Study on Bubbly Flow Behavior in Natural Circulation Reactor by Thermal-Hydraulic Simulation Tests with SF₆-Gas and Ethanol Liquid

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Abstract

An advanced experimental technique has been developed to simulate two-phase flow behavior in a light water reactor (LWR).

The technique applies three kinds of methods; (1) use of sulfur-hexafluoride (SF₆) gas and ethanol (C₂H₅OH) liquid at atmospheric temperature and a pressure less than 1.0MPa, where the fluid properties are similar to steam-water ones in the LWR, (2) generation of bubble with a sintering tube, which simulates bubble generation on heated surface in the LWR, (3) measurement of detailed bubble distribution data with a bi-optical probe (BOP), (4) and measurement of liquid velocities with the tracer liquid. This experimental technique provides easy visualization of flows by using a large scale experimental apparatus, which gives three-dimensional flows, and measurement of detailed spatial distributions of two-phase flow.

With this technique, we have carried out experiments simulating two-phase flow behavior in a single-channel geometry, a multi-rod-bundle one, and a horizontal-tube-bundle one on a typical natural circulation reactor system. Those experiments have clarified a) a flow regime map in a rod bundle on the transient region between bubbly and churn flow, b) three-dimensional flow behaviour in rod-bundles where inter-subassembly cross-flow occurs, c) bubble-separation behavior with consideration of reactor internal structures. The data have given analysis models for the natural circulation reactor design with good extrapolation.
1. INTRODUCTION

A power generation plant, such as nuclear and boiler, employs a high-temperature and high-pressure steam-water two-phase flow system for attaining high heat efficiency. An extensive effort has been directed to scale up of power plants. Though two-phase flow phenomena are investigated, those plants are difficult to design because of the complexity of flow characteristics, and their unknown behavior under different sets of design parameters such as temperature, pressure, and geometry.

For developing those systems, it is important to simulate phenomena in components constituting the systems. One of the important parameters on simulating is physical properties of fluids. Steam-water flow in a high-temperature and high-pressure system behaves quite different from in an atmospheric temperature and pressure system that is used for a basic hydraulic-simulation test. We have been developing an experimental technique using alternative fluids, sulphur hexafluoride (SF₆) gas and ethanol (C₂H₅OH) liquid.

This study focused on clarifying steam-water bubbly flow behavior in a natural circulation reactor, as shown in Fig1.

Natural circulation is induced by hydraulic head difference between horizontal centres of a core and a heat-exchanger in the reactor vessel. The reactor vessel is pressurized by the steam from the boiled water itself. In this situation, there is free surface in the vessel. Steam and water phases will be separated at the surface unless any specific mechanistic device would be introduced. And a portion of steam will go up to a steam dome, while the rest of the steam will be carried under into a down-comer with the liquid. The steam is condensed and hot water is cooled down by heat-exchanger.

We have already carried out steam-water experiments under actual temperature and pressure conditions with a φ30mm-tube type apparatus from Japanese FY2001 to FY2004 as the phase-1 development, and have clarified that our natural circulation system is feasible. This study has also shown some issues to be solved;

1) two-phase flow with small bubbles around φ1mm keeps bubbly flow regime under void fractions less than 40%, in which the current data-base shows that flow regime goes into slag flow regime, commonly.

2) three-dimensional flow behavior in rod-bundles give large effects for the natural circulation system, because inter-subassembly cross-flow will occur in cases like that a subassembly with a small void fraction is loaded next a subassembly with large void fraction.

3) bubble-separation behavior must be evaluated with consideration of reactor internal structures, including the heat exchanger itself, around the free surface because of lack of data-base on the configuration.

![Fig. 1 Outline of integrated primary system reactor](image-url)
As the phase-2 development, we have performed thermal-hydraulic simulation tests with an advanced experimental method from Japanese FY2005 to FY2007. The tests have simulated rod-bundles, core-internal structures in the riser and structures around the free surface. This paper describes about the experiments and recommended evaluation methods for reactor designs of the natural circulation water reactor.

2. EXPERIMENTAL METHODS

2.1 Fluid Materials

Table 1 shows a comparison of physical properties of fluids. On the SF₆-C₂H₅OH system at 30 °C and 0.7MPa, the gas density, gas-liquid density ratio and surface tension are close to those of the steam-water system at 270 °C and 6MPa. For bubbly flow, those parameters have effects on a bubble behavior, such as terminal velocity, flow regime, and pressure drop.

The advantage of this experimental technique is that a test in the atmospheric temperature and a lower pressure easily simulates two-phase flow phenomena in a high-temperature and high-pressure steam-water system and detailed observations and measurements of two-phase flow data, such as void fraction, diameter, velocity, and interference with a structure in a flow channel.

This experimental technique has been used for a study on a stable droplet in a fuel rod of a pressurized water reactor (PWR) under a loss of coolant accident (LOCA) [1]. In the study, the steady droplet diameter and the effects of system pressure and the gas velocity on it was clarified, and also the behavior of droplets was observed.

| Fluid           | Unit | Sulfur hexafluoride (SF₆) | Ethanol liquid (C₂H₅OH) | Steam | Water | Air-Water Freon (R123) |
|-----------------|------|--------------------------|-------------------------|-------|-------|------------------------|
| System pressure | MPa  | 0.3                      | 0.5                      | 0.7   | 8.7-15.5 | 0.1                      |
| Temperature     | °C   | 30                       | 300.9-344.8              | 30    | 97    | 1214                   |
| Gas density     | kg/m³| 18.0                     | 30.8-44.2                | 46.9-101.9 | 1.2                   |
| Liquid density  | kg/m³| 784                      | 710-594                  | 998   | 1214  |
| Gas viscosity   | Pas  | 1.58×10⁻⁵                | 1.98-2.30×10⁻⁵           | 1.87×10⁻⁵ | 1.3×10⁻⁵             |
| Liquid viscosity| Pas  | 1.08×10⁻³                | 8.55-6.81×10⁻⁵           | 7.81×10⁻⁴ | 1.96×10⁻⁴             |
| Surface tension | mN/m | 22.2                     | 14.2-4.7                 | 71    | 7.1   |
| Density ratio   | -    | 43.6                     | 25.5-17.7                | 15.2-5.8 | 833     |
| Density difference | kg/m³ | 766                     | 753-740                  | 663-492 | 986.8  |

2.2 Bubble Generation and Measurement

Our experiments were adopted a bi-optical probe (BOP) to measure void fractions, bubble diameters and interfacial velocities. Fig. 2 shows a tip of the BOP. A clearance between the sensor needles of the tip is about 1mm. The BOPs was installed in the test section and traversed over the cross section of the flow channels.

Bubble sizes to be measured are around 0.1mm described in the following. In this study, an applicability of the BOP for measuring such small bubbles was confirmed by comparing high-speed video, recording bubble contacts at the tip of the BOP, and measured BOP signals.
2.3 Liquid Flow Measurement by Tracer

The liquid cross-flow in the tube bundles was measured with a tracer-technique. Fig. 3 shows a schematic of tracer concentration measurement. The tracer is a fluorescence dye, and fed from the one side of the bundle with a uniform concentration. The tracer is diffused by turbulent and cross-flow due to differential pressure. The tracer concentration is measured with an isokinetic suction method. The liquid cross-flow rate is calculated from the tracer concentrative distributions and the differences between the upstream and downstream. An averaged tracer concentration is calculated in each bundle measurement elevation.

2.4 Bubble Generation Method

This study has focused on bubble behavior in developing bubbly flow, collapse and/or coalescence, along the rod-bundle and the riser. Therefore, it is important to generate small-size bubbles as same as that in the actual reactors. We have established a method to generate such small bubbles with a sintering tube. The bubble sizes have been measured and compared with sizes evaluated by the empirical formula for departure diameter proposed by Levy [2] (see Fig. 4).

Estimated diameters of the departure bubbles are about 0.1–0.3mm under the actual conditions in the LWR core. Fig. 5 shows a bubble diameter distribution measured near the sintering tube surface. The distribution is ranging around 0.05–1mm and the peak is at 0.1mm. The bubble generation device with the sintering tube is confirmed to simulate bubble generation phenomenon from the heated wall in the actual reactors.

\[
Y_B = C \left( \frac{\sigma D_{ht}}{\tau_w} \right)^{1/2} \left( 1 + C' \frac{g_c}{g} \frac{(\rho_h - \rho_c)}{\rho_c} D_{ht} \right)^{1/2} \left[ \frac{1}{\tau_w} \right] \]  

(1.1)

C=0.015, \quad C'=0
Fig. 3 Tracer concentration measurement

Fig. 4 Bubble prior to departure from heated surface

Fig. 5 Bubble diameter distribution measured near the sintering tube (P=0.7MPa[abs], T=30°C).
3. TESTS and Results

3.1 Rod-Bundle Test

Rod-bundle tests were carried out in order to clarify pressure drop and inter-subassembly cross-flow performances in the core which consists from rod-bundles.

(a) Test Apparatus

Fig. 6 shows the schematic diagram of experimental apparatus for a rod-bundle simulation test. The gas was fed by a blower and the liquid by a pump. Each of flow rates was measured by the orifice flow meters.

The test section is shown in Fig. 7. The gas was injected at void-generation devices and recovered at each bundle exit. A gas buffer volume was placed at the apparatus top because pressure distributions give effects on inter-subassembly cross-flow phenomena of gas flow. A part simulating a core configuration consists from two bundles. The bundle has a 4x3 rod array. The outermost rods were half cylinders and four corner rods were quarter ones. The geometry reduces wall effects on flow channels near wall. Bubbles were not generate from the quarter cylinders in order highly to simulate two-phase flow phenomena in the actual rod bundles in the core.

The actual subassembly had a flat-plate grid to support the rod-bundle and the grid blocks out the cross-flow. Hence, we carried out tests with and without the grids to confirm grid effects. (See Fig. 7(d))
Fig. 7 Test section structure of rod-bundle simulation test
The liquid cross-flow in the tube bundles was measured with a tracer-technique. The probe was traversed over the cross section of the test section as shown in Fig. 8. The gas cross-flow rates were estimated by the measured void fraction and velocity.

We carried out simulation tests under several conditions shown in Table 2. By using obtained data, we investigated pressure drop and inter-subassembly cross-flow performances.

![Fig. 8 Tracer concentration measurement location](image)

**Table 2 Experimental cases of rod-bundle simulation test**

| N.o. | Without Grid | With Grid |
|------|--------------|-----------|
|      | A  | B  | A  | B  | G-26 | G-27 | G-28 | G-29 | G-41 | G-43 | G-39 | G-45 |
| 1    | 0.50 | 0.50 | -  | -  | 0.50 | 0.51 | -  | -  | 0.49 | 0.49 | 0.47 | 0.05 |
| 12   | 1.01 | 1.01 | 0.12 | 0.13 | 1.00 | 1.00 | 0.97 | 0.12 | 1.00 | 1.00 | 0.12 | 0.12 |
| 18   | 1.50 | 1.50 | 1.40 | 1.40 | 1.50 | 1.50 | 1.40 | 1.40 | 1.49 | 1.49 | 1.43 | 1.43 |
| 33   | 1.52 | 1.51 | 1.41 | 1.40 | 1.52 | 1.52 | 1.41 | 1.40 | 1.01 | 1.00 | 0.96 | 0.96 |
| 43   | 0.50 | 0.50 | 0.49 | 0.06 | 0.50 | 0.51 | -  | -  | 0.49 | 0.51 | -  | -  |
| 49   | 1.00 | 1.00 | 0.97 | 0.12 | 1.00 | 1.00 | -  | -  | 1.00 | 1.00 | -  | -  |
| 31   | 1.51 | 1.50 | 1.40 | 0.18 | 1.51 | 1.52 | -  | -  | 1.49 | 1.49 | -  | -  |
| 39   | 1.00 | 1.00 | 0.97 | 0.12 | 1.00 | 1.00 | -  | -  | 1.01 | 1.01 | -  | -  |

**Table 2** Experimental cases of rod-bundle simulation test
(b) Results

1) Flow Pattern

Fig. 9 shows the bubble appearances observed at the outlet of the test section. Bundle A and B are high and low void fraction conditions of uniform inlet liquid velocity, respectively. Bubbles flowed without coalescence, even though, the bubbles were dense-packed and contacting each other, and the flow pattern was bubbly flow.

Fig. 10 shows a flow pattern map. A radius of a circle in the Fig.10 indicates a normalized standard deviation of differential pressure fluctuation in the measurement.

| Without Grid | With Grid |
|--------------|-----------|
| A            | B         |
| ![Image](image1.png) | ![Image](image2.png) |
| ![Image](image3.png) | ![Image](image4.png) |

|  | A | B |
|---|---|---|
| $j_g$ [m/s] | 0.96 | 0.12 |
| $j_l$ [m/s] | 1.0 | 1.0 |

Fig. 9 Bubbles observed at the outlet of the test section

Fig. 10 Flow pattern in fuel bundle
The doted line is drawn for flow regime transition between bubbly and churn flow by the modified Mishima-Ishii’s equations [3], which are as follows;

$$\frac{j_g}{\alpha} = C_0(j_g + j_l) + V_{gl} \quad (3.1)$$

$$C_0 = \left[ C_\infty - (C_\infty - 1) \cdot \sqrt{\frac{\rho_g}{\rho_l}} \right] \cdot (1 - \exp(-18 \cdot \alpha_{RB})) \quad (3.2)$$

$$C_\infty = 1.2 \quad (3.3)$$

$$V_{gl} = \sqrt{2} \cdot \left( \frac{\sigma \cdot g \cdot (\rho_l - \rho_g)}{\rho_l^2} \right)^{0.25} \cdot (1 - \alpha_{RB})^{1.75} \quad (3.4)$$

$$\alpha_{RB} = f \cdot \alpha \quad (3.5)$$

$$\alpha = 0.3 \quad (3.6)$$

$$f = \frac{4/\pi (Pt/D_p)^2 - 1}{\left(\sqrt{2} \cdot Pt/D_p - 1\right)^2} \quad (3.7)$$

The equations are considered a geometrical effect on void fractions. Void fractions averaged over the cross-section area of rod bundle are higher than void fractions around the flow channel center and lower around the rod surface. The above equations apply the void fractions around the flow channel center by using Eq. (3.7).

2) Inter-Subassembly Cross-Flow

Fig. 11 shows horizontal distributions of the void fractions and the bubble diameters. The experimental condition was $j_g=0.96\text{m/s}$ for the BundleA, 0.12 for the BundleB, and uniform inlet liquid velocity $j_l=1.0\text{m/s}$. For $H=796\text{mm}$, the void fractions and bubble diameters in the bundle gap was higher than that in the flow center. For $H=1196\text{mm}$, the void fractions and bubble diameters in the flow center was higher than that in the bundle gap. This was because the generated bubbles flowed near the sintering tube coalesced and developed in the flow direction gathering around the flow center. The effect of the gird on the cross-flow was small.

Fig. 12 shows the tracer concentrations and those changing behavior along the tube bundle. Fig. 13 shows the comparison of cross-flow rate between the without and with grid. The effect of the gird on the cross-flow was small.
Fig. 11 Void fraction and bubble diameter in rod bundle

Bundle-A: $j_g : 0.96\text{m/s}$, $j_l : 1.00\text{m/s}$, Bundle-B: $j_g : 1.00\text{m/s}$
Measurement height : $H=726\text{mm}$, 1196mm
Tracer Concentration

Fig. 12 Liquid Cross-Flow Measured by Tracer Technique
(jg(A,B) = (0.96,0.12), jl(A,B) = (1.0,1.0), with grid)

Cross flow rate (kg/m.s)

Fig. 13 Cross-flow between bundle A and B with/without grid
(jg(A,B) = (0.96,0.12), jl(A,B) = (1.0,1.0))
3.2 Gas-Separation Test

The gas separation test was carried out in order to clarify bubble separation performances at the liquid free surface and a helical-type steam generator under downward flow.

(a) Test apparatus

The test apparatus, as shown in Fig. 14, consisted of four parts, i.e a gas generation section, a riser simulation section, a down-comer simulation section, and a horizontal junction which combined the riser and down-comer simulation sections. SF₆ gas was injected at bubble generation devices, and recovered at the top of the riser simulation section without liquid and the bottom of the down-comer simulation section with liquid.

In the down-comer section, the horizontal tubes were placed to simulate a steam generator with helical-type tubes. The tube specifications were a 1/1-scale of a typical steam generator because a test fluid velocity range was similar to the actual reactor operation conditions. The bottom of the section is narrowed to simulate downward flow by heat removal around the steam generator.

![Test apparatus structure of core-internal simulation test](image-url)
Table 3 shows the experimental conditions. The parameters are the gas and liquid velocities, and the liquid free surface level.

Gas separation ratios from the liquid free surface were measured by the flow meter set at the outlet of the gas dome.

Bubble flow behavior near the liquid surface was observed though the observation port mounted on the side wall and the top of the test section.

Void fractions were measured with the BOP traversing it in the horizontal flow direction.

### Table 3 Experimental Conditions

| Parameter                      | Value        |
|--------------------------------|--------------|
| System Pressure                | 0.7 MPa      |
| System Temperature             | 30 °C        |
| Superficial Gas Velocity       | 0.2~0.4 m/s  |
| Superficial Liquid Velocity    | 0.35~0.55 m/s|
| Liquid Free Surface Level      | 100~300 mm   |

(b) Results

Fig. 15 shows the observation of bubble appearances around free surface and horizontal tubes. The bubble near the free surface coalesced and became larger, and finally, collapsed and separated at the surface. When putting riser-plate-slit, there existed a vortex at the down stream of the slit. The liquid free surface level was fluctuating.

In the horizontal tubes bundle, the bubble was absorbed near the horizontal free surface. The bubbles flowing in the tube bundle were trapped at the weak of the tubes, and then coalesced to become larger, sometimes slug. A number of large bubbles of which terminal velocity was higher than downward liquid velocity increased to the free surface and collapsed.

By using obtained data, we have investigated bubble separation performances.

Typical horizontal distributions of void fractions with and without the slit are shown in Fig. 18. The both of the void fraction distributions in the riser simulation section were convex upward and it was estimated that upward velocity distributions were bulging.

In the horizontal flow, the void fractions became smaller along downward, and it was estimated that bubble separation rates were almost constant in the case of the no-slit test. In the case of the slit test, the void fractions downstream of the slit were larger and bubble separation ratios were larger than the no-slit test. This was because the gas was drawn into a whirlpool in that area.

Hence, in the riser section, it is assumed that bubble separation ratios are proportional to ratios of void fractions around the free surface to ones in the riser inlet. The latter ratios were evaluated by the Ishii equation in the Drift-Flux Model [7] and the former are by the Wilson equation [8], which were constructed bubbly flow tests under natural circulation velocity.

\[
\beta = 1 - \frac{\alpha_s}{\alpha_t} \quad (3.8)
\]

\[
\frac{j_g}{\alpha_t} = C_o (j_g + j_l) + \sqrt{2 \left( \frac{\sigma g \Delta \rho}{\rho_l^2} \right)^{1/4}} \quad (3.9)
\]
< Wilson eq. [8]>

\[
\alpha_s = a \left( \frac{\rho_g}{\rho_l - \rho_g} \right)^{0.12} \left( \frac{\Sigma}{D_H} \right)^{0.1} \text{Fr}^b \left( \frac{j_g}{j_g + j_l} \right)^{0.6}
\]  
(3.10)

\[
\Sigma = \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}
\]  
(3.11)

\[
\text{Fr} = \frac{j_g}{\sqrt{\Sigma g}}
\]  
(3.12)

where, \( \text{Fr} < 1.5, \text{Fr} > 10 : a = 0.564, b = 0.67 \)

1.5 \( \leq \text{Fr} \leq 10 : a = 0.619, b = 0.47 \)

In the horizontal junction, the separation ratios was evaluated by a simple model, as shown in Fig. 19, by using a horizontal velocity \( U \) and a vertical terminal velocity \( V \). A bubble with velocity of \( U \) and \( V \) is separated when a vertical migration length of the bubble is longer than \( d_{H_{si}} \) before the bubble moves along a horizontal migration length \( d_L \). The \( V \) is evaluated by the Drift-Flux model with \( C_0=1, j_l=0 \), which values are in vertical open flow-channels, as follows;

< Bubble terminal velocity>

\[
V = \sqrt{2} \left( \frac{\sigma g \Delta \rho}{\rho_l^2} \right)^{1/4} (1 - \alpha_h)^{0.75}
\]  
(3.13)

The gas separation rate is obtained by integrating a product of bubble terminal velocity and its rising time in a differential section \( dL \).

\[
Q_{sep} = \sum_i N_i dH_{u_i} \cdot dA_{r_i}
\]

\[
= \sum_i N_i dL_i \cdot V_i \cdot dA_{r_i}
\]  
(3.14)

The void fraction in each differential section is accounted for calculating terminal velocity. The void fraction is calculated with Smith’s equation [9].

\[
\alpha_h = \left[ 1 + \frac{\rho_g}{\rho_l} \left( \frac{1}{x} - 1 \right) + \frac{\rho_g}{\rho_l} (1 - e) \left( \frac{1}{x} - 1 \right) \left[ \frac{\rho_l / \rho_g + e(1/x - 1)}{1 + e(1/x - 1)} \right]^{1/2} \right]^{-1}
\]  
(3.15)

where, \( e = 0.4 \)

As shown in Fig. 20, we have confirmed that the above evaluation method gives good agreements within \( \pm 20\% \). The method is available in bubble separation ratio evaluations under actual thermal-hydraulic conditions in the core on the natural circulation reactors because of considering fluid properties.
Fig. 15 Bubble behaviour at liquid free surface and tube bundle
Fig. 16 Void fraction distribution around free surface

Fig. 17 Bubble separation model in horizontal junction

Fig. 18 Comparison of gas separation ratio between experiment and calculation
4. CONCLUSIONS
In order to obtain steam-water flow data in the natural circulation LWR, we have carried out gas-liquid two-phase flow tests with the advanced experimental technique, using SF₆-gas and ethanol liquid, measuring with BOP for gas phase, and tracer method for liquid phase. The tests simulated typical two-phase flow phenomena in the reactor vessel of the LWR. The tests have given very detailed and highly visualized data, and so we have established the empirical formulas for evaluating two-phase flow behavior.

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NOMENCLATURE

| Symbol | Description                        | Unit     |
|--------|------------------------------------|----------|
| A      | flow passage cross-section         | [m²]     |
| Aₚ     | free surface area                  | [m²]     |
| Aₒ     | flow passage cross-section at orifice | [m²]    |
| Co     | distribution parameter             | [-]      |
| DH     | hydraulic equivalent diameter      | [m]      |
| Fr     | Froude number                      | [-]      |
| G      | total mass flux                    | [kg/m²s] |
| g      | gravity acceleration               | (9.8m/s²) |
| j      | superficial velocity               | [m/s]    |
| Q      | volume flow rate                   | [m³/s]   |
| x      | quality                            | [-]      |
| L      | distance from the origin           | [m]      |
| U      | horizontal velocity                | [m/s]    |
| V      | vertical velocity                  | [m/s]    |

(Greek letters)

| Symbol | Description                        | Unit     |
|--------|------------------------------------|----------|
| α      | void fraction                      | [-]      |
| µ      | viscosity                           | [Pas]    |
| ρ      | density                            | [kg/m³]  |
| Σ      | Laplace length                     | [m]      |
| σ      | surface tension                    | [N/m]    |
| φₐ     | two-phase multiplier               | [-]      |
| φ₂     | Lockhart-Martinelli parameter      | [-]      |

(Subscripts)

| Symbol | Description                        |
|--------|------------------------------------|
| g      | gas-phase                          |
| h      | horizontal                         |
| l      | liquid-phase                       |
| r      | riser                              |
| s      | surface                            |
| sep    | separation                         |

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