Evaluation of Pb-Bi-Water Direct Contact Boiling Flow in a Vertical Circular Channel using Drift-Flux Model

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Abstract

The characteristics of Pb-Bi-water boiling two-phase flow were investigated in a vertical circular channel. Water was injected into Pb-Bi to circulate Pb-Bi in a loop with an effect of steam lift pump. Pb-Bi flow rates were measured and analytically estimated using balance condition between buoyancy force and pressure losses. The drift-flux model was used to determine void fraction with assumption that bubble sizes were dependent on the fluid surface tension and density ratio of Pb-Bi to steam and water mixture. The result of analysis shows that the deviation from the experimental data was less than 20%.

Keywords: Lead-bismuth, Direct contact, Steam lift pump, Two-phase flow, Drift-flux model

1. Introduction

Lead-bismuth (Pb-Bi) has been considered as a coolant candidate of fast reactors. The advantages of Pb-Bi arise from the possibility of developing passively safe reactors with long lifetimes core, combined with low capital and operating cost. The reactor with a long-life core may be also useful for remote region islands. Smaller reactors are more suitable for transportation to un-industrialized area after being fabricated and assembled in factories. Pb-Bi-cooled Direct Contact Boiling Water Fast Reactor (PBWFR) has been proposed¹⁻³⁾. This reactor uses the steam lift pump concept based on the bubbling of water into Pb-Bi coolant flow to enhance Pb-Bi circulation flow.

Two-phase flow behaviors of steam-water and Pb-Bi have been studied experimentally using Pb-Bi-water direct contact boiling two-phase flow loop. In the previous work, experimental data of changes of temperatures and Pb-Bi flow rate by the water injection into the Pb-Bi flow has been reported^{4,5)}. The two-phase flow characteristic in the channel was determined by the force balance between the buoyancy of two phase flow and the total pressure drop in the Pb-Bi circulation loop^{5,6)} including the two-phase flow pressure drop in the chimney.

In general, without the detail two-phase flow information needed to develop a flow regime map and the associated interfacial relation, the drift-flux models have often been used in the thermal-hydraulic analysis of nuclear and other systems. Appropriate correlations for the drift velocity and the drag coefficient between nitrogen gas and Pb-Bi phase were based on the drift flux correlation of measured pool void fraction⁷⁾. And another correlation for drift-flux model between nitrogen gas and liquid metal for measured loop-type experiment void fraction⁸⁾.

In the previous analytical work⁹⁾, non-dimensional drift-flux model was used, where the gas and fluid superficial velocities depended on the fluid surface tension, and only the density ratio between phases was used for the drift velocity between phases and the distribution parameter.

The purpose of the present study is to investigate two-phase flow characteristics of Pb-Bi-steam-water boiling flow in the channel using the one-dimensional drift-flux model, where the gas and fluid superficial velocities did not depend on the fluid surface tension, and both of the fluid surface tension and the density ratio between phases were considered for the drift velocity between phases, assuming the distribution parameter to be constant.

2. Experimental Apparatus

A schematic diagram of the Pb-Bi-water direct contact boiling two-phase flow loop is shown in Figure 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, an electromagnetic flow meter, and a flow resistance (Figure 2). 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. Boiling occurs in the chimney and serves as a steam lift pump for Pb-Bi circulation flow. The steam goes to turbines after passing through the separator and dryer.

Figure 1. Flow diagram of Pb-Bi-water direct contact boiling two-phase flow apparatus

Figure 2. Schematic of Pb-Bi flow loop in test apparatus

Pb-Bi flow rates obtained from analytical model are compared with existing experimental data taken under various experimental conditions such as pressure of 0.01 – 7MPa, Pb-Bi inlet temperature of 278 – 414°C and injected water temperature of 198 – 228°C.

Figure 3 shows a schematic of the test section, i. e., the pin bundle, the chimney and the upper tank. Detailed specifications of the test section are listed in Table 1. Controlled parameters and the result of the operation are present in Table 2.

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

Table 1. Specifications of test section

Length of the test section	7,000mm
Chimney	
Inner diameter / Length	29.9mm/2,367mm
Upper tank containing separator	
Inner diameter / Length	254.4mm/3,150mm
Heater pin bundle	
Length	1,720 mm
Heater pin	
Number	4
Outer diameter / Length	12 mm / 1,650 mm
Pitch of rod arrangement	15.9 mm
Heated length / Power	1,000 mm / 33.3 kW

Figure 3. Schematic of test section

Table 2. Controlled parameters and result of operation

Parameter	Experimental Condition	Rated Condition
Heater Pin Power (kW)	5-106	133
Pb-Bi Temp. At Outlet (°C)	308-469	460
Injected water Flow rate (kg/h)	5.8-245	256
Temperature (°C)	198-228	220
Steam pressure (MPa)	0.1 – 7	7
	Result	Rated Condition
Pb-Bi temp. at inlet of heater pin bundle (°C)	278-414	310
Pb-Bi flow rate (L/min)	56-61	36.5
Temperature in chimney (°C)	303-316	-

3. Analysis

3.1 System and assumption

Figure 4 shows a schematic diagram of Pb-Bi-water direct contact flow loop. The Pb-Bi flows through the heater pin, the chimney, the upper tank, the cooler, the downward flow pipe and the electromagnetic flow meter. Sub-cooled water was injected into Pb-Bi above the heater pin bundle and boiling occurred. 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 in calculating the buoyancy force in the chimney. The flowchart of the calculation is shown in Figure 5. The Pb-Bi flow is analyzed assuming one dimensional flow. In analysis, it was assumed that the bubble sizes were dependent on the fluid surface tension.

Figure 4. One dimensional flow model for Pb-Bi

Figure 5. One dimensional calculation model for Pb-Bi

3.2 Buoyancy force and pressure drop

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

$$\Delta P = \rho_{dc} h_1 g - [\rho_{dc} h_2 + \rho_3 h_3 + \rho_4 h_4 + \rho_c (1 - \alpha) h_5] g, \quad (1)$$

where h denotes the channel height in each section, ρ is Pb-Bi density estimated from measured Pb-Bi temperature, and suffices 1-5 indicate the channel locations of the downward flow channel, 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, and α is the void fraction.

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

$$\Delta P_{TP} = (\phi_{LO})^2 \Delta P_{LO}, \quad (2)$$

where the pressure drop of Pb-Bi single-phase flow and the velocity are given by

$$\Delta P_{LO} = [\zeta + \lambda(L/D_e)](\rho/2) V_p^2, \quad (3)$$

$$V_p = (G_p + G_f)/(\rho A). \quad (4)$$

where ζ is form loss coefficient, λ is friction loss coefficient, L is length of heater pin, D_e is hydraulic

diameter, V_p is Pb-Bi superficial velocity, G is mass flow rate, and A is total cross sectional area.

The two-phase multiplication factor is expressed by⁵⁾

$$(\phi_{LO})^2 = [1 + x(\rho_p/\rho_w - 1)] [1 + x(\mu_p/\mu_w - 1)]^{-0.25}, \quad (5)$$

where x is the steam quality in a steam and Pb-Bi mixture and is defined as $x = G_f/(G_p + G_f)$, ρ_w is the average density of the steam and water mixture and is defined as $\rho_w = [x_w/\rho_g + (1 - x_w)/\rho_f]^{-1}$, ρ_c is the average fluid density in the chimney and is defined as $\rho_c = \alpha\rho_w + (1 - \alpha)\rho_p$, and μ is dynamic viscosity, and x_w is steam quality

Frictional pressure drop of bare bundle is expressed by

$$\Delta P_b = (\rho/2) f (L/D_e) (V_b)^2, \quad (6)$$

where f is friction loss coefficient, V_b is superficial velocity in bundle.

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

$$Re_L = 300 \times 10^{1.7(P/D - 1)}, \quad (7.a)$$

$$Re_T = 10,000 \times 10^{0.7(P/D - 1)}. \quad (7.b)$$

Re is Reynolds number, L for laminar flow, and T for turbulent flow.

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

$$f_{tr} = f_L(1 - \psi)^{1/3} + f_T \psi^{1/3}, \quad (8.a)$$

in the transition flow

where

$$\psi = (\log_{10} Re - \log_{10} Re_L) / (\log_{10} Re_T - \log_{10} Re_L). \quad (8.b)$$

There are three types of the channels in fuel pin bundle depending on geometry as shown in Figure 6. Geometry factors are given by

$$C_L, C_T = a + b_1(P/D - 1) + b_2(P/D - 1)^2 \quad (9)$$

where a , b_1 and b_2 are constants, and P is pitch of heater pin and the constants are given in Table 3. Cross sectional average friction coefficients C_L and C_T are obtained by

$$C_{fb} = De_b [\sum_{i=1}^3 S_i (De/De_b)^{m/(2-m)} (C'_{fi}/De_i)^{1/(m-1)}]^{m-2} \quad (10)$$

where $S_i = N_i (A_i/A_b)$, De_b is hydraulic diameter in whole bundle, De_i is hydraulic diameter in each sub-channel, $m = 1.0$ in laminar flow, and $m = 0.18$ in turbulent flow.

Pressure loss at three grid spacers shown in Figure 7 is expressed by

$$\Delta P_G = (\rho/2) C_V \varepsilon^2 (V_b)^2, \quad (11)$$

where C_V is modification coeff. for honeycomb type grid spacer,

$$\log_{10}(C_V) = 3.018 - 0.8712 \log_{10}(Re_b) + 8.688 \times 10^{-2} (\log_{10}(Re_b))^2 \quad (12)$$

$$\varepsilon = (A_{sp}/A) \quad (13)$$

Figure 6. Inner, outer and corner channels in fuel pin bundle

Table 3. Constants a, b1, b2 at P/D 15.2/12 = 1.27, W/D= 13.6/12 = 1.13

Sub-channels	Laminar flow			Turbulent flow		
	a	b1	b2	a	b1	b2
Inner channel	35.6	264	-190	0.134	0.0906	-0.0993
Outer channel	44.4	257	-268	0.143	0.0420	-0.0443
Corner channel	58.8	161	-204	0.145	0.0268	-0.0341

Figure 7. Honeycomb type grid spacer

Frictional pressure losses in the pipes and the other flow resistances given by

$$\Delta P = [\zeta + \lambda(L/D)](\rho/2).V^2 \quad (14)$$

3.3 Drift flux model

In the absence of the detailed two-phase flow information needed to calculate the buoyancy force, the drift-flux models have been used in the thermal-hydraulic analysis. The drift-flux model is one of the most practical and accurate models for two-phase flow calculation. The model takes account of relative motion between phases.

In the previous analytical work⁹⁾, non-dimensional drift-flux model have been used¹⁰⁾,

$$\alpha = j_w^+ / [C_0(j_w^+ + j_p^+) + V_{wj}^+]. \quad (15)$$

The void fraction (α) is expressed as a function of the liquid and gas non-dimensional superficial velocities j_p^+ and j_w^+ , respectively, a phase distribution parameter C_0 and the non-dimensional drift velocity between the phases V_{wj}^+ .

Non-dimensional superficial velocities are defined by

$$j_k^+ = j_k / ((g \cdot \sigma \Delta \rho) / \rho_p^2)^{0.25}, \quad k = w, p \quad (16)$$

for the higher viscosity,

$$V_{wj}^+ = 0.92 (\rho_w / \rho_p)^{-0.157}, \quad (17)$$

$$C_0 = 1.2 - 0.2 \sqrt{(\rho_w / \rho_p)}. \quad (18)$$

In the one-dimensional drift flux model used in the present analysis, the void fraction is expressed by the following equation¹¹⁾:

$$\alpha = j_w / [C_0(j_w + j_p) + V_{wj}]. \quad (19)$$

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

$$j_w = G_w / (\rho_w A), \quad (20.a)$$

$$j_p = G_L / (\rho_p A), \quad (20.b)$$

where G_w 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 drift velocity, V_{wj} expressed as follows:

$$V_{wj} = 2.0 [(g \cdot \sigma \Delta \rho) / \rho_p^2]^{0.25}. \quad (21)$$

The distribution parameter is given by:

$$C_0 = 1.1 \quad (22)$$

Measured Pb-Bi temperature in the Pb-Bi flow loop, sub-cooled water temperature, system pressure and heater pin power presented in Table 4 were used for the estimate of Pb-Bi physical properties in the above equations.

Table 4. Experiment data

	1 st Test	2 nd Test	3 rd test
Pressure (MPa)	< 1.0	0.05 – 6.8	5
Pb-Bi Temp. at inlet (C)	290	285-400	280
Water inject. Temp. (C)	219	165-230	210
Heater Power (kW)	34-50	16-34	41-103

The distribution parameter and the drift velocity between the phases are computed by fitting the calculated Pb-Bi flow rate to experimental data.

4. Result and Discussion

After the fitting with the experimental data, the distribution parameter and the drift velocity was obtained as follow:

$$\alpha = j_w / [1.1(j_w + j_p) + 2.0 [(g \sigma \Delta \rho) / \rho_p^2]^{0.25}] \quad (23)$$

Experimental data for Pb-Bi flow rate are compared with an analytical result in Figures 8 and 9. The data was taken in three experimental conditions in Table 4. In Figure 8, the analytical result agreed reasonably well with the experimental data. However, in the 1st test the analytical result have a discrepancy with experimental data. This may be attributed to dependency of the Pb-Bi flow rate on system pressure.

It was found in Figure 9 that at the low system pressure in the 1st test the analytical result was lower than the experimental data and at the low and the high pressure in the 2nd test the analytical result was lower than the experimental data and agreed well at the pressure of 2–4MPa.

The reason is that the pressure losses are higher in analytical calculation rather than in experimental. Table 5 shows the average pressure losses as an analytical result. It is found that at the low system pressure less than 0.22MPa the pressure losses in the chimney is higher than in the heater bundle, which means many bubble are produced in the chimney. Calculated void fraction shows in Figure 10. It is found that the calculated void fraction is high in the low system pressure.

Table 5. Average pressure losses (MPa)

	Bundle	Chimney	Down-comer
1 st Test	0.110662	0.026908	0.050574
2 nd Test			
P < 0.22Mpa	0.082307	0.112858	0.037502
1.0 < P < 2.0MPa	0.10482	0.019533	0.047955
P > 2.0MPa	0.080046	0.009425	0.036487
3 rd Test	0.069804	0.007018	0.03159

Comparison of experimental result for Pb-Bi flow rate with analysis is shown in Figure 11. The author also compared with a previous analytical work using non-dimensional drift-flux model given by

$$\alpha = j_w^+ / \{ [1.2 - 0.2\sqrt{(\rho_w/\rho_p)}] (j_w^+ + j_p^+) + 0.92 (\rho_w/\rho_p)^{-0.157} \} \quad (24)$$

It is found that the deviation of calculation for both models is also less than 20%. It is found that the Pb-Bi flow rate obtained from Eq. (24) is slightly lower than that from Eq. (23).

This error can be reduced if an empirical correlation for the void fraction is obtained experimentally to determine the drift velocity and the phase's distribution parameter.

5. Conclusion

Boiling two-phase characteristic of Pb-Bi-water direct contact has been investigated experimentally and analytically, which contribute the analyses of balance condition between pressure losses and the buoyancy forces in the flow channel. The measured Pb-Bi flow rate has been evaluated using the drift-flux model. It was found that pressure the calculated flow rate was much lower than experimental data at low system and agreed well with experimental data at pressure range of 2–4MPa. If the effect of surface tension is taken in to account for the drift velocity, the calculated Pb-Bi flow rate agreed better with the experimental data.

The deviation between the experimental data and the calculation result is less than 20%.

Figure 8. Pb-Bi flow rate vs. water-steam flow rate

Figure 9. Pb-Bi flow rate vs. system pressure

Figure 10. Calculated void fraction vs. System Pressure

Figure 11. Pb-Bi flow rate experiment vs. analysis

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