Effects of Surface Tension on Void Fraction in a Multiple-Channel Simplifying Triangle Tight Lattice Rod Bundle - Measurement and Analysis*

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Abstract
In order to know the effects of reduced surface tension on void fraction, adiabatic experiments were conducted for both air-water and air-water with surfactant systems at room temperature and pressure. Void fraction data were obtained for bubbly, slug, churn and annular flows in a vertical channel with two subchannels simplifying a triangle tight lattice rod bundle. The void fraction was found to be lower in air-water system than air-water with surfactant one. In addition, the void fractions for both systems were found to be lower than those calculated by various correlations in literatures for circular pipe flow.

In order to study the cause of the above data trend, for annular flows, the void fraction has been calculated by a subchannel analysis using wall and interfacial friction correlations in literatures as constitutive equations, and by assuming the liquid film to be uniform over the wall perimeter. The best agreement between the calculation and the experiment has been obtained when NASCA correlation for wall friction force and modified RELAP5/MOD2 correlation incorporating reduced surface tension effects for interfacial friction force were used.

Key words: Multi-Phase Flow, Void Fraction, Rod Bundle, Experiment, Correlation, Subchannel Analysis, Two-Fluid Model

Introduction
As one of the next generation BWRs, a reduced-moderation water reactor (RMWR) is developing at Japan Atomic Energy Research Institute, reorganized as Japan Atomic Energy Agency since October 2005 (1-8). In their papers, it is written that (i) the RMWR has favorable characteristics such as effective utilization of uranium, multiple recycling of plutonium, high burn-up and long operation cycle, (ii) MOX fuel assemblies with tight lattice arrangement are used to increase the conversion ratio by reducing the moderation of neutron energy, and (iii) increasing the in-core void fraction also contributes to the reduction of neutron moderation.

In such a tight lattice bundle, however, the fluid transfer between subchannels and the void fraction and the pressure drop in each subchannel have never been studied completely. For studying the fluid transfer and the void fraction etc., simplified channel experiments using air-water under adiabatic condition seem superior to rod bundle experiments under diabatic condition. So, the present authors started adiabatic experiments using air-water and a vertical multiple-channel with two subchannels simplifying the triangle tight lattice rod bundle on the flow redistribution phenomena due to void drift (9) and single- and two-phase turbulent mixing (10).
In the present study, the void fraction in each subchannel in the same multiple-channel have been measured and analyzed aiming at the flowing two: (a) To obtain subchannel void fraction data for air-water flows as well as air-water with surfactant flows to determine reduced surface tension effects. This is because the surface tension of the steam-water flow in an actual fuel bundle is much lower than that of air-water flow; (b) To compare the void fraction data with the calculations by a subchannel analysis code rigorously accounting for the channel wall perimeter and flow area instead of using the hydraulic diameter, and by some correlations for circular pipe flow. Results of such measurements and analyses are described in this paper.

Experiment

Figure 1 shows the cross-section of the test channel having two identical subchannels of Ch.1 and Ch.2, simplifying the triangle tight lattice rod bundle. The channel was made of four acrylic resin plates, cut off by shaper to get cylindrical surfaces of 12 mm O.D., and polished to obtain smooth transparent wall. The gap clearance between the subchannels, \( S_{12} \), was 1.0 mm. The hydraulic diameter, \( D_h \), and the flow area of each subchannel, \( A_1 \), are 3.19 mm and 16.63 mm\(^2\), respectively. No spacer was inserted in the channel.

\[
S_{12} = 1.0 \text{ mm} \\
D_h = 12.0 \text{ mm} \\
A_1 = 16.6 \text{ mm}^2
\]

Fig. 1 Cross-section of the test channel

Figure 2 shows the flow loop of the vertical test channel, being almost the same as that used in our previous study \(^{(9, 10)}\). The channel consists of 0.31 m entry, 1.60 m test and 0.31 m discharge sections, and the total length was 2.22 m. Distilled water (or water with surfactant) and air at room temperature and atmospheric pressure merged at a mixer, and their mixture were introduced into two subchannels from the bottom end of the entry section. The flow rates of the
gas and the liquid were measured with calibrated rotameters and positive-displacement-type flow meters within the uncertainties of 3 % and 1 %, respectively. The gas and the liquid introduced were the same flow rates between the subchannels for easily setting hydraulically equilibrium flow in the test section. In the test section, the mixture could go through the gap between the subchannels. In the entry and the discharge sections, however, they could not because of the 1.0 mm thick fins inserted in the boundary between the subchannels, as shown in the left hand side of the figure.

The difference from the previous test section was the insertion of paired quick shut valves allowing void fraction measurement in the test section. The valves were simultaneously operated with a pair of solenoids within about 0.1 s together with a solenoid valve in a by-pass line. In order to obtain accurate mean void fraction data within ±1 %, the operations were repeated 15 to 30 times depending upon the flow condition. Pressure drop and gauge pressure at the mid point of the test section were measured with differential-type and gauge-type pressure transducers within ±1 % and ±2 %. Some pictures were taken with a high-speed video camera and a digital camera to determine the flow regime.

Figure 3 shows the cross-section of two gas-liquid mixers for bubbly flow and for slug, churn and annular flows experiments. The gas was radically introduced from an annular gas plenum to the liquid streams through a lot of 0.3 mm I.D. holes drilled on the tube wall. The mixer for bubbly flow had a solid sphere in the tube similar to Sadatomi et al.’s micro-bubble generator in order to minimize bubble diameter.

Table 1 lists properties of the present test liquids at 20ºC. Water and water with surfactant called PLE (Polyoxyethylene Lauryl Ether) were used to study the effects of reduced surface tension on the flow. The reason of this is that the surface tension of water at a high pressure and temperature condition in actual BWR is very low, and the effects of surface tension on the flow becomes important as the channel diameter decreases as in the present test channel. The table shows that the surface tension of water with PLE is about 60 % of that of water, but the density and the viscosity are almost the same between them. In the present experiment, the surface tension of the water with PLE was measured and controlled at 0.042 ± 0.02 N/m, and temperature of it was controlled at 20 ± 1 ºC because the surface tension was very sensitive to the temperature.

<table>
<thead>
<tr>
<th>Liquids</th>
<th>σ</th>
<th>ρ</th>
<th>µ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.072</td>
<td>998.2</td>
<td>1.002×10⁻³</td>
</tr>
<tr>
<td>Water with PLE</td>
<td>0.042</td>
<td>998.2</td>
<td>0.981×10⁻³</td>
</tr>
</tbody>
</table>

The ranges of volumetric fluxes of air and water (or water with PLE) in the channel as a whole were 0.2 ≤ j₀ ≤ 35 m/s and 0.1 ≤ jₐ ≤ 2.0 m/s. The flow regimes covered were bubbly, slug, churn, and annular flows. The numbers of data points in each flow regime are 3 in bubbly flows, 17 in slug and churn flows and 3 in annular flows.
Experimental results

Typical pictures

Typical pictures are shown in Photos 1 and 2 respectively for churn flow and annular flow. In each photo, the air-water flow is the left and the air-water with PLE flow is the right. The volumetric fluxes of the gas and the liquid, shown in each photo, are the same irrespective of the liquid. In churn flow, a number of very small bubbles exist in the liquid in air-water with PLE flow while such bubbles are few in air-water flow. In annular flow, such bubbles exist also in the liquid film and a lot of waves with a rough interface like sharkskin exist in air-water with PLE flow while the bubbles do not exist and ripple-waves with smooth interface exist in air-water flow. From these pictures, the friction factor at the gas-liquid interface seems higher in air-water with PLE flow than air-water flow in churn and annular flows.

Photo 1 Churn flow at \(j_L = 1.0\) m/s, \(j_G = 6.0\) m/s

Photo 2 Annular flow at \(j_L = 0.2\) m/s, \(j_G = 20\) m/s
Void fraction data

Figure 4 shows the present void fraction data taken for both air-water system and air-water with PLE system. The abscissa is the volume flow quality, \( \beta = \frac{j_G}{j_G + j_L} \). The data points are plotted with different symbols depending on the test liquid and the liquid volumetric flux, \( j_L \). The dotted line and the broken line, calculated respectively by homogeneous flow equation, \( \alpha = \beta \), and by Armand correlation \((12)\), \( \alpha = 0.833 \beta \), are applicable to flows in circular pipes of medium diameter. In slug, churn and annular flow regimes of \( \beta > 0.3 \), the void fraction for both systems are lower than the calculated value by the Armand correlation. This is presumably caused by the two reasons: (i) the present channel is categorized as mini-channel since the hydraulic diameter is only 3.19 mm, thus relative liquid film thickness becomes thicker than that in medium diameter pipe; (ii) the present channel has four corners, allowing slowly moving liquid due to the surface tension effects and being different from no corner in the actual bundle. The second reason is justified by the lower void fraction data of air-water system, i.e., water being the higher surface tension liquid than the water with PLE. From these data, the void fraction in high pressure steam-water flow presumably approach to the calculated values by the Armand correlation or the homogeneous flow equation even in triangle tight lattice rod bundle.

Fig.4 Void fraction data: effects of reduced surface tension and subchannel geometry

Comparison of the present data with calculations by void fraction correlations

Seven correlations \((13-19)\), tested by Coddington-Macian \((20)\) for rectangular array rod bundle data, together with correlations of Chisholm \((21)\), Sakaguchi et al. \((22)\) and Ide-Fukano \((23)\), being valid for different diameter circular pipes data, were tested against the present data. Of these, correlations of Zuber-Findlay \((13)\), Dix \((14)\), Sun et al. \((15)\), Sakaguchi et al. \((22)\) and Ide-Fukano \((23)\) include a term accounting for surface tension effects, while correlations of Bestion \((16)\), Mishima-Hibiki \((19)\), Sakaguchi et al. \((22)\) and Ide-Fukano \((23)\) include a term accounting for pipe diameter effects.

Table 2 lists the results of the mean and the RMS values of the absolute error, \( \varepsilon_{ABS,i} = \alpha_{cal,i} - \alpha_{exp,i} \):

\[
\varepsilon_{ABS,M} = \frac{\sum_i \varepsilon_{ABS,i}}{N} \quad (1)
\]

\[
\varepsilon_{ABS,RMS} = \sqrt{\frac{\sum_i \varepsilon_{ABS,i}^2}{N-1}} \quad (2)
\]

for both air-water and air-water with PLE systems in the present test channel. The best
The best correlation for the present data irrespective of liquid is Sakaguchi et al., and the second best is Ide-Fukano for air-water data and Sun et al. for air-water with PLE data. Why Sakaguchi et al.’s is the best seems that it includes a term accounting for both surface tension and pipe diameter effects as described in the last paragraph. In addition, the void fractions for both systems were found to be 0.02-0.09 lower than calculated values by many correlations for circular pipe flow besides Bestion and Maier-Coddington correlations.

Table 2 Mean and RMS values of absolute error for void fraction correlations

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Air-water</th>
<th></th>
<th>Air-water with PLE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>RMS</td>
<td>Mean</td>
<td>RMS</td>
</tr>
<tr>
<td>Zuber-Findlay</td>
<td>0.029</td>
<td>0.065</td>
<td>0.016</td>
<td>0.046</td>
</tr>
<tr>
<td>Dix</td>
<td>0.044</td>
<td>0.073</td>
<td>0.037</td>
<td>0.059</td>
</tr>
<tr>
<td>Chisholm</td>
<td>0.085</td>
<td>0.104</td>
<td>0.067</td>
<td>0.075</td>
</tr>
<tr>
<td>Sun et al.</td>
<td>0.025</td>
<td>0.062</td>
<td>0.011</td>
<td>0.044</td>
</tr>
<tr>
<td>Bestion</td>
<td>-0.018</td>
<td>0.137</td>
<td>0.020</td>
<td>0.098</td>
</tr>
<tr>
<td>Inoue et al.</td>
<td>0.019</td>
<td>0.102</td>
<td>0.010</td>
<td>0.085</td>
</tr>
<tr>
<td>Mishima-Hibiki</td>
<td>0.047</td>
<td>0.078</td>
<td>0.026</td>
<td>0.057</td>
</tr>
<tr>
<td>Maier-Coddington</td>
<td>-0.018</td>
<td>0.113</td>
<td>-0.027</td>
<td>0.099</td>
</tr>
<tr>
<td>Ide-Fukano</td>
<td>0.020</td>
<td><strong>0.049</strong></td>
<td>0.094</td>
<td>0.116</td>
</tr>
<tr>
<td>Sakaguchi et al.</td>
<td>0.018</td>
<td><strong>0.042</strong></td>
<td>0.013</td>
<td><strong>0.030</strong></td>
</tr>
</tbody>
</table>

Fig.5 Comparison of void fraction data with calculations by representative correlations
Figures 5(a)-(d) show graphical presentations of the representative comparisons. Sakaguchi et al. correlation in Fig. 5 (a) can predict well the data. Ide-Fukano correlation in Fig. 5 (b) can predict well air-water data, but cannot air-water with PLE data. Sun et al. correlation predict well both air-water and air-water with PLE data except in $0.45 < \alpha_{\text{exp}} < 0.75$.

Dix correlation in Fig. 5 (d) over-predicts both air-water and air-water with PLE data in $\alpha_{\text{exp}} > 0.3$, i.e., in slug, churn, and annular flow regions, though it was the best correlation to our $2\times3$ rectangular array rod bundle subchannel data $^{(24)}$. This disagreement is considered to be caused by both the longer perimeter and the smaller hydraulic diameter in the present subchannel than the rectangular array subchannels.

**Analysis and its assessment**

**Analytical method**

In order to justify the above consideration, for annular flows as a first step, the void fraction has been calculated by a subchannel analysis and the results have been compared with the present experimental data. In the present analysis, a simplified subchannel code $^{(24)}$ based on a one-dimensional two-fluid model $^{(25)}$ was used to compute the void fraction. In the code, the following conservation equations of axial momentum for each phase were simultaneously solved with those of mass.

$$\frac{d}{dZ} \left( \rho_G \alpha_G u_G^2 \right) + F_{\text{Hi}} + F_{\text{Gi}} + \alpha_G \frac{dP_G}{dZ} = 0 , \quad (3)$$

$$\frac{d}{dZ} \left( \rho_L \alpha_L u_L^2 \right) + F_{\text{Wi}} - F_{\text{bi}} + F_{\text{Li}} + \alpha_L \frac{dP_L}{dZ} = 0 . \quad (4)$$

Here, the first term in these equations was very small in comparison with other terms, thus neglected. The perimeters of channel wall and gas-liquid interface were rigorously accounted for, and the liquid film on the wall was assumed to be uniform over the wall perimeter as shown in Fig.6 because of hydraulically equilibrium flow, in which the void fraction is identical between subchannels. In addition, the gas core with entrained droplet was assumed to be homogeneous, and the entrained droplet ratio was evaluated from Ishii-Mishima correlation $^{(26)}$.

![Fig. 6 Liquid film distribution assumed](image)

The wall friction force for the gas phase per unit volume, $F_{\text{WG}}$, could be taken to be zero in the present experimental range. The wall friction force for the liquid phase per unit volume (= frictional pressure drop), $F_{\text{WL}}$, and the interfacial friction force per unit volume, $F_{\text{bi}}$ were calculated from the following correlations.
In addition, since the flow to be analyzed was a vertical subchannel flow, the equation of equal pressure drop between the phases was adopted as a closure equation:

\[ \frac{dP_{cL}}{dZ} - \frac{dP_{cI}}{dZ} = 0. \]  

Actually, a numerical iteration method, called “Binary method,” was used until \( \delta E_i \) in Eq. (5) became less than 50 Pa/m by changing the void fraction, \( \alpha_{cL} \).

**Assessment result**

Figures 7(a)-(f) show typical assessment results. Calculated results are different depending on the selection of \( F_{WLi} \) and \( F_{Li} \) correlations. The best agreement between the calculation and the experiment was obtained when \( F_{WLi} \) and \( F_{Li} \) were determined respectively from the NASCA correlation \(^{(33)} \) and the modified RELAP5/MOD2 correlation incorporating surface tension effects \(^{(37)} \), i.e.,

\[ F_{Li} = K_{\sigma} \frac{1}{8} \quad \frac{\alpha_{cL} P_{cL} C_{Di}(u_{cL} - u_{cI})}{|u_{cI} - u_{cL}|}, \]  

\[ K_{\sigma} = 0.286(\sigma_{L} / \sigma_{W})^{-1.541}. \]

\( \sigma_{W} \) in Eq. (7) is the surface tension of water at 30 °C. The RMS error of the best agreement case was 0.032 for air-water and 0.013 for air-water with PLE. Such a small error must validate the present analysis and assumption. In addition, the modified RELAP5/MOD2 correlation for \( F_{Li} \) is considered to be superior to others, because all the calculation using the modified RELAP5/MOD2 correlation showed better agreement irrespective of \( F_{WLi} \) correlations, as shown in Figs. 7 (c), (e) and (f). Contrary to this, the original codes of TRAC-PF1/MOD1, RELAP5/MOD2, and NASCA do not give good predictions, as shown in Figs. 7 (a), (b), (d).
Conclusions

Void fraction data for air-water and air-water with PLE two-phase flows were obtained using a vertical multiple-channel simplifying triangle tight lattice rod bundle. By analyzing the data, the followings have been clarified.

1. The void fraction is lower in air-water flow than air-water with PLE flow due to the surface tension effects appearing in small diameter pipe.
2. The void fraction especially in air-water flows is lower than that calculated by many correlations applicable to circular pipe, besides Sakaguchi et al.’s.
3. The void fraction data in annular flows were best predicted by a simplified subchannel code, by rigorously accounting for the channel wall perimeter and the flow area instead.

Fig. 7 Comparison of void fraction data with calculations by a subchannel code with different $F_{\text{WL}}$ and $F_{\text{ii}}$ correlations
of using the hydraulic diameter, and by using the NASCA correlation for wall friction force and the modified RELAP5/MOD2 correlation for interfacial friction force, irrespective of fluids.

Acknowledgments

The authors appreciate Mr. S. Aramaki for his experimental cooperation and technicians in the machine shop at Kumamoto University for manufacturing the quick shut valves as well as the test channel.

References

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