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LOCAL FRICTIONAL PRESSURE DROP DURING VAPORIZATION OF R-12 THROUGH CAPILLARY TUBES

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Abstract—The local frictional pressure drop during vaporization of R-12 along capillary tubes is experimentally investigated. A model for the prediction of the local frictional pressure drop of two-phase flows during vaporization of R-12 in capillary tubes is presented. This model agrees with the experimental data to within a relative error of about 15%.

Key Words: liquid–vapor two-phase flow, vaporization, frictional pressure drop, refrigerant, capillary tube, refrigeration, metastable flow, flashing flow.

1. INTRODUCTION

A capillary tube is a simple tube, having a diameter of about 1 mm, which is usually used as an expansion and refrigerant flow rate controlling device for small-sized refrigerating systems and household refrigerators. Because a flashing process occurs in the flow of refrigerant in a capillary tube, the flow is separated into two regions, a single liquid region and a liquid–vapor two-phase region. Because the quality of the refrigerant varies along the tube, the frictional pressure drop for two-phase flow during the vaporization process in a capillary tube is difficult to determine. Studies on the frictional pressure drop of two-phase flows in large diameter tubes have been conducted by many researchers (e.g. Martinelli & Nelson 1948; Lockhart & Martinelli 1949; Barroczy 1966; Chisholm & Rooney 1974). For capillary tubes, Mikol (1963) obtained the ratio of the mean frictional pressure drop coefficients for the flow with vaporization to that of the flow without vaporization in the whole tube, which was equal to 0.95. Cooper *et al.* (1957) correlated an expression for the two-phase frictional pressure drop which is a function of the exit quality of the refrigerant. Whitesel (1957a) used the inlet quality and the average value of the inlet and exit quality (Whitesel 1957b) to express the two-phase flow frictional pressure drop. Koizumi & Yokohama (1980) correlated the frictional pressure drop coefficient based on the Blasius equation for smooth tubes, and Ghosal & Sen (1980) carried out experimental research on this subject using a gas–liquid mixture without vaporization. It should be noted that, in all of the above-mentioned investigations, the local frictional pressure drop and the effect of the roughness of the capillary tube were not taken into consideration. In the present paper, the local frictional pressure drop is investigated with regard to the variation in the quality of the refrigerant along the capillary tube and the roughness of the capillary tube.

2. EXPERIMENTATION

Figure 1 shows a schematic diagram of the experimental system using R-12 as the working medium. The system consists of two compressors (1, 2), two condensors (4, 5), an evaporator (13) and a test section (14), which is the experimental capillary tube serving as an expansion device. In the system, there is an oil separator (3), a filter (11), two liquid refrigerant receivers (6, 7) and an oil accumulator (9). The subcooler (8) and electric heater (10) are used to control the temperature of the refrigerant at the inlet of the test section. The mass flow rate of the refrigerant is measured by a "micro motion" flow rate meter (12) which has precision of 0.4%.

The temperatures and pressures along the capillary tube are measured by thermocouples and precision piezometers, respectively. The maximum uncertainties are 0.3°C and ± 0.04 bar for the

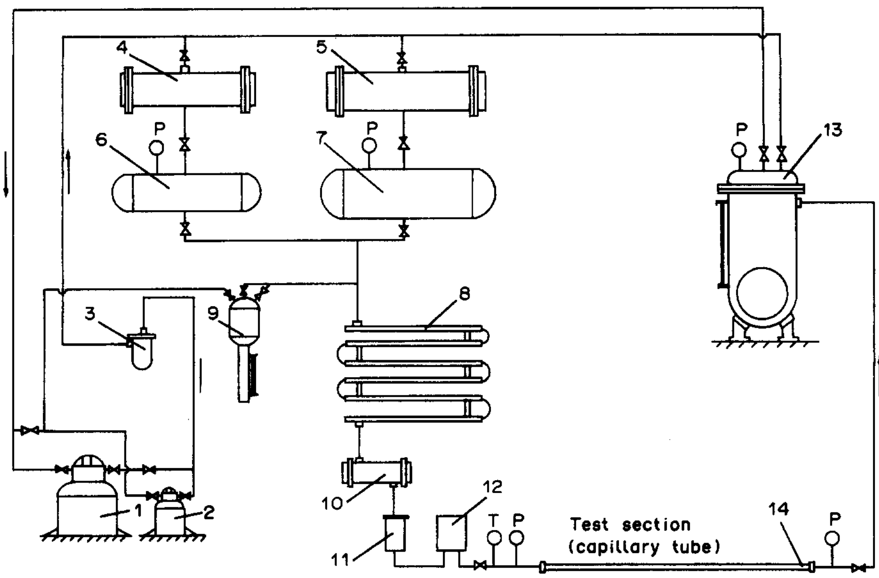

Figure 1. Schematic diagram of the test apparatus: 1, 2—compressor; 3—oil separator; 4, 5—condenser; 6, 7—receiver; 8—subcooler; 9—oil accumulator; 10—electric heater; 11—filter; 12—flow rate meter; 13—evaporator; 14—capillary tube.

temperature and pressure measurements. The distance between two thermocouples is 10 cm near the inlet of the tube and 7.5 cm near the exit, because the change in temperature is larger near the exit. Similarly, the distance between two piezometers is 20 cm near the inlet and 15 cm near the exit.

Two capillary tubes made of copper were used for the present study. They are 1.50 m long, and 0.66 and 1.17 mm i.d., respectively. The ranges of variation of the parameters in the present investigation are as follows:

Inlet temperature	290–326 K
Inlet pressure	6.3–13.2 bar
Inlet subcooling	0–17 K
Mass flux	$(1.44–5.09) \times 10^3$ kg/s · m^2.

A total of 238 sets of data have been recorded in the present study.

3. DISTRIBUTIONS OF QUALITY AND PRESSURE DROP ALONG CAPILLARY TUBES

To determine the position of the inception of vaporization in the experimental capillary tubes, the saturated pressures corresponding to the temperatures measured along the tube were calculated from the equation of state of R-12 from ASHRAE (1976) and plotted together with the pressures measured along the tube in figure 2. Before vaporization of the refrigerant in the capillary tube, the measured temperature of the refrigerant is nearly constant. However, the measured pressure decreases linearly due to the friction losses. At the intersection point of the two pressure curves (a), the measured pressure is equal to the saturated pressure; therefore, the refrigerant is saturated at the intersection point. It can be seen that vaporization does not take place at the intersection. After point a, both the calculated saturated pressure, $P_{s,c}$, and the measured pressure, P_m, follow their original respective directions until they reach section bb′, as shown in figure 2. At point b, $P_{s,c}$ suddenly drops—this is due to the temperature drop caused by absorption of the latent heat of vaporization of the refrigerant at this point. After point c, the two pressure curves join, indicating that $P_m = P_{s,c}$. This means that the thermodynamic equilibrium state is reached after point c. From the above discussion, the flow conditions of the refrigerant in the capillary tube can be described as in table 1.

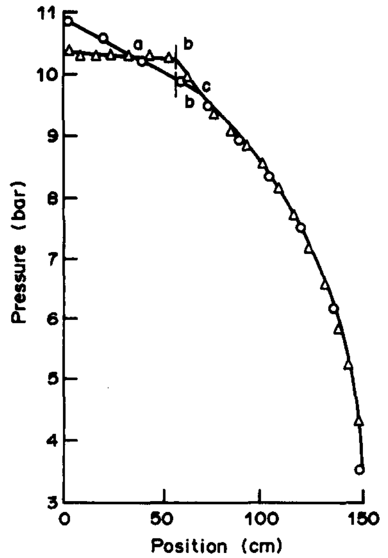

Figure 2. Distributions of measured pressure, P_m, and the saturated pressure calculated from the corresponding temperature measured, $P_{s,c}$, along the capillary tube. Inlet pressure = 10.8 bar, inlet temperature = 316 K, back pressure = 3.0 bar, mass flux = 3975 kg/s · m². △, $P_{s,c}$; ○, P_m.

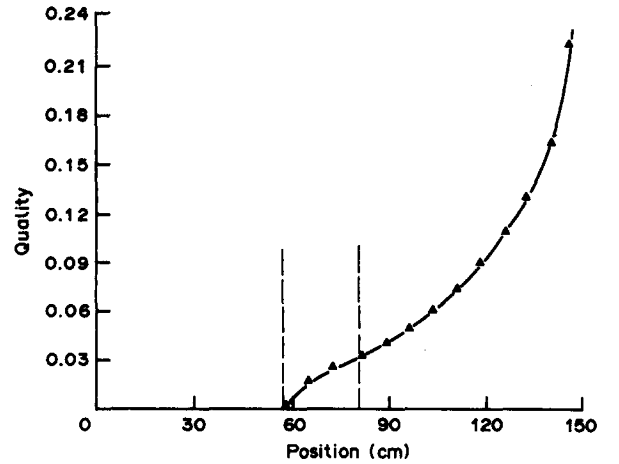

Figure 3. Distribution of quality along a capillary tube. $D = 1.17$ mm, $G = 3975$ kg/s · m², $T_i = 316$ K, $\Delta T = 2$ K.

Because the experimental capillary tube is insulated, the flow of refrigerant can be considered as adiabatic. The energy equation in the two-phase flow region can be written as

$$h_0 = h_t + \frac{(\dot{m}v_t)^2}{2}, \qquad [1]$$

where h_0 and $\dot{m}$ are the stagnation specific enthalpy and the mass flux; and h_t and v_t are the specific enthalpy and the specific volume of the liquid–vapor mixture, which can be expressed as

$$h_t = xh_G + (1 - x)h_L \qquad [2]$$

and

$$v_t = xv_G + (1 - x)v_L, \qquad [3]$$

where x is the quality. Combining [1]–[3], the following equation for the quality, x, is obtained:

$$C_1 x^2 + C_2 x + C_3 = 0, \qquad [4]$$

where

$$C_1 = \frac{\dot{m}^2}{2}(v_G - v_L)^2, \qquad [5]$$

$$C_2 = (h_G - h_L) + v_L \dot{m}^2 (v_G - v_L) \qquad [6]$$

and

$$C_3 = \tfrac{1}{2}\dot{m}^2 v_L^2 + h_L - h_0, \qquad [7]$$

Table 1

From	To	Flow condition
Entrance	Point a	Subcooled, single-phase liquid
Point a	Section bb′	Metastable, single-phase liquid
Section bb′	Point c	Metastable, liquid–vapor two-phase
Point c	Exit	Thermodynamic equilibrium liquid–vapor two-phase

where v_G and v_L are the specific volumes of the vapor and liquid, and h_G and h_L are the specific enthalpies of the vapor and liquid, respectively. The values of v_L, v_G, h_L and h_G at any position in the capillary tube can be calculated, using the equation of state of the working medium, from the measured local temperature or pressure. The quality x can then be obtained by solving the quadratic equation [4]. The result calculated for a capillary tube with $D = 1.17$ mm i.d., $\dot{m} = 3975\ \mathrm{kg/s \cdot m^2}$, $T_i = 316$ K and $\Delta T_{sc} = 2$ K, is shown in figure 3. The curve of the quality indicates that the variation in the quality along the capillary tube is non-linear. From point b to c, the region of two-phase metastable flow, the quality increases rapidly near point b. After point c, the region of the thermodynamic equilibrium two-phase flow, the quality increases more and more rapidly as the flow approaches the exit. Because of the non-linearity of the quality along the capillary tube, an appreciable error would be introduced if the frictional pressure drop was determined using the inlet quality, exit quality or the averaged value of the inlet and exit qualities.

From experimental results, Koizumi & Yokohama (1980) confirmed that the two-phase flow in capillary tube can be approximated as homogeneous. For a homogeneous two-phase flow in a horizontal tube, the momentum equation can be written as

$$\frac{dP}{dZ} = -\dot{m}^2 \frac{dv_t}{dZ} + \left(\frac{dP}{dZ}\right)_f, \qquad [8]$$

where P is the pressure and Z is the axial length variable. In [8], the term on the l.h.s. is the total pressure drop, the first term on the r.h.s. is the accelerational pressure drop and the last term represents the frictional pressure drop.

In order to obtain the distribution of the frictional pressure drop along a capillary tube, the region of two-phase flow is divided into n sections with $Z_v = Z_1, Z_2, \ldots, Z_{n+1} = Z_{exit}$. In each section, the frictional pressure drop $(dP/dZ)_f$ may be taken approximately as constant. Equation [8] then becomes

$$\frac{P_{i+1} - P_i}{\Delta Z} = -\dot{m}^2 \frac{(v_{i+1} - v_i)}{\Delta Z} + \left(\frac{\Delta P}{\Delta Z}\right)_f. \qquad [9]$$

The value of the total pressure drop in section i, $P_{i+1} - P_i$, can be taken from the experimental data. For the accelerational pressure drop, $\dot{m}$ is a measured quantity; the specific volumes v_i and v_{i+1} can be determined using the measured pressure or temperature, and by using the quality x determined by [4]. The frictional pressure drop $(\Delta P/\Delta Z)_f$ can then be evaluated. The distributions of the total pressure drop, the accelerational pressure drop and the frictional pressure drop along a capillary tube with 1.17 mm i.d. are shown in figure 4 for the same experimental conditions as in figure 3.

Figure 4 shows that in the single-phase liquid region, the total pressure drop is equal to the frictional pressure drop, which is almost constant, and that the accelerational pressure drop is zero.

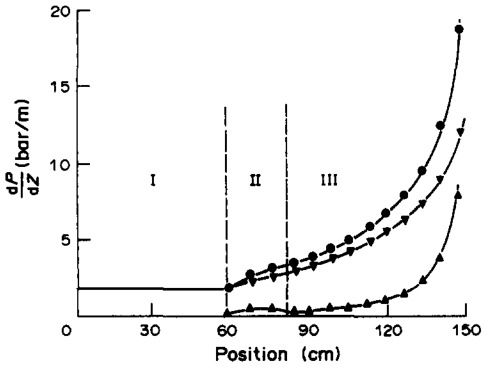

Figure 4. Distribution of pressure drop along a capillary tube. I, single-phase liquid flow region; II, metastable two-phase flow region; III, thermodynamic equilibrium two-phase flow region. ●, total pressure drop; ▼, frictional pressure drop; ▲, accelerated pressure drop.

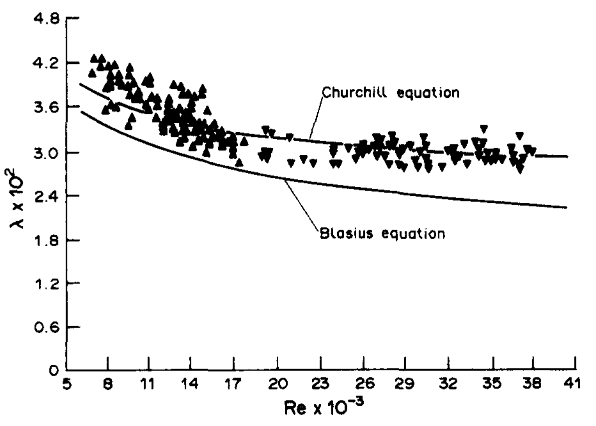

Figure. 5. Comparison of the frictional pressure drop coefficients calculated from Churchill's equation and Blasius's equation with the experimental data. ▲—$D = 0.66$ mm, $\varepsilon = 2.0 \times 10^{-6}$ m; ▼—$D = 1.17$ mm, $\varepsilon = 3.5 \times 10^{-6}$ m.

After the inception of vaporization in the region of two-phase metastable flow, the accelerational pressure drop suddenly appears due to sudden flashing. In the region of thermodynamic equilibrium two-phase flow, both the accelerational and frictional pressure drops increase more rapidly, as the flow approaches the exit of the capillary tube.

4. CORRELATION OF FRICTIONAL PRESSURE DROP

In the single-phase liquid flow region, the experimental value of the frictional pressure drop, obtained from the present study, is about 20% higher than that calculated using the Blasius equation for smooth tubes, which is often used in the investigation of the frictional pressure drop for two-phase flow in capillary tubes (Cooper *et al.* 1957; Koizumi & Yokohama 1980). This is because the diameter of a capillary tube is so small that the relative roughness ε/D has a remarkable effect on the shear stress at the wall. In order to include the relative roughness factor, Churchill's equation (Churchill 1977) for the determination of the coefficient of frictional pressure drop is used:

$$\lambda = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + \frac{1}{(\mathrm{A}+\mathrm{B})^{3/2}}\right]^{1/12}. \qquad [10]$$

In the above equation,

$$\mathrm{A} = \left\{2.457 \ln\left[\frac{1}{\left(\frac{7}{\mathrm{Re}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}}\right]\right\}^{16}, \qquad [11]$$

$$\mathrm{B} = \left(\frac{37530}{\mathrm{Re}}\right)^{16} \qquad [12]$$

and

$$\mathrm{Re} = \frac{\dot{m}D}{\eta}, \qquad [13]$$

where ε is the roughness, D is the tube diameter and η is the dynamic viscosity of the liquid. Equation [10] covers the whole range of Re. In the present study, the experimental range of Re is $4.64 \times 10^3 < \mathrm{Re} < 3.76 \times 10^4$. The roughness of the experimental capillary tubes was measured and found to be 2.0×10^{-6} and 3.5×10^{-6} m when $D = 0.66$ and 1.17 mm, respectively. The coefficients of the frictional pressure drop determined by [10], in comparison with the experimental data, have the standard relative errors of 6.1 and 4.8% for $D = 0.66$ and 1.17 mm, respectively, as illustrated in figure 5.

For the presentation of the frictional pressure drop in the two-phase flow region, $(\mathrm{d}P/\mathrm{d}Z)_t$, in terms of the frictional pressure drop in the single liquid flow regions, $(\mathrm{d}P/\mathrm{d}Z)_{lo}$, we use a multiplier (Martinelli & Nelson 1948; Lockhart & Martinelli 1949), defined by

$$\phi_{lo}^2 = \frac{\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_t}{\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_{lo}}, \qquad [14]$$

where

$$\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_t = \frac{\lambda_t}{D}\frac{\dot{m}^2}{2}v_t \qquad [15]$$

and

$$\left(\frac{\mathrm{d}P}{\mathrm{d}Z}\right)_{lo} = \frac{\lambda_{lo}}{D}\frac{\dot{m}^2}{2}v_L. \qquad [16]$$

Equation [10] is used to determine both the frictional pressure drop coefficients, λ_t, in [15] and λ_{lo} in [16]. Substituting [15] and [16] into [14], we obtain, by utilizing [3],

$$\phi_{lo}^2 = \left[\frac{\left(\frac{8}{\mathrm{Re}_t}\right)^{12} + \frac{1}{(\mathrm{A}_t+\mathrm{B}_t)^{3/2}}}{\left(\frac{8}{\mathrm{Re}_{lo}}\right)^{12} + \frac{1}{(\mathrm{A}_{lo}+\mathrm{B}_{lo})^{3/2}}}\right]^{\frac{1}{12}} \left[1 + x\left(\frac{v_G}{v_L} - 1\right)\right]. \qquad [17]$$

In [17], Re_t is defined as $\mathrm{Re}_t = \dot{m}D/\eta_t$, where η_t is the dynamic viscosity of the two-phase mixture. For the range of experimental Re in the present study, it can be shown that

$$\left(\frac{8}{\mathrm{Re}_t}\right)^{12} \ll \frac{1}{(\mathrm{A}_t + \mathrm{B}_t)^{3/2}},$$

$$\left(\frac{8}{\mathrm{Re}_{lo}}\right)^{12} \ll \frac{1}{(\mathrm{A}_{lo} + \mathrm{B}_{lo})^{3/2}},$$

$$\mathrm{B}_{lo} \ll \mathrm{A}_{lo}$$

and

$$\mathrm{B}_t \ll \mathrm{A}_t.$$

Equation [16] can then be written as

$$\phi_{lo}^2 = \left\{ \frac{\ln\left[\left(\frac{7}{\mathrm{R}_{lo}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]}{\ln\left[\left(\frac{7}{\mathrm{Re}_t}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]} \right\}^{16} \left[1 + x\left(\frac{v_G}{v_L} - 1\right)\right]. \qquad [18]$$

Note that the viscosity η_t used in the Re for the liquid–vapor two-phase flow in [17] and [18] is different from that for the single-phase liquid flow. The Re in the vapor–liquid mixture usually depends on the flow pattern. Some investigations have been reported for the two-phase flow patterns of refrigerants in capillary tubes. Cooper *et al.* (1957) from observations of refrigerant flow in a capillary tube by the naked eye found that the mixture can best be described as "fog flow". The experiments of Mikol & Dudley (1964), with the aid of a high-speed flash device, reveal the flow to be composed of a stream of small bubbles originating at or close to the tube wall. These bubbles increase in size and then the flow becomes a uniform spray of liquid droplets borne by vapor. Koizumi & Yokoyama (1980) also reported that the greatest flow in a capillary tube is a high-speed bubble flow. Zhang *et al.* (1990) reported a low velocity ratio between the vapor and the liquid of a refrigerant in a capillary tube in the critical flow state. In their calculation the value of the velocity ratio was in the range of 1.18–1.24. Petry (1983) also conducted research on the two-phase flow pattern and velocity ratio between the vapor and liquid in the critical flow state. The experimental results showed that in the critical flow state, the flow patterns of the liquid–vapor mixture of the refrigerant in the capillary tubes were mainly fog flow, bubble flow and churn flow. Petry (1983) also presented a formula for the velocity ratio for his research conditions:

$$\log S_c = \frac{1}{\mathrm{A}(\log x)^2 + \mathrm{B}\log x + \mathrm{C}}, \qquad [19]$$

where A = 6.3014, B = 25.5632 and C = 23.3784.

The velocity ratio, S_c, between the vapor and liquid in the critical flow state, as a function of the quality x [obtained by Petry (1983)], is shown in figure 6. From the curve of S_c in figure 6, it is observed that S_c has a maximum value of 5.5 at $x = 0.013$ and is <2 after $x > 0.05$. However, the distance of the capillary tube from $x = 0$ to $x = 0.05$ is a small part of the total two-phase flow region, as shown in figure 3. It is also noted that in the region of $x < 0.05$, due to the small void fraction, the effect of the quality on the frictional pressure drop is relatively small compared with that in the region of $x > 0.05$. So the hypothesis of a low velocity reatio in the whole of the two-phase flow region is acceptable for simplification. For a homogeneous two-phase flow, the viscosity η_t is usually presented either in the form of (McAdams *et al.* 1942):

$$\frac{1}{\eta_t} = \frac{x}{\eta_G} + \frac{1-x}{\eta_L}; \qquad [20]$$

or (Cicchitti *et al.* 1960)

$$\eta_t = x\eta_G + (1-x)\eta_L; \qquad [21]$$

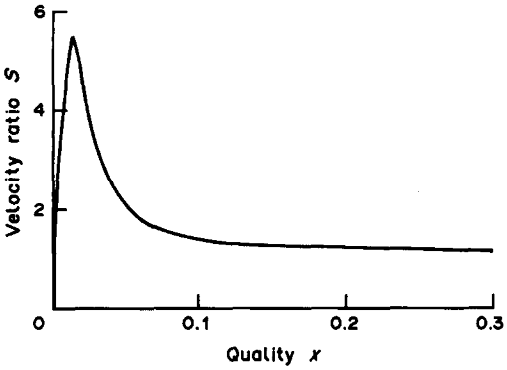

Figure 6. Velocity ratio between the vapor and liquid in the critical flow state vs quality (Petry 1983).

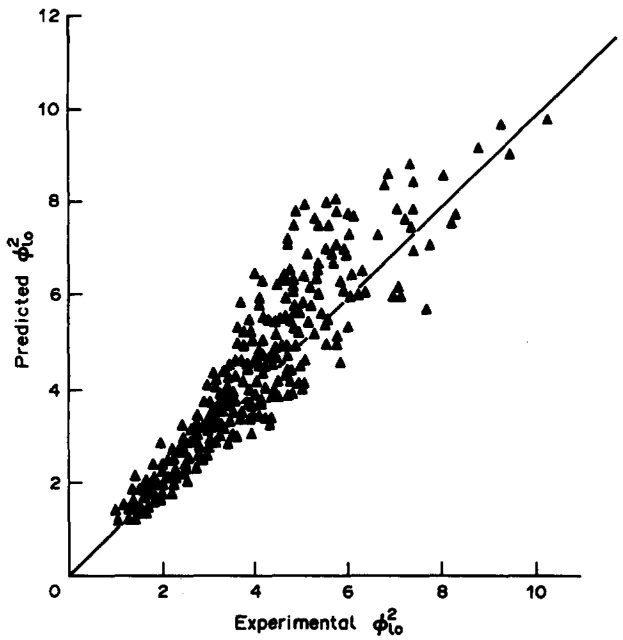

Figure 7. Prediction of ϕ^2_{lo} compared with the experimental data.

where η_G and η_L are the dynamic viscosities of the vapor and liquid, respectively. By calculation, it is known that when using [20] or [21] for the viscosity of the liquid–vapor mixture, the difference between the ϕ^2_{lo} value calculated from [18] and the experimental data is about 24%. The main reason for this difference is that, as mentioned above, in the two-phase flow region, there is a low velocity ratio between the vapor and the liquid. In order to obtain an appropriate prediction of the frictional pressure drop coefficient in the two-phase flow region, the equation for the determination of the viscosity η_t needs to be modified. As shown by results of Zhang *et al.* (1990) and Petry (1983), the velocity ratio does not vary much in the greater part of the two-phase flow region. So a simple modification for x in the expression of viscosity for homogeneous flow [20] is sufficient:

$$\eta_t = \frac{\eta_L \eta_G}{\eta_G + x^n(\eta_L - \eta_G)}. \qquad [22]$$

The exponent n in [22] was determined from the experimental data. In the present study, the range of x appearing in the capillary tubes is $0 < x < 0.25$. For the best fit to the experimental data, the value of the exponent n in [22] is taken as 1.4. Figure 7 shows the comparison of ϕ^2_{lo}, calculated from [18], using [22], with the experimental data, which has a standard relative error of 15.3%.

Figure 8 shows that the variation of ϕ^2_{lo} is a function of x with the local pressure, p, as a parameter for $D = 1.17$ mm, $\varepsilon/D = 3 \times 10^{-3}$ and $G = 3000$ kg/s · m^2. From the curves, it is known that ϕ^2_{lo} increases remarkably with x. The effect of p on ϕ^2_{lo} is as follows: the decrease in ϕ^2_{lo} is weaker at higher p than that at lower p because the volume of the vapor is smaller at higher p. The effect of the mass flux, $\dot{m}$, on ϕ^2_{lo} is shown in figure 9. It can be seen that the effect of $\dot{m}$ on ϕ^2_{lo} is almost negligible.

5. CONCLUSIONS

1. For single-phase liquid flow in a capillary tube, the roughness of the tube wall has a distinct effect on the frictional pressure drop coefficient. Experimental results confirm that Churchill's equation (Churchill 1977) for the determination of frictional pressure drop coefficient is applicable to the flow in capillary tubes.
2. A model for the prediction of the frictional pressure drop in the liquid–vapor two-phase flow region in capillary tubes has been presented. The result obtained from the model is in good agreement with the experimental data. The standard relative error involved in the prediction is about 15%.

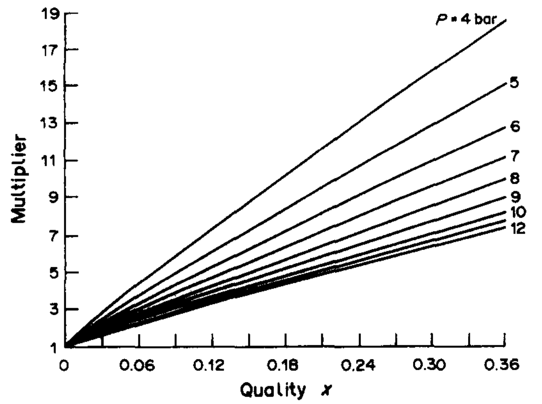

Figure 8. Predicted ϕ_{lo}^2 by [18] as a function of x with p as a parameter. $D = 1.17$ mm, $\varepsilon/D = 3 \times 10^{-3}$, $\dot{m} = 3000$ kg/s · m².

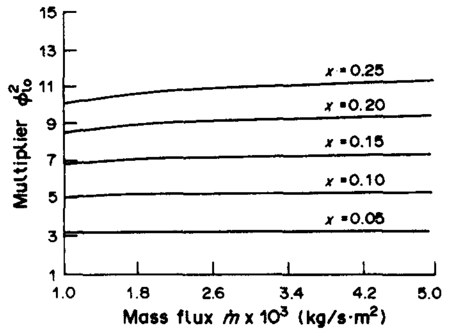

Figure 9. Predicted ϕ_{lo}^2 by [18] as a function of $\dot{m}$ with x as a parameter. $D = 1.17$ mm, $\varepsilon/D = 3 \times 10^{-3}$, $\dot{m} = 3000$ kg/s · m², $P = 5$ bar.

3. For an adiabatic capillary tube, the variation of the quality along the tube is non-linear. The quality increases more rapidly close to the exit of the capillary tube. This results in a strong increase in the multiplier ϕ_{lo}^2 near the exit of the capillary tube.

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