Experimental and Analytical Study of Lead-Bismuth-Water Direct Contact Boiling Two-Phase Flow

NOVITRIAN**, Vaclav DOSTAL*** and Minoru TAKAHASHI***

**Department of Nuclear Engineering, Tokyo Institute of Technology,
N1-18, 2-12-1 O-okayama, Meguro-ku, Tokyo, Japan
E-mail: 04d51452@nr.titech.ac.jp
***Research Laboratory for Nuclear Reactor, Tokyo Institute of Technology,
N1-18, 2-12-1 O-okayama, Meguro-ku, Tokyo, Japan

Abstract
The characteristics of lead-bismuth (Pb-Bi)-water boiling two-phase flow were investigated experimentally and analytically using a Pb-Bi-water direct contact boiling two-phase flow loop. Pb-Bi flow rates and void fraction were measured in a vertical circular tube at conditions of system pressure 7MPa, liquid metal temperature 460°C and injected water temperature 220°C. The drift-flux model with the assumption that bubble sizes were dependent on the fluid surface tension and the density ratio of Pb-Bi to steam-water mixture was chosen and modified by the best fit to the measured void fraction. Pb-Bi flow rates were analytically estimated using balance condition between buoyancy force and pressure losses, where the buoyancy force was calculated from void fraction estimated using the modified drift-flux model. The deviation of the analytical results of the flow rates from the experimental ones was less than 10%.

Key words: Lead-Bismuth, Direct Contact Boiling, Two-Phase Flow, Void Fraction, Drift-Flux Model

1. Introduction

Pb-Bi-cooled direct contact boiling water fast reactor (PBWFR) has been proposed as one of the innovative nuclear reactors[1-4]. This reactor uses the steam lift pump concept based on injection of water into Pb-Bi-coolant flow to circulate Pb-Bi coolant. Therefore, coolant circulation pumps and steam generators used in the conventional Pb-Bi-cooled fast reactor are eliminated [5].

Some studies about the Pb-Bi two-phase flow were carried out. Nishi et al.[6] performed two-phase flow experiments of Pb-Bi-nitrogen mixture in circular tubes with inner diameter of 106.2mm to evaluate gas-lift pump performance in a molten Pb-Bi loop. Kashihara et al.[7] performed a two-phase flow experiment of Wood’s metal-nitrogen mixture in circular tubes with 44mm in inner diameter to verified a slip ratio in Wood’s metal as a study of magneto-hydrodynamic power generation. Saito et al.[8] performed two-phase flow experiment of Pb-Bi-nitrogen mixture in a tube of 24mm in inner diameter, and visualized bubbles using the neutron radiography and determined the void fraction and liquid velocities.

Takahashi et al.[9, 10] studied two-phase flow behavior of steam-water and Pb-Bi experimentally using Pb-Bi-water direct contact boiling two-phase flow loop and reported experimental data of Pb-Bi flow rate induced by water injection into the Pb-Bi flow. The
two-phase flow characteristics in the tube were evaluated analytically by assuming force balance between buoyancy force of two phase flow and total pressure drop in the Pb-Bi loop including two-phase flow pressure drop in the chimney \(7, 10\). However, in the analyses, the void fraction was assumed to be constant. In order to estimate the buoyancy of two phase flow more reasonably, void fraction must be calculated using a two-phase flow model. Without the detail two-phase flow information of a flow regime map, the drift-flux models have been used for the calculation of the void fraction.

In the present study, an empirical correlation for the void fraction of a Pb-Bi-steam and water two-phase flow in a vertical circular tube will be obtained experimentally to determine drift velocity and phase distribution parameter. The purpose of the present study is to estimate void fraction and Pb-Bi flow rate at high system pressure in a vertical circular tube properly using a modified drift-flux model.

2. Experimental Apparatus

The test loop is illustrated in Fig 1. It consists of a Pb-Bi flow loop and a water-steam loop. The Pb-Bi loop consists of the heater pin bundle with four electrical heater pins, the chimney, an upper tank with the separator and dryer, the cooler, the electromagnetic flow meter, and a flow resistance. The water-steam loop consists of the cooler, the pre-heater, the chimney, the upper tank, the condenser and the buffer tank. Sub-cooled water was injected into the Pb-Bi flow in the chimney. The steam was generated in the chimney by the direct contact boiling with hot Pb-Bi. Boiling bubbles served as a gas lift pump for the circulation of the Pb-Bi. Steam was sent to the condenser after passing through the separator and dryer.

Figure 2 shows a schematic of a test section, i.e., the pin bundle, the chimney, and the upper tank. Long straight tube made of stainless steel SUS-304 was used as the chimney and was equipped with electrode void probes and thermocouples for measurement of steam void fraction and Pb-Bi and steam/water temperatures, respectively. Chimney diameter was expanded from 30.0 mm to 38.4 mm and the flow characteristics in the down-stream region was investigated. The influence of expanding cross-section near the injection point is not large on two-phase flow characteristics in the down-stream. Detailed specifications of the test section are listed in Table 1. Operating conditions are summarized in Table 2.
Electrode probes were inserted into the chimney to measure the local void fraction. The probes, schematically shown in Fig 3, were made of stainless steel SUS-304 wire of 0.8 mm O.D. inserted into 1.6 mm O.D. 19.05 O.D. stainless steel tubes. The probes were covered with cement except for the tips so that the wire tip acted as the first electrode and the stainless steel sheath as the second electrode. The electrodes were electrically connected in series with a resistor, to a DC voltage source. The probes were installed in the middle of the chimney and the heights were 630 mm, 930 mm and 1230 mm from injection point and the probe tips were located as close to the axial center of the chimney as possible.

A 5 V DC electric potential was applied between the wire and the stainless steel sheath and digital oscilloscope was used to record the output signals from the void probes which were sampled at a frequency of 500 kHz. When the probe was surrounding by Pb-Bi, a base voltage was recorded as an output signal. When the steam was around the probe, a higher voltage was recorded as an output signal by the digital oscilloscope. Figure 4 (a) shows the sample signal of the digital oscilloscope. The ratio of the time of the signal in which the output voltage was higher than the base voltage (0 V) to the total time gave the local void fraction at the probe tip position.

The measurement error was determined from total time delay (see Fig. 4 (b)) over the total time of measurement. The measurement error was within 10%.

Water injection mass flow rate was measured with the orifice flow meters, and the Pb-Bi mass flow rate was measured with the electromagnetic flow meter.

<table>
<thead>
<tr>
<th>Table 1 Specifications of test section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the test section</td>
</tr>
<tr>
<td>Chimney</td>
</tr>
<tr>
<td>Inner diameter 1/ Length 1</td>
</tr>
<tr>
<td>Inner diameter 2/ Length 2</td>
</tr>
<tr>
<td>Upper tank containing separator</td>
</tr>
<tr>
<td>Inner diameter / Length</td>
</tr>
<tr>
<td>Heater pin bundle</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Heater pin</td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>Outer diameter / Length</td>
</tr>
<tr>
<td>Pitch of rod arrangement</td>
</tr>
<tr>
<td>Heated length / Power</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 Controlled parameters and result of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>Heater Pin power (kW)</td>
</tr>
<tr>
<td>Pb-Bi temp. at outlet (°C)</td>
</tr>
<tr>
<td>Injected water flow rate (kg/h)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Steam pressure (MPa)</td>
</tr>
<tr>
<td>Pb-Bi temp. at inlet of heater pin bundle (°C)</td>
</tr>
<tr>
<td>Pb-Bi flow rate (L/min)</td>
</tr>
<tr>
<td>Temperature in the chimney (°C)</td>
</tr>
</tbody>
</table>
Fig. 2  Schematic of test section

Fig. 3 Schematic of void probe

Fig. 4 Signal from digital oscilloscope
2.1 System and Balance Condition

Figure 5 shows a schematic diagram of the Pb-Bi flow loop. The Pb-Bi flowed through the heater pin, the chimney, the upper tank, the cooler, the downward flow tube and the electromagnetic flow meter (EMF). Sub-cooled water was injected into Pb-Bi flow above the electrically heated pin bundle and subsequently boiled.

Pb-Bi flow rates were calculated analytically using balance condition between the buoyancy force and frictional pressure drops during the flow. The drift-flux model was used to calculate the void fraction and to estimate the buoyancy force in the chimney. It was assumed that the Pb-Bi flow was one-dimensional.

The buoyancy force of steam lift pump effect for Pb-Bi circulation is given by

\[
\Delta P = \rho_s h g - \left[ \rho_s h_3 + \rho_1 h_4 + \rho_2 (1 - \alpha) h_5 \right] g,
\]

where \( h \) denotes the tube height in each section, \( \rho \) is the Pb-Bi density estimated from measured Pb-Bi temperature, and the suffices 1-5 indicate the tube locations of the downward flow tube, an inlet of the heater pin bundle, an exit of heater pin bundle, an inlet of an injection region and an inlet of the chimney, respectively, \( \rho_c \) is the average fluid density in the chimney \( (\rho_c = \alpha \rho_w + (1 - \alpha) \rho_f) \), and \( \alpha \) is the void fraction.

Frictional pressure drop of the Pb-Bi-steam two-phase flow in the chimney is given by

\[
\Delta P_{TP} = \left( \frac{\phi_{lo}}{2} \right)^2 \Delta P_{LO},
\]

where the pressure drop of Pb-Bi single-phase flow, \( \Delta P_{LO} \), and the velocity, \( V \), are given by

\[
\Delta P_{LO} = \left[ \zeta + \lambda \left( \frac{L}{D_f} \right) \left( \frac{\rho}{2} \right) \right] V^2,
\]

\[
V = \frac{(G_p + G_f)}{\rho A}.
\]

where \( \zeta \) is the form loss coefficient, \( \lambda \) is the friction loss coefficient, \( L \) is the length of the section, \( D_f \) is the hydraulic diameter, \( G_p \) and \( G_f \) are the Pb-Bi and water flow rate, respectively.

The two-phase multiplication factor is expressed by

\[
\left( \frac{\phi_{lo}}{2} \right)^2 = \left[ 1 + x \left( \frac{\rho_c}{\rho_w} - 1 \right) \right] \left[ 1 + x \left( \frac{\rho_w}{\mu_w} - 1 \right) \right]^{0.25},
\]

where \( \rho_w \) is the average density of steam and water mixture \( (\rho_w = \frac{x_g}{\rho_b} + (1 - x_g)/(\rho_f)^{1/3}) \), \( x_g \) is
the steam quality and $\mu$ is the dynamic viscosity.

Acceleration loss at the water injection is expressed by

$$\Delta P_a = x G_T^2 \left( \frac{1}{\rho_w} + \frac{1}{\rho_f} \right),$$  

(6)

where $G_T$ is the total mass flux of Pb-Bi and injected water and $x$ is quality defined by

$$x = \frac{G_f}{G_f + G_f}.$$  

Frictional loss of bare bundle is expressed by

$$\Delta P_f = \left( \frac{\rho}{2} f \left( \frac{L}{D_i} \right) \right) v_i^2.$$  

(7)

The flow is classified into the laminar flow in $Re \leq Re_L$, the transition flow in $Re_L \leq Re \leq Re_T$ and the turbulent flow in $Re \geq Re_T$, where

$$Re_L = 300 \times 10^{1.7 \left( \frac{P}{\pi} \right)},$$  

$$Re_T = 10000 \times 10^{0.7 \left( \frac{P}{\pi} \right)}.$$  

(8)

Friction factors are provided as follows: $f_L = C_L / Re$ in the laminar flow, $f_T = C_T / Re^{0.18}$ in the turbulent flow, and $f_w = f_L \left( 1 - \Psi \right)^{1/3} + f_T \Psi^{1/3}$ in transition flow.

where

$$\Psi = \frac{\left( \log_{10} Re - \log_{10} Re_L \right)}{\left( Re_T - \log_{10} Re_L \right)}.$$  

(9)

$Re$ is a Reynolds number and $f$ is a friction factor. The detailed equation of pressure losses can be found in Ref. (9).

Pb-Bi flow rate was estimated by equating the driving head of Pb-Bi circulation in Eq.(1) and total pressure loss.

2.2 Drift Flux Model

To calculate the buoyancy force in the balance condition mentioned above, the void fraction is needed. The drift-flux model is one of the most practical and accurate models for two-phase flow calculation. The model takes into account relative motion between phases.

In the drift-flux model, the void fraction $\alpha$ is the function of the total and vapor superficial velocity, $j (= j_w + j_p)$ and $j_w$, the phase distribution parameter $C_p$, and the drift velocity $v_{wj}$. In this form, steam/vapor production computed from a boiling model is included in $j_w$, and the effect of the relative velocity between the phases is included in $v_{wj}$:

$$\alpha = \frac{j_w}{C_0 \left( j_p + j_w \right) + v_{wj}}.$$  

(10)

The liquid and gas superficial velocities $j_p$ and $j_w$ are defined by

$$j_p = \frac{G_p}{\rho_p A}, \quad j_w = \frac{G_w}{\rho_w A}.$$  

(11)

where $G_p$ is the steam-water flow rate obtained from experimental data, $G_L$ is the unknown
Pb-Bi flow rate obtained from the calculation, and $A$ is the chimney cross-sectional area. The distribution parameter $C_0$ and the drift velocity between the phases $v_{wj}$ are computed by fitting the calculated Pb-Bi flow rate to one of the experimental data.

The measured Pb-Bi temperature in the Pb-Bi flow loop, the sub-cooled water temperature, and the system pressure presented in Table 3 were used for the estimation of Pb-Bi physical properties in Eqs. (11).

<table>
<thead>
<tr>
<th>Table 3 Experiment data for empirical correlation of drift flux model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pb-Bi Temp. at inlet (°C)</strong></td>
</tr>
<tr>
<td>-------------------------------</td>
</tr>
<tr>
<td>Water inject. Temp. (°C)</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
</tr>
</tbody>
</table>

3. Results and Discussions

To obtain the empirical correlation for the drift-flux model, the distribution parameter and the relative velocity between the phases are estimated using the best fit to the available experimental data. The distribution parameter and the drift velocity were obtained as follows:

For system pressure <2 MPa,

$$C_0 = 1.0 - 0.2 \frac{\rho_w}{\rho_p}, \text{ and } v_{wj} = 1.8 \left( \frac{g \sigma \Delta \rho}{\rho_p} \right)^{0.25},$$  \hspace{1cm} (12)

For system pressure 2-7 MPa,

$$C_0 = 0.65 - 0.2 \frac{\rho_w}{\rho_p}, \text{ and } v_{wj} = 1.95 \left( \frac{g \sigma \Delta \rho}{\rho_p} \right)^{0.25}. \hspace{1cm} (13)$$

The formulations above correlates well with similar equations derived for water. Hibiki and Ishii(11) uses the following values for the distribution parameter and the drift velocity for flow in a round vertical tube:

$$C_0 = 1.2 - 0.2 \frac{\rho_w}{\rho_p}, \text{ and } v_{wj} = \sqrt{2} \left( \frac{g \sigma \Delta \rho}{\rho_p^2} \right)^{0.25}. \hspace{1cm} (14)$$

According to the review of Coddington and Macian(12), the distribution factor $C_0$ in water/gas system is always slightly greater than or equal to unity, while in the one-dimensional liquid-metal/gas systems this is less than unity.

Figure 6 shows the relation between Pb-Bi flow rate and measured void fraction for three sets of void fraction data at different experimental condition. It can be seen that the calculated Pb-Bi flow rate agrees well with experimental data.

The measured local void fraction was used in the drift-flux model calculation as the average void fraction. This is based on the assumption that the flow in the section is almost one dimensional partly because in the tube diameter is quite small so the local void fraction is nearly the same at any point of the cross-sectional area and partly because the bubble diameter is large in the Pb-Bi two phase-flow systems(14). This situation is the same with the slug flow in the ordinary fluid flow. This assumption is justified later by the prediction of Pb-Bi mass flow rate. It is very difficult to measure a local void fraction in the other cross-sectional area with a moveable electrode probe because of the apparatus was operated at high pressure and high temperature.

Figure 7 shows the comparison between the calculated and measured void fraction. It is
found that the calculated void fraction agrees well with the measured one and that it is higher than the result in the previous studies (5 - 8).

The “best” fit was obtained with the distribution parameter and the drift velocity prescribed by Eq. (12) and Eq. (13) for system pressure less than 2MPa and 2-7MPa, respectively. This correlation was used to estimate the Pb-Bi flow rate with other experimental conditions (Table 4) where the void fraction was not measured.

Fig. 6 Relation between Pb-Bi flow rate and measured void fraction

Fig. 7 Comparison of drift-flux correlation with measured data

(a) low system pressure

(b) high system pressure

Table 4 Experiment data for estimation Pb-Bi flow rate

<table>
<thead>
<tr>
<th></th>
<th>1st Test</th>
<th>2nd Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>&lt; 1.0</td>
<td>0.05 – 6.8</td>
</tr>
<tr>
<td>Pb-Bi Temp. at inlet (°C)</td>
<td>290</td>
<td>285-400</td>
</tr>
<tr>
<td>Water inject. Temp. (°C)</td>
<td>219</td>
<td>165-230</td>
</tr>
<tr>
<td>Heater Power (kW)</td>
<td>34-50</td>
<td>16-34</td>
</tr>
</tbody>
</table>
Figure 8 shows comparison of the Pb-Bi flow rate between experiment and analysis. It was found that the error between the analytical calculation and experimental data was less than 10%. This is smaller than that in previous analytical calculation\(^{(13)}\), where the empirical correlation for the drift-flux model derived from experimental data was not used.

The experimental data for Pb-Bi flow rate are compared with the analytical results shown in Fig 9. It is found that the calculated Pb-Bi flow rate agrees well with the experimental data.
4. Conclusions

1. Boiling two-phase characteristics of Pb-Bi-water direct contact has been investigated experimentally and analytically and the results improve the analysis of balance condition between pressure losses and the buoyancy forces in the flow tube.

2. The drift-flux model was modified based on the experimental data of measured local void fraction. It was assumed that due to the small diameter of the test section and the large bubble diameter the local void fraction was identical with the average void fraction. The distribution parameter and the relative velocity between the phases were computed using a best fit to experimental data, and the empirical correlation have been obtained with the following drift-flux models:

\[
\alpha = \frac{j_g}{\left(1.0 - 0.2 \sqrt{\rho_u/\rho_p}(j_g + j_f)\right) + 1.8 \left(\frac{g \sigma \Delta \rho}{\rho_p}\right)^{0.25}}
\]

for system pressure less than 2MPa, and

\[
\alpha = \frac{j_g}{\left(0.65 - 0.2 \sqrt{\rho_u/\rho_p}(j_g + j_f)\right) + 1.95 \left(\frac{g \sigma \Delta \rho}{\rho_p}\right)^{0.25}}
\]

for system pressure 2-7 MPa. The modified drift-flux model was used to simulate the Pb-Bi-water boiling two-phase flow and to estimate void fraction.

3. The empirical correlations for drift-flux model have been used to evaluate Pb-Bi flow rate at the other experimental conditions where void fraction was not measured. It was found that the calculated Pb-Bi flow rate agreed well with the experimental data. The deviation between the experimental data and the calculation results was less than 10%.

References


(7) T. Kashihara, M. Saito, A. Nezu, Gas-liquid slip ratio in high density liquid-metal two-phase natural circulation, Proc. 8th Int. Conf. on Nucl. Eng., ICONE-8, Baltimore,


