Two-Phase Flow Analysis Using GAMMA+ and Comparison with the Adiabatic Two-Phase Experiment

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1. Introduction

Two-phase flow phenomena are actively employed in nuclear power plants. For instance, commercial reactors, such as pressurized water reactors (PWRs) or boiling water reactors (BWRs), produce electricity by using superheated steam generated from boiling phenomena. Furthermore, advanced-type reactors, such as molten salt reactors (MSRs), are incorporating two-phase flow phenomena. Representatively, a helium bubbling system is suggested as one of system inducing two-phase flow phenomena in MSRs.

The helium bubbling system has been adopted in various MSRs to eliminate insoluble fission products (IFPs). IFPs circulate the entire primary loop of MSRs alongside liquid fuel and attach to surfaces of specific structural materials [1]. This adhesion can lead to corrosion and reduce the heat transfer efficiency. To address these issues, a helium bubbling system was developed. Helium bubbles are injected into the riser channel in MSRs through this bubbling system. The IFPs attach to the surface of injected helium bubbles, and thereafter, helium bubbles transport the IFPs up to the upper part of the system. The IFPs, transported by helium bubbles, can be eliminated through fission products collection devices installed at the upper part.

Simultaneously, the helium injection significantly affects the entire fluidic performance of the liquid fuel. The circulation capability of liquid fuel can be changed via helium bubbling [2]. The complicated two-phase flow patterns also vary the heat transfer efficiency and frictional pressure drop. In particular, helium bubbling effect is significantly important to the natural circulation MSR. To summarize, a comprehensive understanding of the two-phase flow phenomena is required to concretize the helium bubbling system in MSRs.

To this end, a well-established two-phase flow model is required. The fluidic performance under the two-phase flow system can be predicted using this model. However, some models for two-phase flow analysis include significant uncertainties. Consequently, the two-phase flow models, existing in the numerical code, should be evaluated and validated. Thus, in this study, we simulated two-phase flow using GAMMA+ code and compared the numerical results with the experimental outcomes.

2. Setup for numerical calculation

2.1 Experimental data

The experimental outcomes for comparison to numerical results were obtained from adiabatic two-phase natural circulation experiment, which was performed in the authors' laboratory [2]. Two loops having different riser channel sizes, 2 inches and 3 inches, respectively were fabricated to investigate the helium injection effect according to variations of channel size. Deionized water was used as the working fluid and helium was utilized as injected gas. Helium was injected through a gas nozzle located at the lower part of the loop and released into the laboratory atmosphere via vent holes located at the uppermost surface of the upper pool. Helium injection rate was controlled using mass flow controller from 1 to 15 lpm (liter/minute). Fig. 1 (a) shows brief information on the experimental loops.

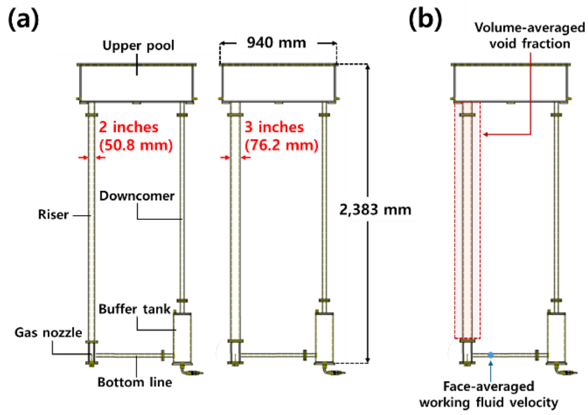

Fig. 1. (a) Schematic of experimental loops and (b) obtained data from the experiment

In this experiment, void fraction and working fluid velocity were obtained since those values are regarded as major thermal-hydraulics parameters under two-phase flow conditions. The working fluid velocities were measured using an ultrasonic flowmeter installed at the bottom line. By using the velocity values, volume-averaged void fraction for the riser channel was calculated through Livingston et al. correlation as shown in Eq. (1) [3]. Here, $U_{g,s}$ and $U_{l,s}$ are superficial velocities of gas-phase and liquid-phase, respectively. U_T is a terminal rise velocity of a single bubble. In this experiment, U_T was set as 0.277 m/s, based on our previous research.

$$\varepsilon = \frac{U_{g,s}}{U_T + 1.1\left(U_{g,s} + U_{l,s}\right)} \tag{1}$$

2.2. Two-phase flow analysis using GAMMA+

In this study, the GAMMA+ code, developed by the Korea Atomic Energy Research Institute (KAERI), was utilized for the two-phase flow analysis. The GAMMA+ code was initially designed for system transient analysis in high-temperature gas-cooled reactors (HTGRs) and is capable of multidimensional heat and mass transfer simulations [4]. This versatile code has been extended to various reactor types, including sodium-cooled fast reactors (SFRs), lead-cooled fast reactors (LFRs), and MSRs. Specifically, the GAMMA+ code was employed to analyze the thermal-hydraulic performance of MSRs under two-phase flow conditions.

In this study, the drift flux model, which assumes that the gas and liquid phases exist in a mixed state rather than separately, was employed for two-phase flow analysis [5]. This model enables a more straightforward two-phase flow analysis compared to the two-fluid model and provides greater accuracy than the homogeneous equilibrium model (HEM). The detailed information on the form loss coefficient data for the experimental loops, which are input values in GAMMA+, was insufficient. To address this, the form loss coefficient was calibrated based on the velocity values measured in the experiment for a helium injection case at 1 lpm in each loop. Fig. 2 shows nodalization for the experimental loop fabricated in GAMMA+. All boundary and initial conditions were set to be identical to experimental conditions.

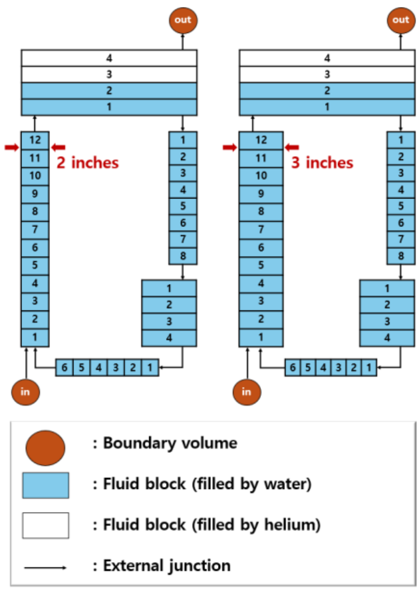

Fig. 2. Nodalization of experimental loop

3. Results and discussion

Numerical results and experimental outcomes showed a similar trend for the velocity of the working fluid. Fig. 3 shows the discrepancies of working fluid velocity between GAMMA+ and experiment. The relative errors between GAMMA+ and experiment showed 0.04 – 7.93 % and 0.50 – 1.68 % in the 2 and 3 inches riser channel, respectively. The velocity values between GAMMA+ and experiment at the case of 1 lpm were the same because the form loss coefficients of each riser channel were calibrated based on the helium injection rate of 1 lpm.

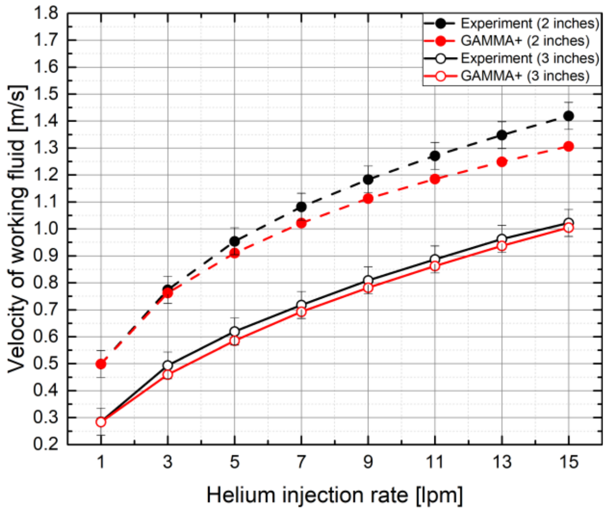

Fig. 3. Comparison of the working fluid velocity between experiment and GAMMA+ according to the widths of the riser channels

According to the simulation results on the working fluid velocity, more errors were observed in the 2 inches case. The superficial velocity of helium increases as the width of riser channel gets narrow, although helium injection rate was maintained identical. In other words, bubble interactions and turbulent effects occur more frequently in the 2 inches riser channel compared to the 3 inches riser channel during the helium injection as identical amount. Thus, it was predicted that larger errors were observed at the narrow channel.

Fig. 4 shows the discrepancies for the volume-averaged void fraction between GAMMA+ and experiment. As the working fluid velocity increases, the volume-averaged void fraction typically decreases due to the reduced bubble residence time in the riser channel. This tendency was observed in GAMMA+ calculation. As the velocities calculated in GAMMA+ were underestimated in both channels compared to the experiments as shown in Fig. 3, the void fraction was generally found to be higher compared to the experimental outcomes. However, when the helium injection rate was below 8 lpm in the 3 inches riser channel, the void fraction values calculated using GAMMA+ were underestimated compared to experimental results. This discrepancy was attributed to the fact that the void fraction values calculated by GAMMA+ exhibited a linear trend, unlike the experimental results, for the 3 inches riser channel.

The discrepancies on the void fraction between GAMMA+ and the experiment increased as the helium injection rates increased. The relative errors between GAMMA+ and experiment showed 4.61 – 8.69 % and 0.02 – 14.12 % in the 2 and 3 inches riser channel, respectively.

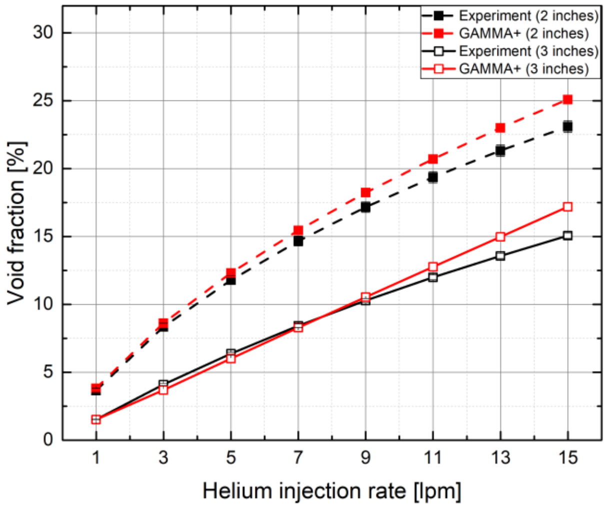

Fig. 4. Comparison of the void fraction between experiment and GAMMA+ according to the widths of the riser channels

In the experiment, interfacial forces between two phases and the bubble interaction mechanism, including wake entrainment, are included. However, numerical calculation cannot simulate all the actual two-phase flow phenomena observed in the experiment. In other words, the errors between GAMMA+ and the experiment are due to some approximations and assumptions based on the drift-flux model in the numerical code. Furthermore, inaccurate form loss coefficients for the experimental loop also contributed to these errors.

4. Summary and conclusion

In this study, the results of two-phase flow analysis numerically calculated through the GAMMA+ were compared to the experimental outcomes. GAMMA+ showed high prediction abilities for the void fraction and working fluid velocity in the two-phase flow system. However, there is still room for improvement, such as insertion of the accurate form loss coefficients. The major findings of this study can be summarized as follows:

- ✓ Numerical results and experimental outcomes showed similar trend for the velocity of working fluid
- ✓ The relative errors of working fluid velocity between GAMMA+ and experiment showed 0.04 – 7.93 % and 0.50 – 1.68 % in the 2 and 3 inches riser channel, respectively
- ✓ The relative errors of void fraction between GAMMA+ and experiment showed 4.61 – 8.69 % and 0.02 – 14.12 % in the 2 and 3 inches riser channel, respectively
- ✓ The discrepancies of void fraction between GAMMA+ and experiment became larger as helium injection rates increase
- ✓ The working fluid velocities calculated through GAMMA+ were underestimated compared to the experimental outcomes, and as a result, the void fraction values in GAMMA+ were generally overestimated compared to the experimental values in both channels

This study can contribute to improving the two-phase flow model in GAMMA+. Employing the advanced and enhanced two-phase flow analysis model, the helium bubbling effect in the MSRs can be analyzed elaborately.

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