit pressure losses are proportional to the average kinetic energy of the mixture.

$$\Delta P_{E/E} \propto \frac{G^2}{2\rho_{Avg}} \qquad \text{where } \rho_{2\phi} = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l} \right)^{-1} \tag{9}$$

Figure 2 shows the results of the entrance/exit pressure drop experiments for the 6-port and the 14-port microchannel using air-water mixtures, R134a and R410A (the results include single and two-phase flow of the refrigerants).



a) 6-port Microchannel



a) 14-port Microchannel

Figure 2: Entrance/Exit Pressure Drop vs. the average Kinetic Energy of the Mixture

Collier and Thome (1996) relations for enlargements and contractions under-predict pressure drop losses in the transition pieces. The data suggests, however, that the homogeneous kinetic energy parameter of the model developed by Collier and Thome is the dominant factor for correlating pressure drop through the transition blocks. The behavior is approximately linear. Differences between the data and the homogeneous flow model of Collier and Thome (1996) may be associated with momentum dissipation at the webs of the microchannel in the entrance. In other words, the vena contracta that is associated with the mixture entering the multi-port microchannel is complex, generating higher dissipation.

The experimental results of entrance/exit pressure losses were correlated with the average kinetic energy as Figure 2 suggest. A constant that multiplies the average kinetic energy of the mixture is sufficient to calculate the entrance/exit pressure losses, and subtract them from the total pressure drop.

Two-phase pressure drop measurements in microchannels were performed with R410A, R134a, and air-water mixtures using the 6-port and the 14-port aluminum microchannel. Entrance/exit pressure losses were subtracted from the overall test section pressure drop.

Niño, Payne, Hrnjak, Newell, and Infante Ferreira (2001) concluded that two-phase pressure drop is strongly dependent on the physical properties of the fluid or mixture. It should be addressed that the liquid to vapor density ratio of air-water is 1000 to 2, compared with 1000 to 20 for R134a, and 1000 to 40 for R410A.

Two-phase pressure drop correlations were examined in the current study to look for the best equation that could predict pressure drop data in the wide range of fluid and flow conditions listed above. In general, none of the correlations based on the separated flow model (Lockhart-Martinelli based-correlations) predict two-phase pressure drop in microchannels over the range of parameters studied in this investigation, even though some of them were developed for relatively small hydraulic diameter tubes. Extremely high systematic errors were found in the prediction of pressure drop when the correlations were extrapolated to small channels and low mass fluxes. A detailed analysis of the correlations is found in Niño, Hrnjak, and Newell (2002). Surprisingly, the error is not associated with the numerical values of the coefficients and exponents of the function Φ_{lo}^2 that are chosen by the authors of the correlations to fit their experimental data. The systematic errors are related to the calculation of the single-phase friction factor f_{lo} assuming only liquid flowing at the same mass flux as the mixture and include the value in the two-phase flow correlation. Recalling Eq. (6) and Eq. (7), the two-phase pressure drop correlations studied are in the form:

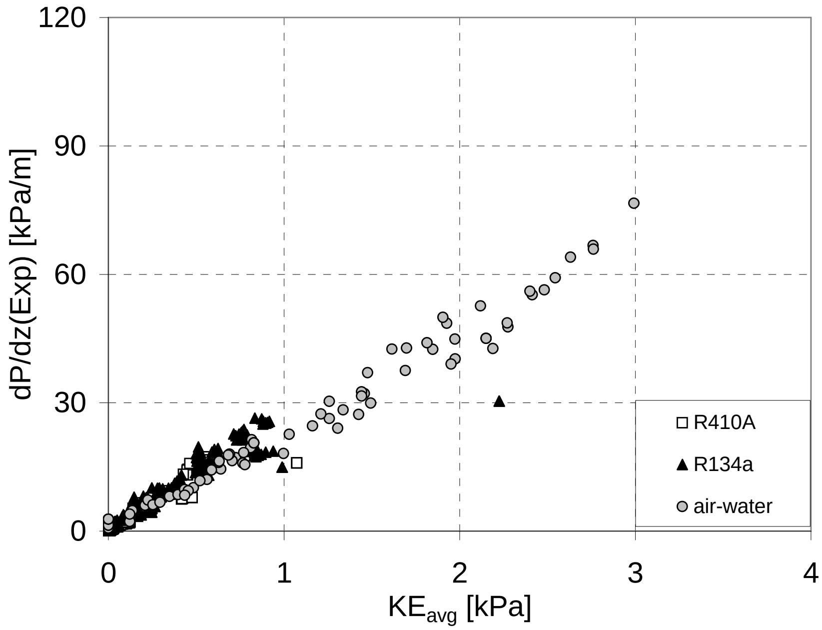
$$\left(\frac{\Delta P}{\Delta z}\right)_{2\phi} = \Phi_{lo}^2 \left(2\, f_{lo} \frac{1}{D_h} \frac{G^2}{\rho_l}\right) \tag{10}$$

For the range of mass fluxes studied (50 to 300 kg/(s.m^2)), most of the Reynolds numbers of the experimental data falls in the laminar and transition region assuming only liquid flowing through the microchannel of small hydraulic diameter (because of the high viscosity of the water, all the Reynolds numbers of the air-water experimental data are small if only water is assumed to be flowing in the channels). Friction factor in the turbulent region is almost constant. Friction factor in the transition region varies, and it increases drastically in the laminar region when Reynolds number decreases. Therefore, the systematic errors in the calculation of pressure drop with correlations based on annular flow are due to either the extrapolation of the turbulent friction factor functions using low Reynolds numbers or using laminar functions to calculate the friction factor of the flow assuming only liquid flowing.

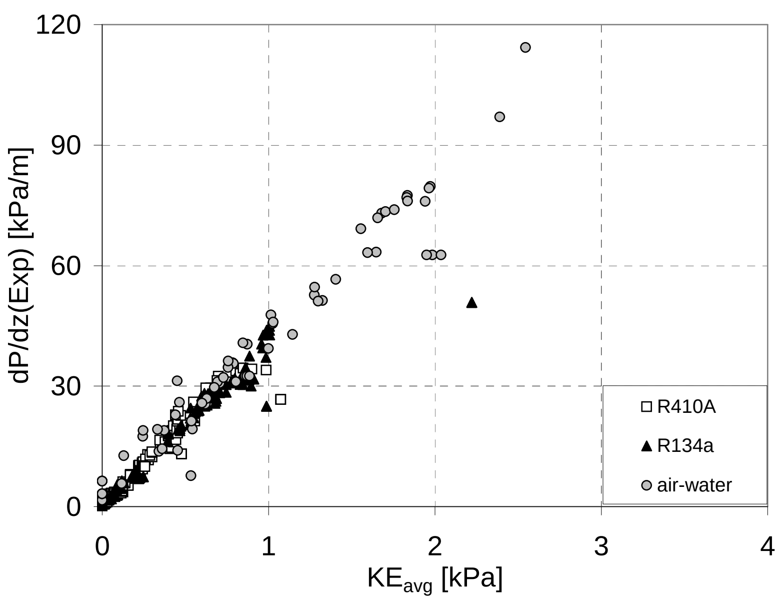
Moreover, the Lockhart-Martinelli parameter loses its sense for pressure drop predictions at low mass fluxes or with refrigerants where intermittent flow is the principal regime. Niño, Hrnjak, and Newell (2003), and Coleman and Garimella (1999) observed intermittent flow regime at low mass fluxes. The intermittent region increases with the density of the vapor.

Average Kinetic Energy Method for Pressure Drop Predictions in the Intermittent Region

As an alternative approach for predicting pressure drop, a modeling basis similar to that described for the transition sections was applied to microchannel tubes. Pressure drop data for air-water mixtures as well as refrigerants are found to correlate very well if they are plotted against the average kinetic energy of the fluid, as shown in Figure 3.



a) 6-port



b) 14-port

Figure 3: Two-phase Pressure Gradient vs. Average Kinetic Energy of the Mixture

The results suggest that the pressure drop in both 6 and 14 port microchannels also can be expressed as a function of the velocity "head" dissipated in the tube by friction in the walls and irreversibilities associated with two-phase interactions. The slope of the curves in Figure 3 is essentially constant for the range of fluids, qualities and mass fluxes examined in this study.

Figure 4 shows two-phase pressure drop plotted against the average kinetic energy divided by the hydraulic diameter. In this case, the dependence of diameter has been incorporated into the results. The experimental results of both microchannels using R134a, R410A, and air-water collapse in one curve.

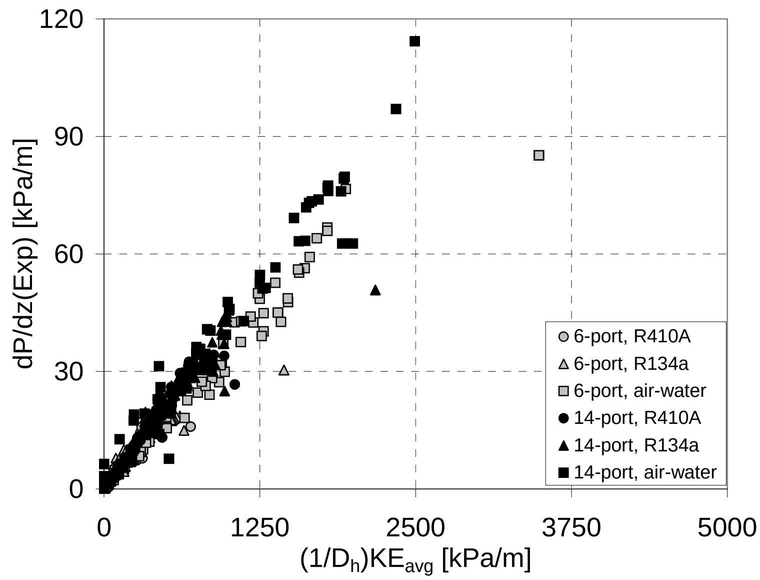


Figure 4: Two-phase Pressure Gradient vs. Average Kinetic Energy of the Mixture Divided by the Hydraulic Diameter

These results indicate that the two-phase friction factor, which is the slope of the data, is essentially constant. The value of the friction factor is approximately 0.045, which is interesting because it is approximately the same as the friction factor in the single-phase transition between laminar and turbulent flows. Additionally, this trend indicates that the dissipation of the flow's kinetic energy is nearly constant at a level of approximately 4 to 5% per tube length equivalent to the hydraulic diameter. Therefore, pressure drop in microchannels in the intermittent region can be calculated using Eq. (11):

$$\left(\frac{\Delta P}{\Delta z}\right)_{2\phi} = 0.045\frac{1}{D_h}KE_{Avg} \qquad (11)$$

where $KE_{Avg} = \frac{1}{2}\frac{G^2}{\rho_{2\phi}}$ and $\rho_{2\phi} = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l}\right)^{-1}$

The average kinetic energy method predicts the pressure drop in the microchannels except the region where fully annular flow regime is expected (mass fluxes higher than 150 kg/(s.m^2), and qualities from approximately 60% to 100% for refrigerants, and mass fluxes higher than 75 kg/(s.m^2) and qualities from approximately 40% to 100%

for air-water mixtures). It should be addressed that the range of qualities where annular flow is observed reduces when mass flux decreases. In general, the average kinetic energy method predicts pressure drop of regions where intermittent flow is the most probable flow regime (the intermittent flow region increases when vapor density increases and/or the hydraulic diameter decreases).

Although the Average Kinetic Energy Method and the Homogenous Flow Model appear to be similar, they are distinctly different. The Average Kinetic Energy Method does not calculate a friction factor based on average properties of the mixture as opposed to the Homogeneous Flow Model. It was demonstrated that this friction factor causes systematic errors at small diameters and low mass fluxes, although the definition of homogenous is valid at these ranges. The Average Kinetic Energy Method plots two-phase pressure drop against the average kinetic energy of the mixture and calculates the slope of the curve for two-phase pressure drop predictions. Looking closely at Equation 11, it is noticeable that the two-phase density ($\rho_{2\phi}$) is also calculated assuming a homogeneous void fraction. As stated above, homogenous void fraction is suitable to describe flows where the liquid and vapor phase are moving at the same velocity.

The Annular Flow Region

In summary, pressure drop in microchannels is flow regime dependent at the flow conditions specified in this study. The average kinetic energy method successfully predicts pressure drop on the intermittent flow region. However, none of the available correlations based on the separated flow model predict pressure drop correctly in the annular region when extrapolated to low mass fluxes and small diameters. All correlations are based on the development of the multiplier Φ_{lo}^2 that compares the dissipation due to the interactions between the vapor, liquid, and the walls of the pipe with the frictional dissipation assuming only liquid flowing through the pipe at the same mass flux. It was found that the systematic errors of the correlations are related to the single-phase friction factor that is calculated assuming only liquid flowing at the same mass flux of the mixture.

A new correlation is developed in this section for the annular flow region in microchannels. The correlation is also based in the separated flow model developed by Lockhart and Martinelli (1949) and Martinelli and Nelson (1948). Instead of correlating the multiplier Φ_{lo}^2, the new correlation for pressure drop predictions is based on the two-phase multiplier Φ_{vo}^2 that compares the irreversibilities of two-phase flow moving through a pipe compared with the irreversibilities of only vapor moving in the same pipe at the same mass flux.

$$\Phi_{vo}^2 = \frac{\left(\frac{dP}{dz}\right)_{2\phi}}{\left(\frac{dP}{dz}\right)_{vo}} \qquad \text{where} \qquad \left(\frac{dP}{dz}\right)_{vo} = 2 f_{vo} \frac{1}{D_h} \frac{G^2}{\rho_v} \tag{12}$$

A correlation based on the separated model can correlate either two-phase multiplier Φ_{lo}^2 or Φ_{vo}^2 as Lockhart and Martinelli (1949) suggest. The two-phase multiplier Φ_{vo}^2 was chosen to avoid systematic errors when calculating friction factor in Equation 12, because Reynolds numbers of only vapor flowing at low mass fluxes in small channels will still have turbulent behavior, therefore the friction factor value is almost constant for a wider flow conditions and fluid properties.

Experimental observations performed by Damianides and Westwater (1988), Triplett, Ghiaasiaan, Abdel-Khalik, LeMouel and McCord (1999), and Coleman (2000) have demonstrated that stratified flow regime is suppressed in tubes smaller than 2mm. They concluded that surface tension forces lift the liquid around the tube walls promoting annular flow or intermittent flow in conditions where stratified flow would be expected. Based on these findings, the effect of surface tension was analyzed for pressure drop characterization in this study. Table 1 shows that the Weber number relates the inertial forces to surface tension forces. Choosing the vapor inertial force as a reference,

$$We_v = \frac{\left(\frac{(xG)^2}{\rho_v}\right)}{\frac{\sigma}{D}} \tag{13}$$

In this case, the Weber number is used to compare the vapor inertial force with the interfacial force that the vapor needs to break barriers of liquid and promote annular flow.

The following parameter is created for the development of the multiplier Φ_{vo}^2.

$$A_{annular} = \left[\left(X_{tt} + \frac{1}{We_v^p}\right)\left(\frac{\rho_l}{\rho_v}\right)^q\right] \tag{14}$$

From the definitions stated within this study, both parameters X_{tt} and $1/We_v$ are characteristics of the annular flow. The density ratio is a variable that gives a similarity condition between two different fluids in order to be compared in the same reference system. In other words, the density ratio will adjust the dissipation and energy ratios, so all the fluids would behave dynamically similar. The Weber number is important for air-water mixtures, but does not have a significant effect on refrigerant pressure drop predictions for the diameters used in this study (1mm to 1.6mm). Surface tension of air-water mixtures is 72 mN/m compared with the surface tension of refrigerants that ranges from 7 to 10 mN/m.

Figure 5 shows the two-phase multiplier reduced with the expression $A_{annular}$ that relates the Lockhart-Martinelli parameter, the Weber number and the liquid to vapor density ratio. The graph collapses the experimental results of the 6-port and the 14-port microchannel using two-phase flows of air-water, R134a and R410A in an annular flow configuration. Values of q=0.9 p=1.3 are chosen for curve fitting.

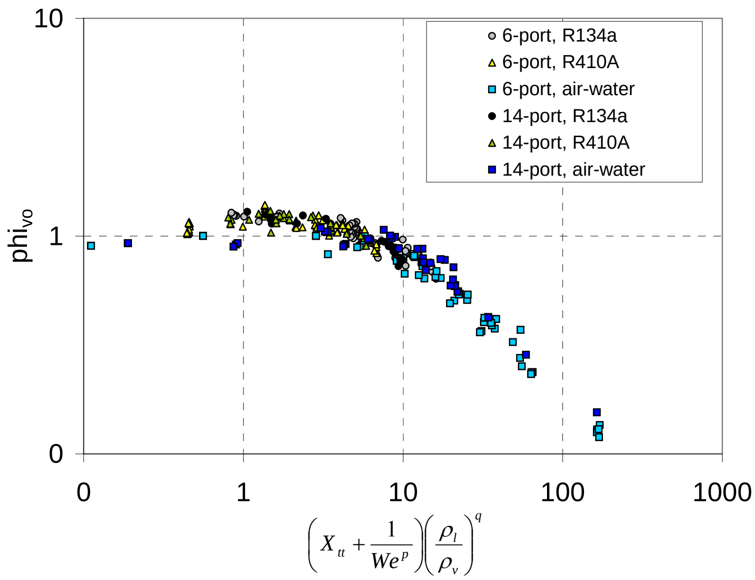


Figure 5: Experimental Results of Φ_{vo}^2 for Microchannels Reduced with Xtt, We and (ρl/ρv) to Characterize Two-phase Pressure Dropin Annular Region

Therefore, two-phase pressure drop can be predicted using the following correlation:

$$\left(\frac{dP}{dz}\right)_{2\phi}=\Phi_{vo}^2\left(\frac{dP}{dz}\right)_{vo}$$

$$\Phi_{vo}^2=\exp(-0.046X_{ann})+0.22[\exp(-0.002X_{ann})-\exp(-7X_{ann})]$$

$$X_{ann}=\left[\left(X_{tt}+\frac{1}{We_v^{1.3}}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.9}\right]$$

$$\left(\frac{dP}{dz}\right)_{vo}=2f_{vo}\frac{1}{D_h}\frac{G^2}{\rho_v} \qquad (15)$$

The Transition Region from Intermittent to Annular Behavior

A flow transition model is necessary to determine the point or region at which the transition from intermittent to annular flow regime occurs, in order to use the flow regime dependent model described above. However, generalized flow transition models have not been developed yet from the two-phase observations in small channels. Coleman (2000) is one of the first studies that predict flow transition lines for small tubes in an investigation with small tube geometries ranging from 0.424mm to 4.91mm using air-water mixtures and R134a in condensation. Based on the work of Traviss and Rohsenow (1973) and Soliman (1982), Coleman (2000) suggested a constant value of the liquid film Froude number for prediction of transitions between flow regimes. The liquid film Froude number defined in Soliman (1982) is given by Eq. (16):

$$Fr_l = 0.0244\left(\frac{\Phi_v}{X_{tt}}\right)^{1.5}\frac{\mathrm{Re}_l^{1.6}}{Ga^{0.5}} \qquad \mathrm{Re}_l \le 1250 \tag{16a}$$

$$Fr_l = 1.28\left(\frac{\Phi_v}{X_{tt}}\right)^{1.5}\frac{\mathrm{Re}_l^{1.04}}{Ga^{0.5}} \qquad \mathrm{Re}_l > 1250 \tag{16b}$$

Where

$$\Phi_v = 1 + 1.09X_{tt}^{0.039}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.875}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.125}$$

$$\mathrm{Re}_l = \frac{xGD_h}{\mu_l}$$

$$Ga = \frac{g\rho_l^2 D_h^3}{\mu_l^2}$$

Where Re_l is the liquid film Reynolds number, and Ga is the Galileo number (i.e. the ratio of gravity to viscous forces). Table 2 summarizes the liquid Froude numbers at which Coleman (2000) observed flow transition from intermittent to a different flow regime. The transitions between different flow regimes and patterns were given in a tabular form for each hydraulic diameter and fluid properties.

Table 2: Transition from Intermittent to Annular Flow Regime (Air-water) or Wavy Flow (R134a in Condensation). Investigation performed by Coleman [19]

D [mm]	Fr_l	Fluid
5.50	1.75	Air-water
2.60	2.70	Air-water
1.75	3.2	Air-water
1.30	3.5	Air-water
4.91	1.75	R134a
3.00	2.70-4.50	R134a
2.00	3.2-9	R134a
1.00	3.5-20	R134a

The present study calculated the liquid Froude number for the experimental results of two-phase pressure drop using the 6-port and the 14-port microchannel with refrigerants and air-water mixtures. The results of liquid Froude number were compared with Table 2 to identify approximately the regions where intermittent or annular flow regime occurs. The data was separated in order to analyze each flow regime independently. The regions predicted by Table 2 agree well with observations of two-phase flow in the microchannels of similar hydraulic diameter and fluid properties used in the work of Niño, Hrnjak, and Newell (2002). For R410A, the values of R134a were used because of the similarity between density ratios.

However, a general expression that could be applied to other fluids has not been developed yet. It is recommended to use the Average Kinetic Energy Method when there is no knowledge of the transition between flow regimes, nor the portion of the tube where intermittent and annular flow regime exists.

Conclusions

Pressure drop data for two rectangular port microchannel tubes were presented and analyzed. A variety of fluids were used in the experiment for a more general analysis. Experiments to measure the entrance/exit pressure drop were performed. These pressure losses were characterized by using the kinetic energy of the mixture assuming a homogeneous density. The entrance/exit effects were subtracted to isolate the pressure drop in the microchannel.

Early studies of the experimental data analyzed by Niño, Payne, Hrnjak, Newell, and Infante Ferreira (2001) concluded that pressure drop is flow regime dependent: A change from a homogeneous to an annular flow character is observed in two-phase flow pressure drop data for the refrigerants as mass flux and quality levels are increased. The homogenous flow condition tends to be one in which the flow is well-organized, resulting in a low pressure drop that is relatively insensitive to mass flux and quality changes. When the flow transitions to annular flow characteristics, higher pressure drop occurs with significant dependence on mass flux and quality conditions. Two-phase pressure drop of air-water mixtures shows an annular type behavior even for low mass fluxes.

Large tube and small tube correlations fail to predict pressure drop in the microchannels studied. Systematic errors of the correlations are caused when extrapolated to smaller diameter and/or lower mass flux range than the conditions where they were developed. In general, semi-empiric correlations create systematic errors when extrapolated to different test conditions including refrigerant properties, mass flux ranges, and tube size if the correlation fails to describe the physics of the flow. However, two-phase flow behavior is still a very difficult science to describe using physical models because of several variables that must be account for at the interface between two-phases.

Due to the dependency of the flow regime, two pressure drop models where developed. Two-phase pressure drop results with R410A, R134a, and air-water mixtures were separated based on the liquid Froude number and predictions of flow regime transition of Table 2 based on Coleman (2000).

For the intermittent flow regime, an alternative method was developed for pressure drop predictions based on the homogenous flow model which uses the average kinetic energy of the mixture. For the flow conditions and the microchannels used, the relation between the two-phase pressure drop and the average kinetic energy of the mixture is linear.

$$\left(\frac{\Delta P}{\Delta z}\right)_{2\phi} = 0.045\frac{1}{D_h}KE_{Avg} \quad \text{where} \quad KE_{Avg} = \frac{1}{2}\frac{G^2}{\rho_{2\phi}} \quad \text{and} \quad \rho_{2\phi} = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_l}\right)^{-1} \qquad (11)$$

For the annular flow regime, a new correlation based in the separated flow model of Lockhart and Martinelli (1949) was developed. The correlation uses a two-phase multiplier that compares the dissipation of the two-phase flow, compared to the dissipation of only vapor flowing at the same mass flux. The multiplier is a function of the Lockhart-Martinelli parameter, the Weber number, and the liquid to vapor density ratio. Two-phase pressure drop in the annular flow regime can be predicted with the following correlation:

$$\left(\frac{dP}{dz}\right)_{2\phi} = \Phi_{vo}^2 \left(\frac{dP}{dz}\right)_{vo} \tag{15}$$

$$\Phi_{vo}^2 = \exp(-0.046 X_{ann}) + 0.22[\exp(-0.002 X_{ann}) - \exp(-7 X_{ann})]$$

$$X_{ann} = \left[\left(X_{tt} + \frac{1}{We_v^{1.3}}\right)\left(\frac{\rho_l}{\rho_v}\right)^{0.9}\right]$$

$$\left(\frac{dP}{dz}\right)_{vo} = 2 f_{vo} \frac{1}{D_h} \frac{G^2}{\rho_v}$$

The density ratio is found to be an important parameter that gives a similarity condition between mixtures of different properties. In other words, pressure drop correlations based on a reduced range of fluid properties can be adapted for pressure drop predictions with different properties by using the liquid to vapor density ratio.

It should be addressed that the pressure drop correlation developed in this study is flow regime dependent. Therefore, when describing flows at quality of zero (all liquid) and quality of one (all vapor), single-phase flow equations must be applied to these cases, because it is a completely different flow regime and no interactions between phases.

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