Development of Two-phase Flow Numerical Simulation Platform for Evaluating Boiling Heat Exchanger Design

YOSHIYUKI KONDO[*1] LING CHENG[*1]
YOSHITERU KOMURO[*2] ATSUSHI KODAMA[*2]

Many MHI products involve two-phase flow phenomenon, which is the simultaneous flow of gas and liquid phases. Establishment of an accurate and reliable analysis method for two-phase flow is much difficult than the prediction for single phase flow, since complicated interfacial transfer of mass, momentum and energy couples gas and liquid phases. A two-phase flow analysis technology based on the two-fluid model has been developed to carry out the validation and design evaluation for related products. This paper briefly introduces the new developed two-phase flow analysis technology and its applications.

1. Introduction

Many MHI products involve the simultaneous flow of gas and liquid phases. Examples of such products include steam generators that are key components of nuclear power plants, evaporators of centrifugal chillers, and reboilers of chemical plants. The accurate prediction on the thermal hydraulic behavior of gas-liquid two-phase flow is indispensable for ensuring the reliability of these products. For many years, MHI has continuously carried out intensive research studies on developing and applying the advanced two-phase flow analytical technique. This paper briefly introduces the new developed two-phase flow analysis technology and its applications.

2. Two-phase flow analysis method

A porous media approach combined with appropriate boiling heat transfer and tube bundle flow resistance correlations, has been proposed to simulate the heat transfer tube bundles inside a heat exchanger. The mass conservation equation, momentum conservation equation and energy conservation equation of the gas phase and the liquid phase in porous media are given as follows.

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

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

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

In these equations, γ is the volume fraction of the fluid, α_k is the volume fraction of the k phase, Γ_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 interface area concentration.

$k = g$ means the gas phase and $k = f$ means the liquid phase.

Figure 1 shows the interfacial mass and momentum transfer in the gas-liquid two-phase flow. Unlike single phase flow, momentum transfer occurs due to the velocity difference between the gas and liquid phases. Gas-liquid interface drag M_d is calculated by the constitutive equation

*1 Chief Staff Manager, Heat Transfer Research Department, Research & Innovation Center
*2 Heat Transfer Research Department, Research & Innovation Center

(4). The gas-liquid interfacial area concentration a_i is calculated from the void fraction α_g and the physical properties by applying the interfacial area concentration correlation.

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

C_D is the drag coefficient which can be evaluated from empirical correlations. Drag coefficient correlations usually depend on the physical properties and the bubble velocity. Equations (5) show one example of drag coefficient correlations. u_r is the relative velocity between the gas and liquid phase, D_b is the bubble diameter, ρ_f is the liquid density, and μ_m is the two-phase mixture viscosity.

$$C_D = \frac{24}{Re_b}\left(1 + 0.1Re_b^{0.75}\right),\ Re_b = \frac{\rho_f u_r D_b}{\mu_m} \tag{5}$$

In a heat exchanger, heat transfer occurs due to the temperature difference across the heat transfer tubes. **Figure 2** shows our simulation code models convective heat transfer in the tube, heat conduction of the tube wall, and boiling heat transfer or single-phase convective heat transfer outside the tubes. The simulation code considers the thermal coupling between fluids across heat transfer tubes and derives the heat flux passing through the tube wall.

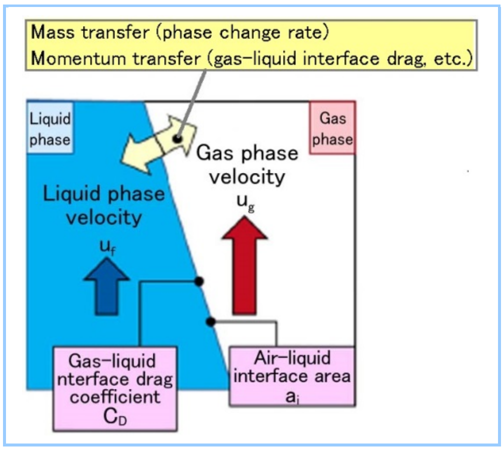

Figure 1 Gas-liquid phase action in two-phase flow analysis

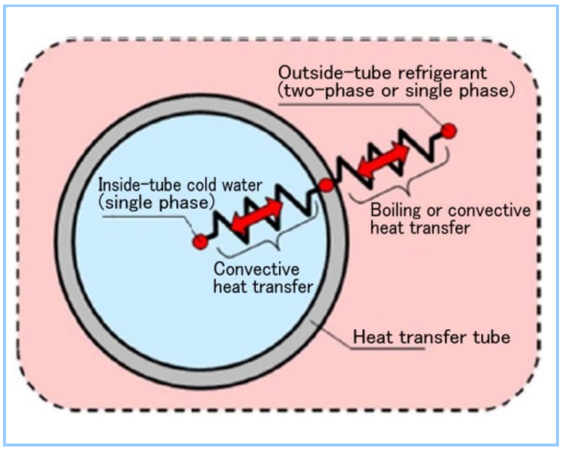

Figure 2 Concept of heat transfer inside and outside tube

3. Design calculation examples

3.1 Steam generator

Figure 3 shows the steam generator (SG) of a nuclear power plant. SG is a heat exchanger that is composed of the U-shaped heat transfer tube bundle with primary coolant flows inside the tubes. SG transfers the heat generated in the nuclear reactor core from primary coolant to the secondary coolant flowing outside the heat transfer tubes.

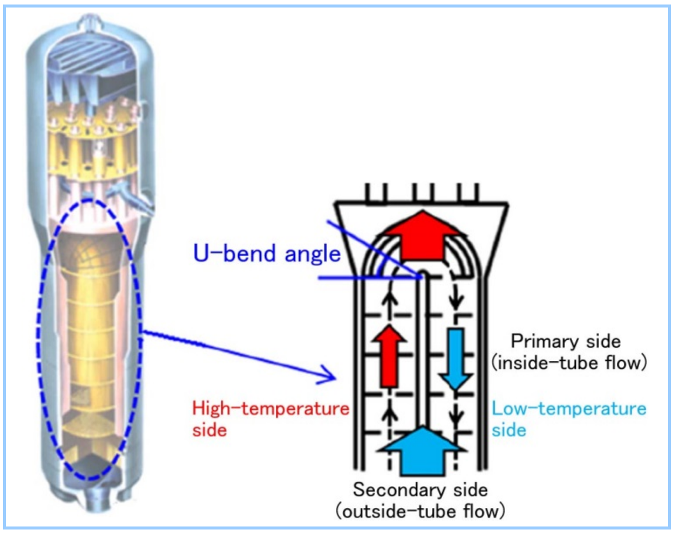

Figure 3 Structure of steam generator

Top region of the SG U-shaped heat transfer tube bundle is exposed to cross flows. In such a tube bundle, a phenomenon called fluid-elastic vibration occurs in which excessive tube vibrations are generated when the flow velocity exceeds a certain value.[1] The two-phase density distribution and flow velocity distribution are required evaluation factors for determining the occurrence threshold of fluid-elastic vibration.

The gas-liquid two-phase flow behavior outside the heat transfer tube bundle is influenced by tube arrangement and two-phase flow regimes. In addition, gas-liquid separation occurs at the large open space above the U-bend tube bundle. A two-fluid model is required to evaluate above gas-liquid flow separation phenomenon.

Actual plant simulation models the heat transfer across U-bend tubes. This paper, however, only reports a sample validation study on a series of adiabatic tests performed with a simulant fluid. Because primary coolant and secondary coolant are thermally decoupled in an adiabatic system, only the gas-liquid two-phase flow outside the tube bundle is analyzed and reported here.

A U-bend tube bundle apparatus of 1/2 scale of the actual plant is used to perform the test. SF6 (sulfur hexafluoride-ethanol) is chosen as the working fluid. SF6 is capable to mimic the actual plant fluid physical properties (steam and water density ratio, surface tension, etc.) under normal temperature and lower pressure conditions.[2, 3]

Prediction results on void fraction and gas-liquid interfacial velocity distribution are presented in **Figure 4**. This figure plots the void fraction and flow velocity distribution with respect to the U-bend angle (shown in Figure 3) at the outermost periphery of the U-bend tube. Analysis predicts low void fraction (which means a larger amount of liquid) region exists in the vicinity of the 160° U-bend angle, which is caused by the gas-liquid separation occurs in the large open space above the U-bend. The two-fluid model analysis code is capable to closely reproduce the gas-liquid separation phenomenon.

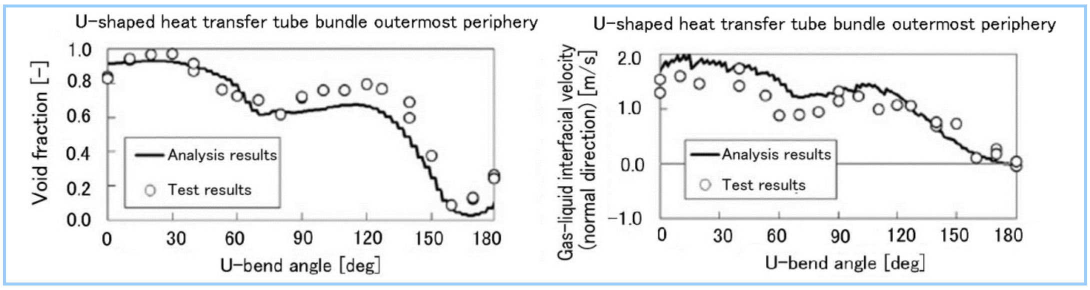

Figure 4 Analysis results of steam generator

3.2 Reboiler[4] in chemical plant

Figure 5 shows an example of MHI chemical plant system. This paper reports the design analysis for the device called reboiler, which heats up and evaporates the process liquid. As presented in **Figure 6**, superheated steam enters the thin heat transfer tubes in the reboiler and fully condensed there. Saturated process liquid flows outside the tubes and receives heat. A part of the heated process liquid evaporates and leaves the reboiler in two-phase state.

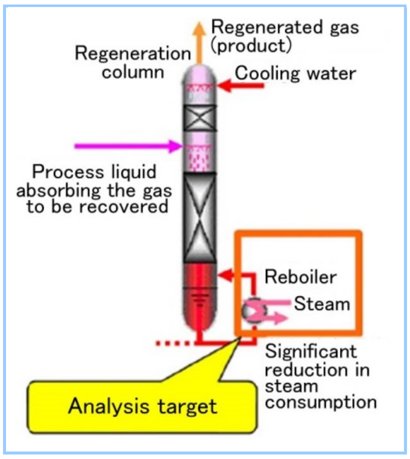

Figure 5 Reboiler in chemical plant

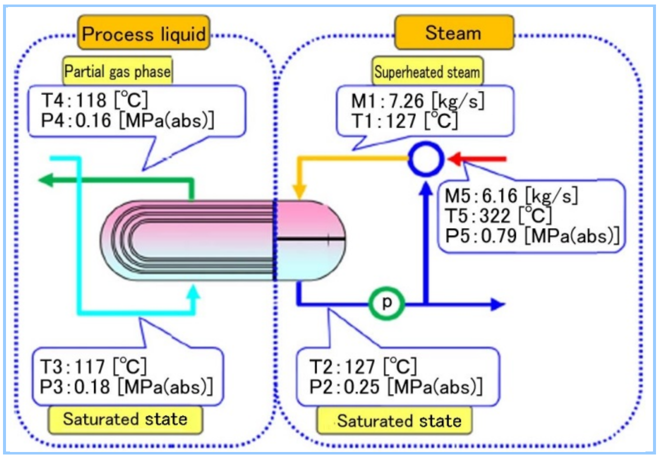

Figure 6 System diagram of periphery of reboiler (example)

The two-phase flow simulation tool can be applied to evaluate the reboiler performance. As shown in **Figure 7**, the prediction accuracy of the heat transfer rate of the demonstration plant is 10% (−10% in this example; which means the plant performance is underestimated). **Figure 8** shows the distribution of quality (mass flow rate fraction of the gas phase). The capability to predict the occurrence of a high-quality region inside the reboiler makes it possible to identify the operation conditions leading to the deterioration of the heat exchange performance. It can be confirmed that high quality zones shown in Figure 8 correspond to the low heat transfer rate zones in **Figure 9**.

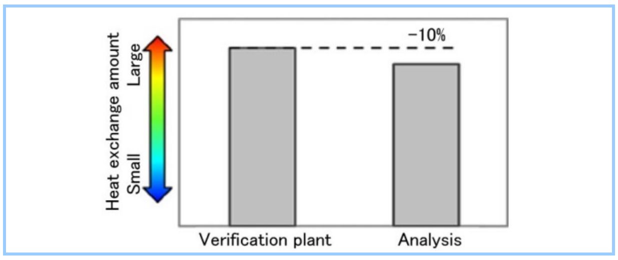

Figure 7 Analysis results of heat exchange amount

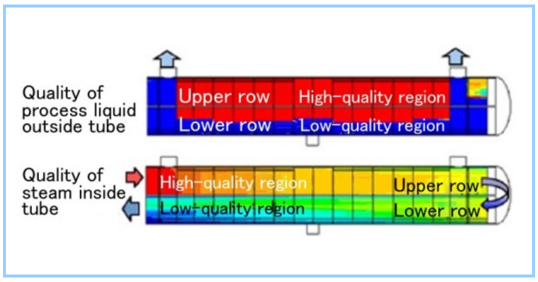

Figure 8 Evaluation of quality (mass flow rate fraction of gas phase) distribution

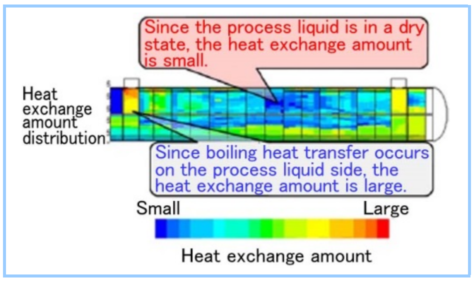

Figure 9 Evaluation of heat exchange amount distribution

3.3 Centrifugal chiller[5]

Figure 10 to **Figure 12** illustrate the evaporator of a centrifugal chiller. The refrigerant flowing outside the heat transfer tubes exchanges heat with the water flowing inside the heat transfer tubes. Knowledge of the heat exchange rate distribution is necessary for the structural integrity evaluation on those long heat transfer tubes, and the liquid level of the refrigerant is an important parameter for designing the gas-liquid separation device. By performing two-phase flow analysis of the evaporator, these design indices can be evaluated.

Figure10 Chiller external view (quoted from ETI-Z series brochure)

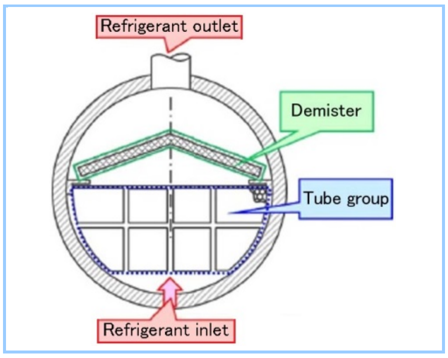

Figure 11 Evaporator sectional view

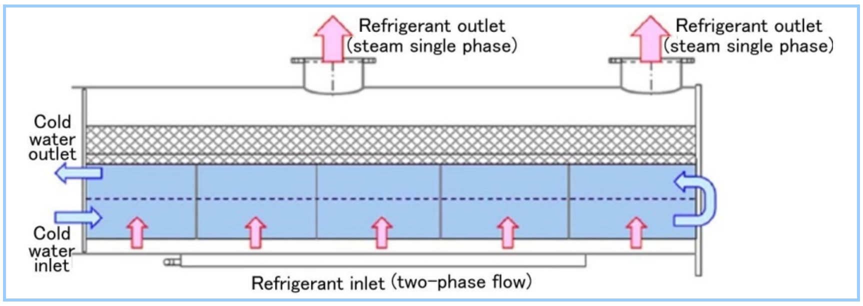

Figure 12 Evaporator side view

Design analysis focuses on the fluids flow inside the shell side of the evaporator, and the tube bundle is treated as a porous media (resistance simulating body). The thermal hydraulic analysis of the whole evaporator was performed with modelling the heat exchange between the cold water in the tubes and the refrigerant outside the tubes. From the void fraction contour (gas volume fraction distribution) presented in **Figure 13**, it is possible to identify the occurrence of low-void regions (regions with larger amount of liquid). Such result is essential for properly designing the gas-liquid separator inside the evaporator. Furthermore, temperature distribution in the tube axial direction can be derived from the heat flux contour shown in **Figure 14**. Such result is essential for assessing the structural integrity under uneven temperature distribution.

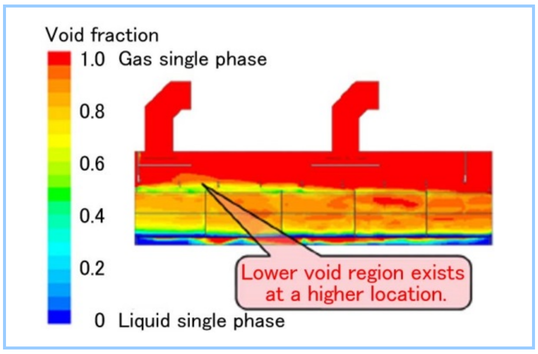

Figure 13 Void fraction distribution resulting from analysis

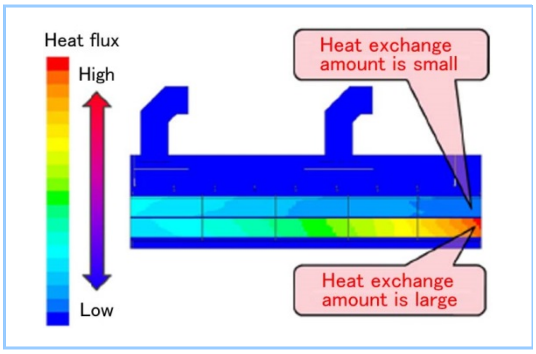

Figure 14 Heat flux distribution resulting from analysis

4. Conclusion

A two-phase flow simulation technology based on the two-fluid model has been developed in MHI. Validation and design evaluation has been performed for the steam generator of a nuclear power plant, the reboiler of a chemical plant and the evaporator of a centrifugal chiller. In the steam generator design, the new developed simulation tool is capable to evaluate the flow velocity and void fraction distribution along the U-bend tubes, thus is able to avoid the occurrence of flow-elastic vibration. In the reboiler design, the new developed simulation tool is capable to evaluate the heat exchange performance. For the evaporator of centrifugal chiller, the new developed simulation tool is capable to predict the heat exchange rate and the void fraction distribution. The void fraction distribution is essential for the design evaluation of the liquid level and gas-liquid separation performance in the evaporator. The heat exchange rate is essential for the structural integrity assessment of the evaporator.

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