Experimental results of the effect of gas composition on void fraction and bubble behavior for gas-liquid two-phase flow under stagnant water condition

Miki SAITO*, Taizo KANAI*, Satoshi NISHIMURA* and Yoshihisa NISHI*
*Central Research Institute of Electric Power Industry
2-6-1 Nagasaka Yokosuka, Kanagawa 240-0196, Japan
E-mail: mi-saito@criepi.denken.or.jp

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Abstract
Fission product removal by pool scrubbing is known to be largely affected by the gas-liquid two-phase flow regime. The pool scrubbing performance of various carrier gases was evaluated in two-phase flow experiments by injecting helium, nitrogen, or argon through a pool of stagnant water in a column with an inner diameter of 0.5 m and a height of 8 m. The gases were supplied through a cylindrical nozzle with an inner diameter 69 mm at superficial gas velocities ranging from 0.013 to 0.053 m s\(^{-1}\). Measurements were conducted using a camera and two sets of a 128 \(\times\) 128 wire-mesh sensors, separated by 40 mm. The visually observed gas hold-up and wire-mesh sensor-measured average void fraction decreased with increasing fraction of lighter gas in the supplied gas. Detailed analysis of the flow regime using the obtained wire-mesh sensor signals revealed that lighter gases led to a greater fraction of relatively large bubbles in the flow compared to heavier gases, causing the gas phase with the lighter gases to have a higher average rise velocity in the flow. This leads to a hypothesis that, compared to heavier gases, lighter gases break up less or coalesce more in the flow, resulting in distinct two-phase flow characteristics depending on the inlet gas composition.

Keywords: Pool scrubbing, Gas-liquid two-phase flow, Void fraction, Wire-mesh sensor, Bubble

1. Introduction

When a severe accident (SA) occurs at a nuclear power plant, fission products (FPs) in the fuel may escape into the environment from the damaged reactor core through the containment vessel and other routes. Minimizing the amount of FPs released into the environment during an SA is crucial for reducing public exposure to radioactive materials, and various countermeasures have been developed for this purpose. One such countermeasure is pool scrubbing, in which the carrier gas containing FPs is bubbled through a liquid filter before getting released outside for depressurization of the containment vessel (Sehgal, 2012). However, FP removal during pool scrubbing occurs under a complex flow regime and the efficiency is difficult to predict. To improve the prediction of the FP removal efficiency during pool scrubbing, SA analysis codes are being updated using the latest knowledge of the underlying scrubbing phenomena.

Alongside the physical and chemical properties of the FPs, aspects of the two-phase flow dynamics, such as the bubble size, surface area, and rise speed, affect the FP removal performance during pool scrubbing. In general, the flow field is influenced by the size and depth of the pool, gas volume ratio, and nozzle dimensions. Pool scrubbing experiments using these parameters have been reported in numerous previous studies. Instead, this study focuses on the evaluation of the effect of the carrier gas composition on the two-phase flow dynamics under the same physical conditions of the pool. Conventional pool scrubbing models have been developed from experimental data using air or N\(_2\) as the FP carrier gas. During an SA at a nuclear power plant, however, other gaseous species such as noble gases and H\(_2\) are likely to be present. Thus, one must consider the applicability of current pool scrubbing models to cases involving different carrier gases. As FP decontamination by pool scrubbing is known to be heavily affected by the gas-liquid two-phase flow regime (Kanai et al., 2016), the initial aim of this study is to obtain detailed and highly precise experimental two-phase flow data for
various types of gases. Two-phase flow experiments were thus conducted three different carrier gases: He, which was selected as a substitute for the H$_2$ that is expected to be released in considerable quantities during an SA (Sehgal, 2012); N$_2$, the conventional carrier gas; and Ar, which was included to evaluate the behavior of heavier gases. He-N$_2$ gas mixtures with various volumetric ratios were also examined to determine the influence of the gas mixtures on the two-phase flow characteristics. The goal of the current work is to elucidate the general effects of different gas properties on gas-liquid two-phase flow. The obtained data will subsequently be used to examine the precise effects of the gas species expected to be present during a nuclear SA.

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>H$_2$</td>
<td>Hydrogen</td>
<td>$M$</td>
<td>Molar mass</td>
<td>g mol$^{-1}$</td>
</tr>
<tr>
<td>He</td>
<td>Helium</td>
<td>$\rho$</td>
<td>Density</td>
<td>kg m$^{-3}$</td>
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<tr>
<td>N$_2$</td>
<td>Nitrogen</td>
<td>$\mu$</td>
<td>Viscosity</td>
<td>Pa s</td>
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<tr>
<td>Ar</td>
<td>Argon</td>
<td>$j_G$</td>
<td>Superficial gas velocity</td>
<td>m s$^{-1}$ (evaluated at 20 ℃, 4 m hydrostatic pressure and atmospheric pressure)</td>
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<table>
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<th>Subscript</th>
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<th>Description</th>
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<tr>
<td>$G$</td>
<td>Gas</td>
<td>$R$</td>
<td>Gas constant</td>
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<tr>
<td>$L$</td>
<td>Liquid</td>
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2. Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 1. The test section consists of a transparent acrylic cylindrical column with a height of 8.0 m and an inner diameter of 0.5 m. This setup allows for a complex, high-void, turbulent flow regime with reduced wall effects, resembling the actual conditions expected during pool scrubbing. The gases were supplied from 47 L cylinders fitted with pressure regulators and at an initial pressure of 14.7 MPa. To confirm that the flow rates set on the mass-flow controllers were accurately supplied to the test section, the actual average flow rates were calculated using Boyle-Charles’ law from the measured temperature and pressure of the cylinders (Saito, et al., 2020). The gas cylinders were replaced when the primary pressure fell below 2 MPa to maintain a steady supply pressure. Sensors were also placed at the gas inlet nozzle to monitor the temperature and pressure conditions at the nozzle, which remained at around 15 ℃ and 35.67±0.04 MPa (4 m hydrostatic pressure) respectively, throughout the experiments.

For the visual observations, the two-phase gas hold-up was evaluated by taking the average and standard error from several video frames using image analysis, which were considered to account for the fluctuation of the two-phase level. Quantitative evaluation of the two-phase flow was accomplished using a wire-mesh sensor (WMS). In a WMS, the electrical conductivity is measured at the intersections of adjacent grids of wires (Prasser, et al., 1998) to reveal the phase distribution across the column cross section using the difference in conductivity.

In this work, the WMS was installed 2 m downstream of the inlet nozzle. The WMS consists of two layers of 128 × 128 wires with a horizontal interwire spacing of 3.9 mm and a vertical interwire spacing of 2.8 mm as illustrated in Fig. 2. The diameter of the wires is 0.25 mm, which has negligible influence on the flow field yet provided sufficient signal intensity. Two sets of WMS were used, separated by 40 mm. Signal collection was performed using a Teletronic WMS 200 system (Teletronic, 2015) with a measurement frequency and duration of 1000 frames s$^{-1}$ and 50 s, respectively, which afforded the two-phase flow data in a three-dimensional matrix (128 × 128 × 50000). Each element in the matrix held the electrical conductivity information.

The gases were supplied in the following six compositions: 100% He, 75% He + 25% N$_2$, 50% He + 50% N$_2$, 25% He + 75% N$_2$, 100% N$_2$, and 100% Ar. The total flow rate of the gases was varied from 200 to 800 L min$^{-1}$, in steps of 100 L min$^{-1}$. The experiments were performed under atmospheric temperature and pressure. The physical properties of the gases used in this work, along with those of H$_2$ and water, are summarized in Tab. 1 (Poling, et al., 2001). For the He – N$_2$ mixtures, the densities were calculated from the weighted average of $R$ and equation of state of an ideal gas. The viscosities were obtained using Wilke’s equation (Wilke, 1950) with Sutherland’s constant (Sutherland, 1893).
Fig. 1  Schematic diagram of the experimental setup. The test section consists of a column with a height of 8.0 m and an inner diameter of 0.5 m. The column was initially filled with deionized water to 4.0 m (collapsed water level), and gas was supplied from a nozzle with an inner diameter of 69 mm at the bottom of the column, which gives the L/D of 4. Three gases, namely He, N₂, and Ar were supplied from gas cylinders fitted with gas-specific mass flow controllers for flow rate control. Temperature and pressure sensors were located at the positions indicated by T and P, respectively. A camera was positioned near the initial water surface for visual observation and two sets of WMS separated by 40 mm were installed 2.0 m from the bottom of the test section.

Fig. 2  Detailed schematic diagram of WMS (left) and a typical cross-sectional measurement result of the two-phase flow (right).
Table 1 Physical properties of the studied gases and water at atmospheric temperature and pressure (Poling, et al., 2001).

<table>
<thead>
<tr>
<th></th>
<th>$M$ [g mol$^{-1}$]</th>
<th>$\rho$ [kg m$^{-3}$]</th>
<th>$\mu$ [10$^{-5}$ Pa s]</th>
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</thead>
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<td>2.016</td>
<td>0.083</td>
<td>0.88</td>
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<tr>
<td>He</td>
<td>4.003</td>
<td>0.166</td>
<td>1.96</td>
</tr>
<tr>
<td>He 75%, N$_2$ 25%</td>
<td>10.01</td>
<td>0.416</td>
<td>1.94</td>
</tr>
<tr>
<td>He 50%, N$_2$ 50%</td>
<td>16.01</td>
<td>0.666</td>
<td>1.88</td>
</tr>
<tr>
<td>He 25%, N$_2$ 75%</td>
<td>22.01</td>
<td>0.915</td>
<td>1.82</td>
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<tr>
<td>N$_2$</td>
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<td>1.16</td>
<td>1.75</td>
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<tr>
<td>Ar</td>
<td>39.95</td>
<td>1.45</td>
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<td>H$_2$O</td>
<td>18.02</td>
<td>998</td>
<td>1.00E02</td>
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3. Results and Discussion

3.1 Gas Hold-Up

The influence of the composition on the flow behavior was apparent from the observed two-phase gas hold-up levels. The gas hold-up level difference between He and N$_2$ under the same flow $j_G$ shown in Fig. 3. At $j_G$ of 0.052 m s$^{-1}$, the gas hold-up levels for He and N$_2$ were approximately 380 and 600 mm, respectively. The results of the gas hold-up levels for all experimental conditions are plotted in Fig. 4 as the gas hold-up fraction, that is the fraction of gas in the total volume defined by the two-phase height (Fig. 3). As mentioned in Section 2, the average and standard errors were considered for the plot shown in Fig. 4. The hold-up fraction increased with increasing gas flow rate, as expected, and also with increasing atomic/molecular weight of the gas. Furthermore, a clear difference in flow regimes was observed, with a higher degree of bubbly flow for heavier gases and more slug/churn-like flow for lighter gases at the same $j_G$.

In previous studies, several authors have established correlations between the gas hold-up fraction and two-phase physical properties. The empirically derived correlations between the gas hold-up fraction and $j_G$, obtained in this work and in selected previous studies, for He, N$_2$, and Ar are compared in Fig. 5. Although some of the previously reported empirical correlations also indicate a greater gas hold-up fraction for heavier gases, in accordance with the results of this work, none of the previously obtained equations appear to precisely match the current data. One reason for the differences both between the previous correlations and between those correlations and the current results may be the broad range of experimental conditions, such as the column size, gas, initial liquid height, and gas flow rate. This suggests that the obtained correlations are specific to the experiment and a more comprehensive understanding of the underlying phenomena is essential for obtaining a more general correlation that is applicable to a wider range of conditions.

![Fig. 3](image.png)

Flow Rate 800 L min$^{-1}$, $j_G$ 0.052 m s$^{-1}$

For each set of experimental conditions, several frames were analyzed to calculate the average gas hold-up fractions and standard errors.
Fig. 4  Average gas hold-up fractions and standard errors obtained from analysis of the video image. The best-fit curves were obtained by least-squares fitting of exponential functions.

Fig. 5  Comparison of the empirical correlations by previous studies and results of this work of the gas hold-up fraction and superficial gas velocity for He, N$_2$, and Ar (Hikita, et al., 1980, Sotelo et al., 1994, Urseanu, et al., 2003, Wilkinson, et al., 1993). These authors have correlated the two-phase gas hold-up fraction and superficial gas velocity with variables such as the gas/liquid phase properties, experimental setup dimensions, and some constants for numerical fitting.

3.2 Void Fraction and Gas-Phase Velocity

In addition to the visual observation of the two-phase gas hold-up, void data across the column cross section at a height of 2 m were measured using the WMS. As expected from the results discussed in Section 3.1, the use of heavier gases as the inlet gas led to a higher average void fraction. The time-averaged void fractions across the column cross section for He, N$_2$, and Ar at a gas flow rate of 800 L min$^{-1}$ ($j_G = 0.052$ m s$^{-1}$), are presented in the top plot of Fig. 6. These
plots clearly illustrate an increase in the void fraction for heavier gases, and the He-N$_2$ mixtures of various ratios exhibited the same pattern (not shown in the figure for clarity). The bottom plot of Fig. 6 shows the normalized void fractions, averaged over the radial distance from the column center under the same conditions. This plot demonstrates that the inlet gas composition influenced not only the average absolute values of the void fraction at the WMS measurement points but also the radial distribution characteristics across the column cross section. The plot illustrates that the heavier gases display a more evenly distributed void fraction than the lighter gases.

![Image of plots showing void fraction distributions for He, N$_2$, and Ar](image)

**Fig. 6** Top: Time-averaged void fractions across the column cross section for He, N$_2$, and Ar at a gas flow rate 800 L min$^{-1}$ ($j_G = 0.052$ m s$^{-1}$), averaged over the measurement time of 50 s. Bottom: Normalized radial distributions of the plots at the top, averaged over the radial distance from the column center where the error bars indicate the standard error. The solid lines indicate moving average.

The time-cross-section-averaged void fractions with the best-fit curves for all the gas compositions and flow rates studied in this work are shown in Fig. 7. The variation of the void fraction and its cross-sectional distribution suggested differences in the rise speed of the gas phase in the two-phase flow between different inlet gas compositions. To further examine this behavior, a cross-correlation of the signals from the two sets of WMS, one upstream and one downstream, was performed. As a bubble rises, a time delay in the signals between the two WMS can be discerned. Thus, by considering the physical WMS distance and the time delay, the gas phase velocity could be calculated. The obtained velocity, as a function of the radial distance, is plotted in Fig. 8 for all of the gases at a flow rate of 800 L min$^{-1}$ flow rate.
$(j_G = 0.052 \text{ m s}^{-1})$ as a representative example. This signal cross-correlation analysis revealed that lighter gases had a higher rise velocity for all of the flow rates examined. As faster escape from the liquid phase is associated with a lower void fraction at a given time, these results are in accordance with the void fraction observations shown in Fig. 6 and Fig. 7.

![Fig. 7 Variation of the WMS-measured time-cross-section-averaged void fraction as a function of superficial gas velocity. The best-fit curves were obtained by least-squares fitting of exponential functions.](image)

![Fig. 8 Radial distributions of the gas-phase velocity for all the gases at a flow rate of 800 L min$^{-1}$ ($j_G = 0.052 \text{ m s}^{-1}$), obtained by cross-correlation of the signals from the upstream and downstream WMS. Each plot was averaged over the radial distance from the column center and error bars are omitted for clarity.](image)

The influence of the gas properties on the gas phase velocity was further evaluated by plotting the time-cross-section averaged void fraction and velocity against the inlet gas density for various flow rates, as shown in Fig. 9. It can again be seen that both the void fraction and gas phase velocity increased with increasing inlet gas flow rate. Furthermore, the void fraction and gas phase velocity were found to increase and decrease, respectively, with increasing gas density. On the basis of these results, it can be speculated that several gas properties, including those plotted in Fig. 9 and perhaps...
others such as elasticity and surface tension, influence the gas-liquid two-phase flow behavior. However, a comprehensive physical explanation of exactly which properties of the inlet gas affect the gas-liquid two-phase flow and the precise nature of these effects has yet to be ascertained. It can be surmised that an additional and deeper examination of the bubble behavior for various gases is necessary owing to the influence of the gas phase properties during two-phase flow on the flow regime in pool conditions.

![Graph showing void fraction variation with respect to inlet gas density](Image)

Fig. 9  Left: Variation of time-cross-section averaged void fraction with respect to the inlet gas density for gas flow rates of 200, 400, 600, and 800 L min\(^{-1}\) (\(j_G = 0.013, 0.026, 0.039,\) and 0.052 m s\(^{-1}\), respectively). Right: Cross-section averaged gas phase velocity under the same conditions. Error bars are omitted for clarity.

3.3 Further WMS Signal Analysis

![Graph showing extracted bubble data](Image)

Fig. 10  Gas phase signals measured by the WMS with time as the z-axis (left), and an example of a single extracted bubble (right). The individual bubbles were extracted by defining each three-dimensional, 6-connected element of gas phase signals as a bulk and these were plotted using the triangular surface method on obtained signal matrices. The extracted bubble has a physical size in the z-axis direction in millimeters, where the time axis was converted to length by cross-correlating the signals from the upstream and downstream WMS to determine its rise speed.
In addition to the void fraction, the bubble characteristics are another important factor for predicting the FP removal efficiency during pool scrubbing. As such, a detailed analysis of the gas phase was performed to attain a deeper understanding of the results presented in Section 3.1 and Section 3.2, and thus the bubble behavior. The WMS signals, in addition to providing void fraction data, can be used to extract information on the gas phase bulks (i.e. the bubbles) in the flow. Information was obtained in the form of a matrix with time as the z-axis as shown in Fig. 10. The obtained matrix contains signals from the liquid phase, “0”, and gas phase, “1”, depending on the electrical conductivity at each measurement point. The bubbles were extracted as bulks of gas phase signals in a matrix form as illustrated in Fig. 10. Each bulk was then labeled as an individual bubble.

![Fig. 11](image)

Fig. 11 Left: Number of bubbles detected by the downstream WMS during 10 s of measurement at a gas flow rate of 800 L min\(^{-1}\) (\(j_0 = 0.052 \text{ m s}^{-1}\)). The standard errors are also shown. Right: Volume fraction distributions (semi-transparent lines, left axis) and cumulative distribution functions (dashed lines, right axis) versus sphere-approximated radius. The moving averages of the bars are also shown (solid lines). For clarity, only the main three gases (He, N\(_2\), and Ar) are plotted.

One piece of information that can be extracted is the total number of bubbles detected by the WMS. The number of bubbles detected over 10 s of measurement for each gas at a flow rate of 800 L min\(^{-1}\) (\(j_0 = 0.052 \text{ m s}^{-1}\)), is shown in Fig. 11. It can be seen that the number of detected bubbles increased as the supplied gas became heavier. In addition, the average rise speed was determined by cross-correlating the signals from the upstream and downstream WMS as discussed in Section 3.2, from which the time axis could be converted into physical dimension.

The physical dimensions of the extracted bubbles were used to calculate the bulk volumes. As observed in Fig. 10, both the size and the shape of the bubbles in the flow varied greatly. Therefore, each bubble was approximated as a sphere of the corresponding volume to obtain the radius for subsequent comparison and analysis. The normalized volume fraction distributions and cumulative distribution functions with respect to the sphere-approximated radius for He, N\(_2\), and Ar are shown in Fig. 11. The plot suggests that the heavier gases exhibit less variation in bubble size during the two-phase flow, while the lighter gases contain a significant fraction of relatively large bubbles in addition to small bubbles.

The normalized volume fractions plotted in Fig. 11 suggest that as the fraction of heavier gas in the supplied gas increases, so too does the probability of bubble break-up (or improbability of coalescence) in the two-phase flow. This is in accordance with the previous observations: as smaller bubbles rise more slowly owing to their lower buoyant force, a flow containing smaller bubbles causes the gas-phase to remain longer in the two-phase mixture, allowing for a larger void fraction as described in previous sections. Differences in the bubble break-up rate at the same gas flow rate would mean that different numbers of bubbles exist in the flow depending on the inserted gas specie, which is in agreement with the results shown in Fig. 11. As large, fast-rising bubbles are thought to deviate less from their original paths, the differences in the bubble volume fraction distributions explain the differences in the WMS-measured void and velocity distributions observed in Fig. 7 and Fig. 8.
Nevertheless, the reasons for why the bubble break-up or coalescence rates may differ depending on the composition of the inlet gas are still unclear. Conventionally, two-phase flows have been evaluated using parameters such as Reynolds number, Weber number, Froude number, Morton number, and Eotvos number. These parameters treat the effects of the physical properties of the phases, such as density and viscosity, as ratios of values between the phases. However, the order of magnitude of the ratio of density and viscosity between water and gas is sufficiently small, -5 to -3, that the effect of the change in gas species can be considered negligible. The same can be said for the viscosity ratio between the two phases (Poling, et al., 2001). On the other hand, the Morton number and Eotvos number are greatly affected by surface tension. Yet, from the observation of the curvature of a single bubble at the nozzle, no difference in surface tension due to the use of different gas species was found at the experimental level (Saito, et al., 2020). A more precise experimental data or a deep understanding of their molecular interactions at the surface is needed. Another reason for the observed experimental results could be the difference in kinetic energy of gas molecules resulting from the difference in molecular mass. A further investigation of the effects of surface tension and kinetic energy of bubbles with different gas compositions will be considered in future work by conducting more precise, small-scale studies of bubble break-up and coalescence.

If the bubble break-up and coalescence rates are dependent on the gas composition as hypothesized, this may affect the efficiency of FP decontamination during pool scrubbing. This would necessitate investigation of not only the mechanism of FP removal in a single bubble but also the effects of bubble break-up and coalescence on FP removal in order to develop a robust pool scrubbing model with a comprehensive physical background. Thus, future work should also include additional two-phase experiments to investigate the influence of SA conditions (steam, high temperature, high pressure, etc.) on the observed differences between gas species, and application of the experimental data to the development of a more comprehensive pool scrubbing model. In addition, the location at which the differences in the void and bubble behavior occur, namely, whether this takes place at the nozzle or at a particular height, is important in pool conditions. Such investigation of flow in vertical directions will also be included in future work.

4. Conclusion

Two-phase flow experiments in a stagnant pool of deionized water were performed using He, N\textsubscript{2}, and Ar to obtain experimental data regarding the general effects of gas properties on gas-liquid two-phase flow. Both the visually observed two-phase gas hold-up fraction and WMS-measured void fraction were found to increase with increasing fraction of heavier gas in the supplied gas. The average gas phase velocity determined by cross-correlating the upstream and the downstream WMS signals, was found to decrease with increasing fraction of heavier gas. Plots of the void fraction and cross-correlated velocity in the radial direction suggested differences in not only the overall magnitude but also the distribution characteristics depending on the inlet gas composition.

The results suggest that the difference in the observed flow behavior upon varying the inlet gas may be attributable to differences in the flow regimes, and thus bubble behavior, for different gases. Further analysis of the obtained WMS signals led to a new hypothesis that the bubble break-up and/or coalescence rates may vary for different gas compositions, resulting in distinct flow behavior. Although the experimental results are in agreement with this hypothesis, a complete explanation for why this may be the case has not yet been discovered. Moreover, to relate such two-phase flow behavior to the decontamination factor for pool scrubbing, more comprehensive data such as the interface concentration of bubbles may be necessary. Therefore, it can be concluded that additional data are required on both the large and small scales, with a broader range of gas species, to ascertain the effects of gas properties on two-phase flow in pool conditions and furthermore on the FP decontamination efficiency during pool scrubbing for actual severe nuclear accident scenarios.

References


