Two-Phase Wall and Interfacial Friction Forces in Triangle Tight Lattice Rod Bundle Subchannel *

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Abstract
In order to obtain the data on wall and interfacial friction forces for two-phase flows in a triangle tight lattice subchannel, adiabatic experiments were conducted for single- and two-phase flows under hydrodynamic equilibrium flow conditions. In the experiment, air was used as the test gas, while water and water with a surfactant as test liquids to know the effects of the reduced surface tension on the wall and the interfacial friction forces. The data showed that both the wall and the interfacial friction forces were higher in air-water with a surfactant system than air-water one. In the analysis, the respective data have been compared with the predicted values by existing correlations, and the existing correlations were modified to improve its prediction accuracy against the present data. The modified correlations can predict well the present data on the wall and the interfacial friction forces for both air-water and air-water with a surfactant systems.

Key words: Two-Phase Flow, Wall Friction, Interfacial Friction, Tight Lattice Rod Bundle, Subchannel.

1. Introduction
A triangle tight lattice rod bundle is planning as the next generation BWR fuel rod bundle in Japan(1). The hydraulic diameter and the cross-sectional area of the subchannel in the triangle tight lattice rod bundle are extremely small and are respectively about a quarter and one-eighth of those of the center subchannel of the square array bundle in a typical BWR. In addition, most correlations for calculating two-phase flow parameters, such as void fraction and pressure drop, have never been based on the experimental data on small diameter channels less than 10 mm. Therefore, the applicability of such correlations to the flow in the tight lattice rod bundle subchannel is doubtful. In this connection, the first purpose of this study is to provide experimental data needed to examine the existing correlations on the two-phase flow parameters since the published data on such flow parameters is limited in the triangle tight lattice subchannel(2). The second purpose is to develop a new correlation applicable to the present experimental data.

In the experiments, a vertical multiple channel with two subchannels simplifying the triangle tight lattice rod bundle was used as the test channel to obtain the data on wall and interfacial friction forces for two-phase flows, and at first water and air at room temperature and near atmospheric pressure were used as the test fluids. However, the surface tension of the fluid in an actual fuel rod bundle is much lower than that for air-water system since the flow is a steam-water one at high-temperature and high-pressure. Thus, in order to know the effects of the reduced surface tension on the wall and the interfacial friction forces.
forces, additional experiments were conducted for air-water with a surfactant system. In the system, the surface tension was about 0.6 times of that for air-water system.

In the analyses, both the wall and the interfacial friction forces data have been compared with the predicted values by correlations in literature as well as by the newly developed one. Results of such experiments and analyses are described in this paper.

2. Experiments

2.1 Test channel and measurement

Figure 1 shows the cross-section of the present test channel, being the same as our previous studies (3-7). The channel consisted of two identical subchannels, each surrounded by three partial rods in a triangular array. In order to get hydraulically smooth inner walls and to observe a flow, the test channel was machined from transparent acrylic slabs and polished quite well. No spacer was inserted in the channel.

Figure 2 shows the construction of the test apparatus. The section was mainly divided into three sections, an entry (0.31 m in length), a test (1.6 m) and a discharge (0.31 m) sections from the bottom to the top.

After measuring the inlet gas and the liquid flow with calibrated rotameters and positive displacement flowmeters within the uncertainties of 1% and 3%, the fluids were introduced into each subchannel from a mixer. In order to set a hydrodynamic equilibrium flow in the test section, the flow rate of each phase introduced had to be the same between the subchannels.

The pressure drop, \( \frac{dP}{dz} \), and the system pressure (gauge pressure at the mid point of the test section), \( P_{sys} \), were measured with differential-type and gauge-type pressure transducers within \( \pm 1\% \) and \( \pm 2\% \). Some pictures were taken with a high speed video camera and a digital still camera to observe the flow regime. The mean void fraction for the two subchannels had been measured with well-known quick shut valve method by Sadatomi et al. (7). The accuracy of void fraction data was within 1%. These pressure drop and void fraction data were used to determine the wall and the interfacial friction force data.

2.2 Determination of wall and interfacial friction force data

The two-phase wall friction force per unit volume, \( F_{Ww} \), which is the same as the frictional pressure gradient, \( \frac{dP}{dz} \), was determined by subtracting the gravitational and the accelerational components from the measured total pressure gradient, as follows:

\[
F_{Ww} = \frac{dP}{dz} = \frac{dP}{dz} \left( \frac{\rho_g \alpha + \rho_l (1 - \alpha)}{\rho_{w,eff} v_0 + \rho_l j \beta u_0} \right). \tag{1}
\]

The contribution of the acceleration component was very small and was 0.01% to 3% of the total pressure gradient in the present experimental range. The gas-liquid interfacial friction force, \( F_I \), was determined from...
\[
F_i = -\rho_0 j_i \frac{du}{dZ} - \rho_g \alpha - \frac{\alpha dP}{dZ}, \tag{2}
\]

where
\[
\frac{du}{dZ} = -\frac{j_i}{\alpha} \left( \frac{1}{\rho_0} \frac{dP}{dZ} + \frac{1}{\alpha} \frac{d\alpha}{dZ} \right). \tag{3}
\]

These equations are derived from momentum equations for the gas and the liquid in steady, adiabatic and one-dimensional two-fluid model\(^{(8)}\), and their details are given by Tsubone et al.\(^{(9)}\).

### 2.3 Experimental conditions

Air at room temperature and at near atmospheric pressure was used as the test gas, while water and water with a surfactant called Polyoxyethylene Laury Ether as the test liquid. Table 1 lists properties of the present test liquids at 20 °C. PLE, the abbreviation of water with the surfactant, were used to study the effects of the reduced surface tension on the flow behavior. The table shows that the surface tension of PLE is about 60% of that of water, but the density and the viscosity are almost the same between them. The ranges of volumetric fluxes of the liquid and the gas in the channel as a whole were 0.1 \( \leq j_L \leq 2.0 \) m/s and 0.3 \( \leq j_G \leq 37 \) m/s. The range of the void fraction was 0.12 < \( \alpha \) < 0.96. Flow patterns observed were bubble flow, slug or churn flow and annular flow.

### Table 1 Properties of test liquids at 20 °C

<table>
<thead>
<tr>
<th>Liquids</th>
<th>( \sigma ) [N/m]</th>
<th>( \rho ) [kg/m(^3)]</th>
<th>( \mu ) [mPa( \cdot )s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.072</td>
<td>998.2</td>
<td>1.002</td>
</tr>
<tr>
<td>PLE</td>
<td>0.042</td>
<td>998.2</td>
<td>0.981</td>
</tr>
</tbody>
</table>

### 3. Results and Discussions

#### 3.1 Wall friction data

**3.1.1 Friction factor in single-phase liquid flow**

Figure 3 shows friction factor data obtained from the single-phase liquid flow experiments. The ordinate is the Darcy friction factor, \( f_D \), and the abscissa the Reynolds number, \( Re \). Data points are labeled according to the working liquids. No significant difference is seen between water and PLE data.

![Fig. 3 Darcy friction factor data in the present tight lattice subchannel](image-url)

Broken lines are the calculations by Hagen-Poiseuille’s equation for laminar flow and Blasius’ equation for turbulent flow, while solid line by Churchill’s correlation\(^{(10)}\) modified with a geometry factor by Rehme\(^{(11)}\) for laminar flow and Sadatomi et al.\(^{(12)}\) for turbulent flow. The geometry factors are \( C_l = 80.1 \) and \( C_t = 0.3303 \) respectively for laminar and turbulent flows. The transition Reynolds number from laminar to turbulent flows was taken to be \( Re_l = 1400 \) based on our observation\(^{(5)}\). The friction factor data agree with the calculation by the modified Churchill’s correlation within ±25%.

**3.1.2 Two-phase frictional pressure drop data**

Figure 4 shows the data on two-phase frictional pressure drop, \( dP/dZ \), being the same as the friction force between the...
liquid and channel wall, \( F_{WL} \), because the wall is always wetted by the liquid under the present flow conditions. The data for air-water and air-PLE systems are plotted against the gas volumetric flux, \( j_G \), and the liquid flux, \( j_L \), as a parameter. \( F_{WL} \) for both systems increase with \( j_G \) at a fixed \( j_L \). In general, \( F_{WL} \) is higher in air-PLE system than air-water one. According to our previous study\(^7\), the void fraction is higher in air-PLE system than air-water one, i.e., the void fraction increases with decreasing of the surface tension. Thus, mean liquid velocity, \( u_L = j_L / (1 - \alpha) \), increases with decreasing of the surface tension. As a result, the wall friction force becomes high in lower surface tension system (i.e., air-PLE one).

**Fig. 4** Two-phase frictional pressure drop data for the present tight lattice subchannel

Figure 5 shows the data on the two-phase frictional multiplier\(^{13}\) defined as

\[
\phi^2 = \left( \frac{dP_f}{dZ} \right)_L / \left( \frac{dP_f}{dZ} \right)_G, \tag{4}
\]

where \( (dP/dZ)_L \) is the frictional pressure gradient when the liquid in the two-phase mixture flows alone in the same channel. The abscissa is the Lockhart-Martinelli parameter, \( X \), given by

\[
X^2 = \left( \frac{dP_f}{dZ} \right)_L / \left( \frac{dP_f}{dZ} \right)_G, \tag{5}
\]

where \( (dP/dZ)_G \) is the frictional pressure gradient when the gas flows alone in the same channel. The multiplier is higher in air-PLE system than air-water one. Weak effects of the liquid volumetric flux are seen on the data for both systems. The multiplier increases with \( j_L \) at a fixed \( X \).

**Fig. 5** Two-phase frictional multiplier data for the present tight lattice subchannel

Five solid lines are the calculation of the following Chisholm-Laird correlation\(^{14}\),

\[
\phi^2 = 1 + C / X + 1 / X^2, \tag{6}
\]

with different \( C \)-values. The four lines correspond to the \( C \)-values by Chisholm-Laird\(^{14}\) and the one line by Mishima-Hibiki\(^{15}\) correlation:

\[
C = 2 \left( 1 - e^{-0.339D_L} \right), \tag{7}
\]
where $D_H$ is the hydraulic diameter. The data for PLE lie between the calculations with $C = 13.4$ and 21, while those for air-water system between ones with $C = 10$ and 13.4.

### 3.2 Interfacial friction data

Figure 6 shows the data on the interfacial friction force, $F_I$, for the present tight lattice subchannel. $F_I$ increases with $j_G$ and $j_L$. As for the reduced surface tension effects, $F_I$ is higher in air-PLE system than air-water one.

![Fig. 6 Interfacial friction force data for the present tight lattice subchannel](image)

### 4. Examination of Correlations

#### 4.1 Wall friction correlations

Correlations from papers and thermal-hydraulic analysis codes were tested against the present two-phase wall friction force data. The correlations are; homogeneous flow model with three different viscosity models (McAdams\(^{116}\), Beattie-Whalley\(^{117}\), Dukler et al.\(^{119}\)); Lockhart-Martinelli (L-M) model\(^{13}\) with five different $C$ models (Chisholm-Laird\(^{14}\), Mishima-Hibiki\(^{15}\), Lee-Lee\(^{19}\), Koyama et al.\(^{20}\), Miyara et al.\(^{21}\)); Friedel’s correlation\(^{22}\); Separated flow model (Chierici et al.\(^{23}\), Ali et al.\(^{24}\), Casagrande’s correlation\(^{25}\), Chen et al.\(^{26, 27}\) correlations (modified homogeneous ver. 1 and 2, modified Friedel); TRAC-PF1/MOD1\(^{28}\); RELAP5/ MOD2\(^{29}\); NASCA\(^{30}\), TRACE\(^{31}\). Of these, the L-M models with $C$-value by Lee-Lee, Koyama et al., Miyara et al., Casagrande’s and Chen’s correlations include a term accounting for surface tension effects. Table 2 lists the test results. The mean and the r.m.s values of the relative error are defined as

$$e_m = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{F_{W,i} \text{cal} - F_{W,i} \text{exp}}{F_{W,i} \text{exp}} \right) \times 100.$$  

$$e_{rms} = \left[ \frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{F_{W,i} \text{cal} - F_{W,i} \text{exp}}{F_{W,i} \text{exp}} \right)^2 \right]^{1/2} \times 100.$$  

For both air-water and air-PLE systems, the homogeneous flow model with Beattie-Whalley’s viscosity model, and the L-M model with Mishima-Hibiki’s $C$ model can predict reasonably well the present data. In these models, r.m.s errors are 12.5% and 18.7% for air-water system, while 15.3% and 18.8% for air-PLE one, respectively.

To improve the prediction accuracy of the L-M model, we propose a new $C$ model by modifying the Mishima-Hibiki’s one as follows.

$$C = 21\left[1 - \exp(-0.319D_H(\sigma_L/\sigma)^{0.3} (G_{L0}/G_i)^{0.1})\right]$$

Here, $G_{L0}$ is the reference liquid mass flux of 1000 kg/(m$^2$·s), and $\sigma_L$ the surface tension of water at 20 °C. Figure 7 shows prediction results by L-M method with Eqs. (6) and (10). The mean and r.m.s errors in the prediction are 4.90% and 14.7% for air-water system, while -0.08% and 14.4% for air-PLE one, respectively.
Table 2 Mean and RMS values of errors for wall friction correlations

<table>
<thead>
<tr>
<th>Model or correlation</th>
<th>Water</th>
<th>PLE</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\epsilon_m$ (%)</td>
<td>$\epsilon_{rms}$ (%)</td>
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<tr>
<td>Homogeneous flow model</td>
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<tr>
<td>McAdams</td>
<td>11.07</td>
<td>23.44</td>
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<tr>
<td>Beattie-Whalley</td>
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<td></td>
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<td>Unicel</td>
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<td>-2.49</td>
<td>22.67</td>
<td>-11.35</td>
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<tr>
<td>Beattie-Whalley</td>
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<td>Mishima</td>
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<td>Lee - Lee</td>
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<td>Keyama et al.</td>
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<td>Miyata et al.</td>
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<td>48.54</td>
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<td>Casagrande’s correlation</td>
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<td>112.01</td>
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<tr>
<td>Chen et al.’s correlation</td>
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<td>Mod. Hom. ver.1</td>
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<td>Mod. Hom. ver.2</td>
<td>-59.41</td>
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<td>Mod. Friedel</td>
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<td>TRAC-PF1/MOD1</td>
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<td>RELAP5/MOD2</td>
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<td>52.56</td>
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<tr>
<td>NASCA</td>
<td>-6.76</td>
<td>30.80</td>
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<tr>
<td>TRACE</td>
<td>-36.18</td>
<td>50.37</td>
</tr>
</tbody>
</table>

Fig. 7 Comparison of $F_{WL}$ between experiment and calculation by L-M model with a new C model

4.2 Interfacial friction correlations

The correlations used in two-fluid model based thermal-hydraulic codes, TRAC-PF1/MOD1(28), RELAP5/MOD2(29), NASCA(30), and TRACE(32), are tested against the present gas-liquid interfacial force data, $F_i$. Figures 8 (a) and (b) show the examples of comparisons between the experiment and the calculation by the NASCA and the TRACE. Similar to the NASCA correlation, the TRAC and the RELAP correlations over-predict very much the present data, especially for slug or churn flow region for both air-water and air-PLE systems. However, the TRACE correlation under-predicts the data for bubble and slug flows, and the predictability is much better than others tested.

Fig. 8 Comparison of the interfacial friction forces between experiment and calculation

In order to find a better prediction method for bubble flow and slug-churn flow, Tomiyama et al.’s correlation(33) was tested against the present data in a void fraction range of $\alpha < 0.7$. 
Here, $F_{WG}$ is taken as zero and $F_{WL}$ is calculated by Katsuhara’s correlation$^{(34)}$. $C_0$ and $u_{Gj}$ are the distribution parameter and the drift velocity in the drift-flux model$^{(35)}$:

$$u_{Gj} = C_0 j + u_o = C_0 \left( j_{ij} + j_k \right) + u_o,$$  \hspace{1cm} (14)

and are calculated from Ishii’s correlation$^{(36)}$. The predictability of Tomiyama et al.’s correlation is much better than other correlations, as shown in Fig. 8 (c). We, therefore, modify Tomiyama et al.’s correlation to improve the prediction accuracy.

Many researchers (e.g., Mishima-Hibiki$^{(15)}$, Kariyasaki et al.$^{(37)}$) suggest that the drift velocity becomes zero for the bubble and slug flows in small diameter pipe of less than about 5 mm. Thus, $u_{Gj}$ can be taken as zero in the present calculation. On the other side, the distribution parameter, $C_0$, is determined from by the least-squares method as shown in thick lines in Figs. 9 (a) and (b), and $C_0$ for the respective cases are listed in Table 3. For vertical circular pipes of 1 to 5 mm I. D., Mishima-Hibiki$^{(15)}$ proposed the following $C_0$ correlation,

$$C_0 = 1.2 + 0.510 \exp(-0.691D).$$  \hspace{1cm} (15)

For vertical non-circular channels, Sadatomi et al.$^{(12)}$ suggested that $C_0$ is nearly equal to the ratio of the maximum velocity to the mean velocity in turbulent flow in the channel. In addition, they obtained $C_0 = 1.34$ for the isosceles-triangular channel with an apex angle of 20 degree and a height of 55 mm. This value is close to the present data for the air-PLE system. The above Sadatomi et al.’s suggestion seems applicable to the tight lattice subchannel if surface tension effects are negligible as in the case of air-PLE system.

Figure 10 shows prediction results by a modified Tomiyama et al.’s correlation, in which $u_{Gj}$ is taken as zero, $C_0$ in Table 3 is used, and $F_{WL}$ is calculated by the L-M model with $C$-value by Eq. (10). The modified correlation can predict extremely well the present data for bubble flow and slug-churn flow in $\alpha < 0.7$ irrespective of the test liquids.

![Fig. 9 Gas velocity data for the present tight lattice subchannel](image)

**Table 3 Distribution parameter data for the present tight lattice subchannel**

<table>
<thead>
<tr>
<th>Liquids</th>
<th>$C_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha &lt; 0.3$</td>
<td>$0.3 &lt; \alpha &lt; 0.7$</td>
</tr>
<tr>
<td>Water</td>
<td>1.147</td>
</tr>
<tr>
<td>PLE</td>
<td>1.379</td>
</tr>
</tbody>
</table>
Fig. 10 Prediction results by modified Tomiyama et al.’s correlation against $F_I$ data for bubble and slug-churn flows of $\alpha < 0.7$

We also studied $F_I$ correlations applicable to annular flow regime of $\alpha > 0.8$. In this regime, $F_I$ is usually given by

$$F_I = \tau_\ell / \delta Z / (A \delta Z) = \tau_\ell / A,$$

(16)

where, $\tau_\ell$ is the gas-liquid interfacial shear stress, $A$ the flow area, $\delta Z$ the axial distance, $\ell$ the perimeter of gas and liquid interface. In this study, $\ell$ is evaluated by assuming a uniform liquid film thickness along the wall perimeter as shown in Fig. 11 (Sadatomi et al.(7)). In addition, $\tau_\ell$ is calculated by

$$\tau_\ell = f I \rho \frac{H}{2},$$

(17)

where $f I$ is the interfacial friction factor. Since we have experimental data on $F_I$ and the void fraction at several $j_G$ and $j_L$ conditions, we can obtain $f I$ data by substituting the above data in Eqs. (16) and (17).

Fig. 11 Liquid film assumed(7)                  Fig. 12 Interfacial friction factor data

Figure 12 shows the resulting $f I$ data against the void fraction, $\alpha$. The line represents the well-known Wallis’ correlation(38) applicable to vertical flow in circular pipes:

$$f I = 0.005[1 + 78(1 - \alpha)].$$

(18)

The $f I$ data for the air-PLE system is higher than that for the air-water one and agrees reasonably well with the Wallis’ correlation.

Figure 13 shows comparisons of $f I$ between experiment and calculation by Nigmatulin et al.’s(39), Fukano-Furukawa’s(40), Henstock-Harratt’y’s(41), Fore et al.’s(42) correlations. Henstock-Harratt’y’s and Fore et al.’s correlations over-predict very much the present data. Nigmatulin et al.’s correlation predicts well air-PLE data alone. Fukano-Furukawa’s correlation gives better result irrespective of the test liquids, though it over-predicts a little bit the data.

In order to improve the prediction accuracy of $F_I$ in the annular flows, we try to modify Fukano-Furukawa’s correlation by incorporating surface tension effects as follows:
Fig. 13 Comparison of $f_I$ between experiment and calculations by four correlations

$$F_I = K_s F_{I,F-F} \quad \text{and} \quad K_s = 0.60 (\sigma_w / \sigma)^{0.10}.$$  \hspace{1cm} (19)

Here, $F_{I,F-F}$ is the calculation by the original Fukano-Furukawa’s correlation. Fig. 14 shows a comparison of $F_I$ between experiment and calculations by the original and the modified Fukano-Furukawa’s correlations. The modified one can predict the present annular flows data of $\alpha > 0.8$ within r.m.s error of 14 %.

Fig. 14 Comparison of $F_I$ between experiment and calculation by the original and the modified Fukano-Furukawa’s correlations

Fig. 15 Prediction results by Eq. (20) against the $F_I$ data for flows in churn to annular flows transition
For a transition region from churn flow to annular flow of $0.7 < \alpha < 0.8$, according to Mishima and Ishii\(^{42}\), Kawahara et al.\(^{43}\) proposed the following linear interpolation equation:

$$F_I = (1 - n)F_{I07} + nF_{I08}, \text{ where } n = 10\alpha - 7.$$  \hspace{1cm} (20)

Here, $F_{I07}$ is the calculated value of $F_I$ by Tomiyama et al.’s correlation at $\alpha = 0.7$, $F_{I08}$ the value by Fukano-Furukawa’s one at $\alpha = 0.8$. In the present calculation, modified versions of Tomiyama et al.’s and Fukano-Furukawa’s correlations were used for the calculations of $F_{I07}$ and $F_{I08}$. Figure 15 shows the results of a comparison. The calculation predicts the data within about 100% besides one point.

5. Conclusions

In order to obtain experimental data on the wall and the interfacial friction forces, $F_{WL}$ and $F_I$, for a triangle tight lattice subchannel, experiments were conducted for single- and two-phase flow under hydrodynamic equilibrium flow conditions. As the liquids, water and water with a surfactant, PLE, were used to know the reduced surface tension effects. By analyzing the data, we found the followings:

- Darcy friction factor for the single-phase flows can be predicted with the Churchill’s correlation modified with the geometry factors by Rehme and Sadatomi et al. respectively for laminar and turbulent flows.
- Both $F_{WL}$ and $F_I$ are higher in the air-PLE system than the air-water one.
- For $F_{WL}$, homogeneous flow model with the Bettie-Whalley’s mixture viscosity correlation can predict the present data within -20% for both the test liquids. Lockhart-Martinelli model has a similar accuracy in the prediction if $C$ was calculated by a new correlation, Eq. (10).
- For $F_I$, Tomiyama et al.’s correlation can predict well the data for bubble, slug and churn flows of $\alpha < 0.7$ if modified $C_0$, $u_{Gj}$ and $F_{WL}$, accounting for subchannel size and geometry, were used. Fukano-Furukawa’s one can predict well the data for annular flows of $0.8 < \alpha < 0.8$, if the reduced surface tension effects were incorporated. In a transition region from churn to annular flows of $0.7 < \alpha < 0.8$, an interpolation equation with the modified Tomiyama et al.’s and Fukano-Furukawa’s correlations gives better results.

Finally, it should be noted that some correlations, which could predict well the air-PLE data, are presumably valid to actual steam-water flow in the tight lattice subchannel because the surface tension in the steam-water flow is much smaller than air-water flow.

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References


