# Development of Numerical Evaluation Method for Unsteady or Phase-changing Gas-liquid Two-phase Flow


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*Mitsubishi Heavy Industries Group provides plant piping and heat exchangers. When designing these products, the so-called gas-liquid two-phase flow phenomenon must be considered. Gas-liquid two-phase flow involves physical phenomena such as phase change and gas-liquid interfacial drag, which do not occur in single-phase flow. It is very difficult to predict or evaluate gas-liquid two-phase flow compared to single-phase flow. We have developed a two-phase flow analysis method based on the two-fluid model and conducted performance and design index evaluations for related products. This article introduces the overview of the technology.*

## 1. Introduction

It is known that in the piping of chemical plants and oil production facilities, piping vibration induced by the two-phase flow inside the pipes may occur [(1)]. Therefore, in the design of plant piping, it is necessary to predict the unsteady behavior of gas-liquid two-phase flow in pipes such as the continual collision of liquid slugs with the elbows.

On the other hand, in a heat exchanger installed in an indoor unit or outdoor unit of an air conditioner, a refrigerant in a gas-liquid two-phase flow is distributed in a structure with a cone-type distributor, T-junction pipes, multiple-branch pipes, etc. It is important to accurately evaluate the distribution property of the refrigerant in design or performance estimation for a heat exchanger.

In addition, in the design of equipment involving two-phase flow, an abrupt phase change may become a design issue and it is important to develop an analysis method to address such a phenomenon.

This article introduces the analysis method and analysis example for the unsteady behavior of gas-liquid two-phase flow in pipes and its distribution at branch pipes. Efforts to apply the analysis method to the depressurized boiling phenomenon (flashing) involving an abrupt phase change are also described.

## 2. Two-phase flow analysis method

For the reproduction of gas slug or liquid slug in pipes and the evaluation of the distribution of gas and liquid in branch pipes, the two-fluid model processing gas phase and liquid phase by different equations is adopted. Using the generalized thermal hydraulics analysis code "ANSYS Fluent" as a platform, the constitutive equation required for two-fluid model analysis was used as a user-defined function to construct the analysis method. The governing equations for the two-fluid model and the major constitutive equations for the drag model, etc., were already described in the previous article [(2)]. The governing equations (mass conservation, momentum conservation, energy conservation) are given as follows:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \overrightarrow{u_k}) = \Gamma_k \qquad (1)$$

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$$\frac{\partial}{\partial t}(\alpha_k \rho_k \overrightarrow{u_k}) + \nabla \cdot (\alpha_k \rho_k \overrightarrow{u_k} \cdot \overrightarrow{u_k}) = -\alpha_k \nabla p + \nabla \cdot \left(\alpha_k \overline{\overline{\tau_k}}\right) + \alpha_k \rho_g \vec{g} + M_k \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_k \rho_k h_k) + \nabla \cdot (\alpha_k \rho_k h_k \cdot \overrightarrow{u_k}) = -\nabla \cdot (\alpha_k q_k) + \Gamma_k (h_{ki} - h_k) + a_i \cdot \overline{\overline{q_k''}} \tag{3}$$

where $\alpha_k$ is the volume fraction of the *k* phase, $\Gamma_k$ is the mass source term of the *k* phase, $M_k$ is the momentum source term of the *k* phase, $q_k$ is the heat input of the *k* phase, $\overline{\overline{q_k''}}$ is the heat flux at the gas-liquid interface and $a_i$ is the gas-liquid interfacial area concentration. *k=g* means the gas phase and *k=f* means the liquid phase.

**Figure 1** shows the interaction between the gas phase and liquid phase. Unlike single-phase flow, momentum transfer occurs due to the velocity difference between the two phases. Gas-liquid interfacial drag $M_d$ is calculated by the constitutive equation (4). The gas-liquid interfacial area concentration $a_i$ is calculated by applying the constitutive equations as a function of the gas void fraction $\alpha_g$ and the physical properties. As an example, equation (5) is applied to adiabatic bubbly flow. In equation (5), σ is the surface tension, Δρ is difference in gas-liquid density, $g$ is the gravity acceleration, ε is turbulent energy dissipation rate, and $\nu_f$ is kinematic viscosity coefficient of the liquid phase.

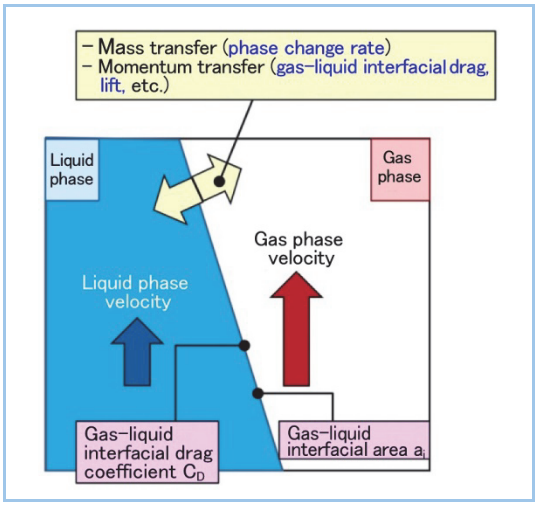


**Figure 1 Gas-liquid interaction in two-phase flow analysis**

$$M_d = -a_i \cdot \frac{C_D}{2} \cdot \rho_f \cdot \overrightarrow{u_r} \cdot |u_r| \tag{4}$$

$$a_i = \frac{3.02}{Lo} \cdot \left(\frac{L_o}{D_H}\right)^{0.335} \cdot \alpha_g \cdot \left(\frac{\varepsilon^{1/3} Lo^{4/3}}{\nu_f}\right)^{0.239} \tag{5}$$

$$Lo = \sqrt{\frac{\sigma}{\Delta\rho g}} \tag{6}$$

In equation (4), $C_D$ is drag coefficient, which is calculated by constitutive equations. For different flow regimes, different constitutive equations should be applied. One example is presented in equation (7), where $u_r$ is gas-liquid relative velocity, $D_b$ is bubble diameter, $\rho_f$ is liquid density and $\mu_m$ is mixture dynamic viscosity.

$$C_D = \frac{24}{Re_b}\left(1 + 0.1 Re_b^{0.75}\right), \quad Re_b = \frac{\rho_f u_r D_b}{\mu_m} \tag{7}$$

In order to predict the unsteady behavior of gas-liquid two-phase flow, the constitutive equation for evaluating the lift force $M_d^L$ that acts on a bubble due to the velocity gradient existing in a direction perpendicular to the flow was incorporated. The lift was calculated by equation (8), and the equation by Hibiki[4] was used for the lift coefficient $C_L$.

$$M_d^L = -\alpha_g \cdot \rho_f \cdot C_L \cdot \overrightarrow{u_r} \times \left(\nabla \times \overrightarrow{u_f}\right) \tag{8}$$

## 3. Analysis examples

As analysis examples, analyses of gas-liquid two-phase flow behavior in pipes, two-phase flow distribution behavior in branch pipes and flashing (depressurized boiling phenomenon) are described.

### 3.1 Unsteady two-phase flow in pipes

The test configuration[1] used in the analysis is shown in **Figure 2**. In a pipe with an inner diameter of 52.5 mm, the flow passes through the vertical pipe, through the 90° elbow and into the horizontal pipe. Among the conditions for air-water testing, the condition of slug flow occurring in the vertical pipe was analyzed. As shown in the contour figure of the void fraction (instantaneous value at a certain time) in **Figure 3**, slug bubbles are reproduced in the pipe. Using the time history of the void fraction and pressure in the analysis results, the exciting force acting on the elbow was evaluated by the method described in the reference document[1]. For the comparison of the exciting force obtained by the analysis and the exciting force measured in the test, the envelopes (visible outlines) of the frequency spectra are illustrated in **Figure 4**. The peak frequency of the exciting force due to the collision of liquid slug following slug bubbles is within 5 to 10 Hz, and the analysis reproduces the tendency obtained by the test. In the same way, the other flow velocity conditions were verified, and it was confirmed that the analysis method using the two-fluid model can be applied to unsteady two-phase flow behavior.

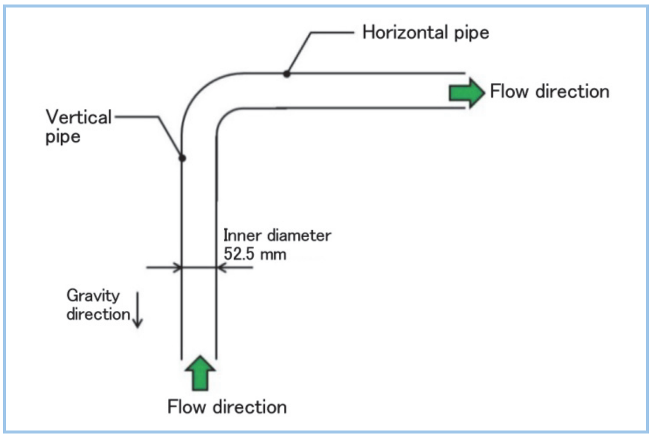


**Figure 2 Outline of the test apparatus**

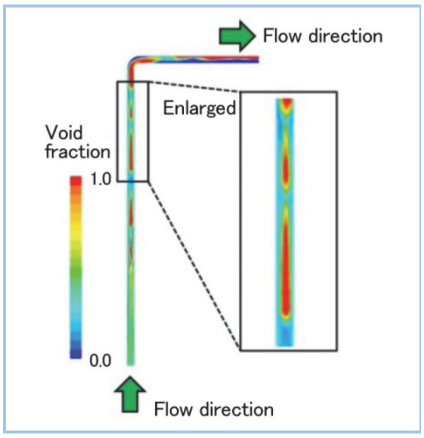


**Figure 3 Contour of the void fraction in the analysis results (instantaneous value)**

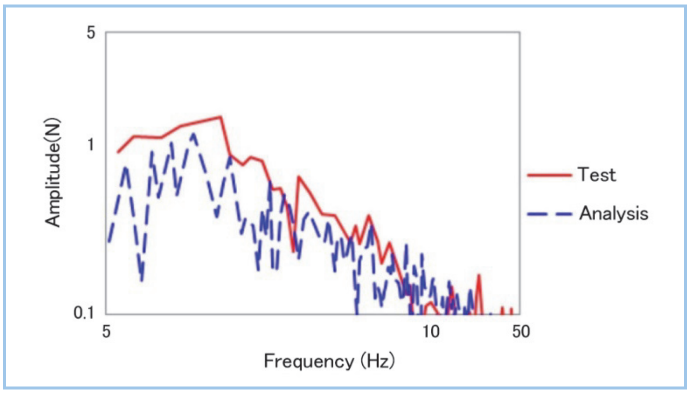


**Figure 4 Comparison of the frequency spectra**

### 3.2 Two-phase flow behavior in multiple-branch pipes

Unsteady two-phase flow analysis for a multiple-branch pipe with many branches was conducted and the prediction accuracy of the flow distribution ratio to each branch pipe was evaluated. The analyzed piping configuration is presented in **Figure 5**. In accordance with the comparison test, the analyzed piping configuration has a main pipe with an inner diameter of about 8 mm and four branch pipes with an inner diameter of about 4 mm were used. The analysis was conducted under two different conditions in which the gas mass flow ratio at the inlet of the main pipe differs, while the sum of the gas and liquid mass flows remains constant.

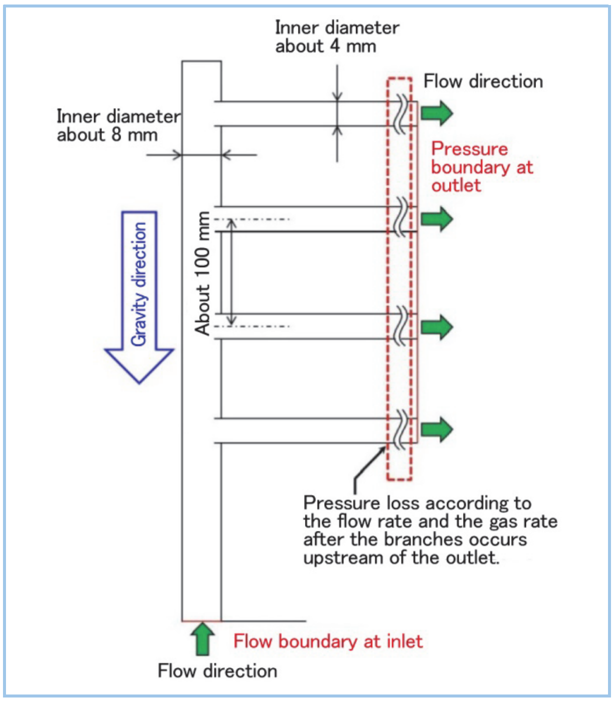


**Figure 5 Outline of the multi-branch pipes**

The flow distribution ratios obtained by the analysis can be seen in **Figure 6**. It was found that the liquid phase inflow into branch pipe 3 is less than that into the other pipes, and that the larger the gas ratio at the inlet, the larger the inertial force and the larger the liquid phase inflow ratio in the downstream branch pipes. These tendencies were reproduced in the analysis. From the results, it was confirmed that unsteady two-phase flow analysis using the two-fluid model can be applied to a system with branches.

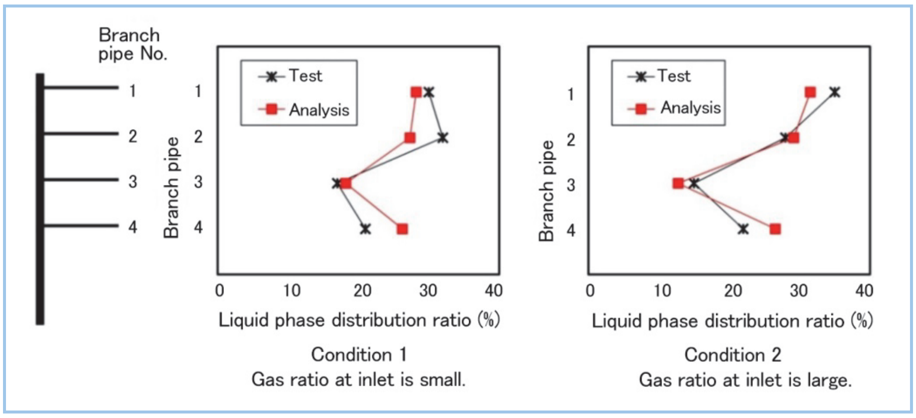


**Figure 6 Comparison of liquid phase distribution ratios**

### 3.3 Flashing

**Figure 7** shows the analysis configuration which is the same as the test apparatus used in the experiment (5). Single-phase water flows in from the inlet of the test equipment and is depressurized at the throttle part. Here, when the static pressure is reduced to the saturation pressure or lower, the depressurized boiling phenomenon which is called flashing occurs. In the analysis system, both the inlet and outlet were pressure and thermal boundary layers and the entire pipe wall was a thermally insulated boundary layer. In the calculation, a constant value (400 kPaA) of the saturated vapor pressure was used for the analysis. As noted in **Figure 8**, the mass flow in this system was evaluated with a prediction error of about 15%. However, the number of verification examples is limited, and an increase in this number is necessary for application to products. **Figure 9** is a comparison of the void fraction distribution in the flow direction between the test and the analysis. The void fraction distribution in the axial cross section approximately reproduces the test results.

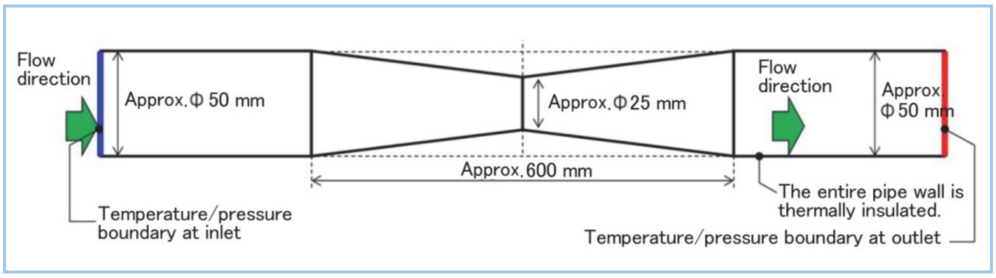


**Figure 7 Outline of the analysis system**

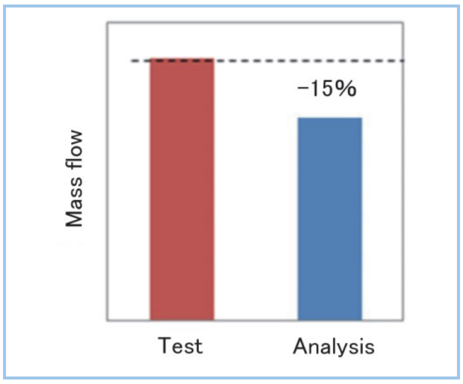


**Figure 8 Comparison of the mass flow between the decompression boiling flow analysis and the test**

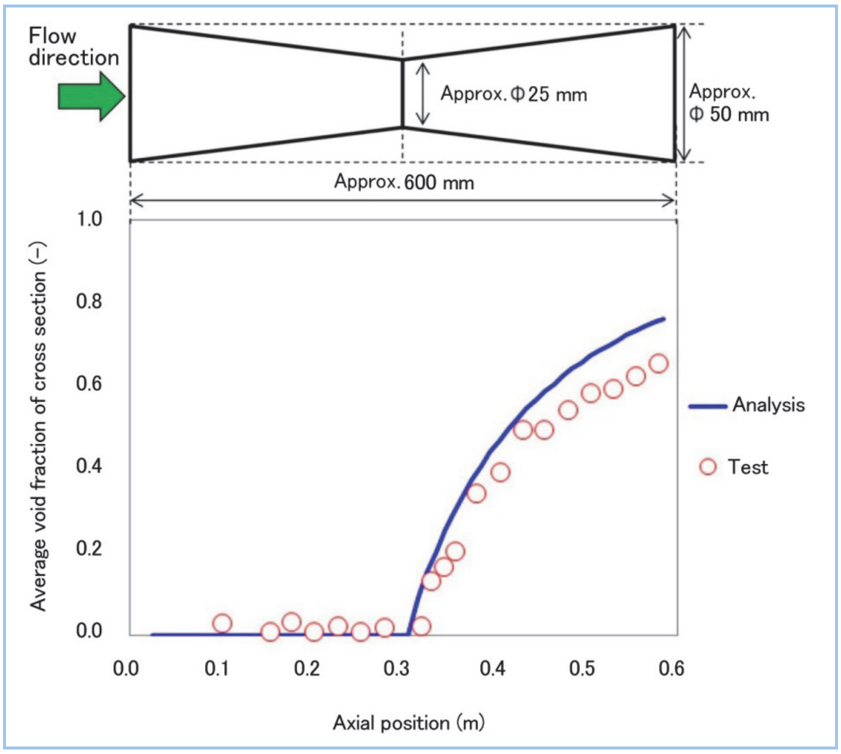


**Figure 9 Comparison of the pressure/void fraction between the decompression boiling flow analysis and the test**

## 4. Conclusion

We developed the analysis method for unsteady two-phase flows based on the two-fluid model. The gas-liquid two-phase flow behavior in pipes, the two-phase flow distribution behavior in branch pipes and the depressurized boiling phenomenon (flashing) were analyzed, and the analysis results and the test results were compared to validate the analysis method. As a result, it was confirmed that the analysis method could be applied to the prediction of the two-phase flows. We will make efforts to improve the reliability of piping design and improve the performance of heat exchangers using the analysis method.

## References

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