Experimental investigation on bubble behaviors in a water pool using the venturi scrubbing nozzle

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1. Introduction

A containment filtered venting system (CFVS) is a mitigation measure that prevents over-pressurization of the containment building during a severe accident in a nuclear power plant (NPP). Following the Fukushima Daiichi accident, increasing concern over severe accident mitigation at NPPs in Korea has prompted the need for protection against containment failure due to overpressurization [1]. Accordingly, the Korean CFVS was developed. The CFVS releases gas from the containment building into the environment to protect the integrity of containment structures by reducing the internal pressure. In severe accidents, however, the gas in the containment contains large amounts of fission products from the degraded reactor core, which can greatly increase the risk of radiation exposure of the public. To minimize this risk, the CFVS releases the containment atmosphere to the environment through a series of radioactive material decontamination processes.

The Korean CFVS is a wet type filtration system, whereby gas mixtures such as steam, air, and fission product are discharged from the containment pass through the CFVS tank, after which a large proportion of fission products are filtered before the gas is finally vented to the environment [2]. The CFVS tank filled with the scrubbing liquid is injected with gas from the containment through venturi nozzles installed at the bottom of the tank. Fig. 1 shows a schematic of the Korean CFVS. Fission products retained by the gas injected into the CFVS tank are removed through two main processes: a pool scrubbing process in the tank pool and a scrubbing liquid injection process at the top of the tank. Therefore, the accurate prediction of the fission product decontamination by pool scrubbing is a key factor in evaluating the overall decontamination performance of the CFVS. However, the decontamination performance varies significantly according to various conditions (e.g., operation conditions, aerosol characteristics, and particle size distributions, thermohydraulic factors of the CFVS).
Many studies have been conducted on aerosols and pool scrubbing phenomena to predict the decontamination effect of pool scrubbing. For example, the Electric Power Research Institute (EPRI) conducted experiments to develop a pool scrubbing code and revealed the ultimate bubble size distribution in a water pool for all injector geometries. The bubble mean equivalent diameter was approximately 5.6 mm; however, this was only valid for elevations higher than ten initial globule diameters from the injector outlet [3].

In addition, pool scrubbing experiments (e.g., ACE, GE, SPARTA, and UKAEA) were conducted under various conditions to identify the critical parameters of pool scrubbing in addition to developing and optimizing the pool scrubbing prediction model [4]. The results of POSEIDON-II experiments performed by the Paul Scherrer Institute (PSI) were compared with the calculation results of the BUSCA pool scrubbing code [5]. This research identified the effects of various factors on pool scrubbing, such as the steam content of the injection gas, pool height, injected gas flow rate, the temperature difference between the pool and injected gas, and aerosol particle sizes. However, in some cases, code-calculated decontamination factor (DF) values are more conservative than experimentally determined DF values [5]. These differences might be caused by incorrect assumptions about the bubble size and flow regime in the pool, which in turn can have a significant impact on DF values.

Bubble size is a key factor in pool scrubbing, in addition to aerosol particle size and the operation and design conditions [3,4,6]. However, traditional pool scrubbing codes such as BUSCA and SPARC assume that the initial bubble sizes are stable, and they employ a single average bubble size [6,7]. Besides, the gas injection flow rates (4.68 kg/h - 20.98 kg/h) and nozzle sizes (9.9 mm–20.2 mm) used in previous experiments are based on values obtained over a relatively narrow range compared with the design and operation conditions of a CFVS tank [3]. These limitations can make it difficult to predict the bubble behavior and decontamination effect in a CFVS tank using existing experimental and analytical results.

In this study, the hydrodynamic behavior of bubbles in the water pool is analyzed according to the injection flow rates [8]. To clearly understand bubble behavior in the actual CFVS tank, a real scale test section for the injection venturi nozzle installed in the Korean CFVS tank is used for experiments. The experimental conditions considered in this study, i.e., a large diameter venturi nozzle (106 mm), have not been considered previously. Therefore, this study presents a unique model that can be used to predict bubble sizes for venturi nozzles with large diameters. The experimental results are then used to develop prediction models for the void fraction and bubble sizes under the hydrodynamic operation conditions of a CFVS tank.

2. Experimental details

2.1. Experimental setup

Tests were conducted at the TRISTAN facility in the PSI using the submerged venturi nozzle. A simple illustration of the TRISTAN facility is shown in Fig. 2 [9]. It has four main parts: the inlet, lower channel, wire-mesh sensor, and upper channel. The cross-sectional area of the channel is 0.25 m² (0.5 m × 0.5 m). It has a total height of 6.1 m, and the inlet has separate gas and water injections. The model of the venturi nozzle was installed at the inlet (Fig. 3), and the test apparatus was filled with demineralized water. The venturi nozzle had two slits in the sides of its lower part, through which the water was injected. Air was injected from the bottom of the venturi nozzle. Inside the venturi nozzle, the water broke into small droplets, effectively retaining the radioactive fission products in the pool. The mixture of small droplets and injected air rose to the water pool in the upper channel. Furthermore, a wire-mesh sensor (WMS) was used to investigate bubble behavior in the water pool with respect to the gas injection flow rate.

To analyze the formation and characteristics of bubbles in the water pool, appropriate measuring points and method were
The WMS was installed in a fixed position on the top of the lower channel of the apparatus. Bubble behavior information can only be obtained from the lower channel using the WMS. The height of the installed venturi nozzle was approximately 820 mm. Furthermore, the venturi nozzle was installed approximately 310 mm below the lower channel. The actual height of the channel for observation was 2080 mm. To observe the potential breakup of the initial globules and the final bubble size, measurements were conducted at 0.1, 0.2, 0.3, 0.4, 0.5, 1.25, and 1.75 m above the venturi nozzle outlet. As mentioned above, the WMS cannot be easily moved because it is installed at a fixed axial position in the apparatus. Thus, the distance between the WMS and the venturi nozzle outlet was changed by installing extension pipes in the gas injection line, enabling the measurement of all axial distances from above the venturi nozzle outlet to the position of the WMS. Air was used only as the injected gas, and the temperature of the injected gas and the pool were kept the same. This was done to obtain conservative results by minimizing the positive effect on bubble formation and pool scrubbing according to the steam content of injected gas during actual CFVS operation. Table 1 summarizes the test conditions. The injection gas flow rates were chosen to be equal to the operating range of the model venturi nozzle.

2.2. Measurements

Images obtained from a high-speed camera (HighSpeedStar 5.1 camera operated with the LaVision DaVis 8 software) were used to identify the size of the initial globule at the outlet of the venturi nozzle. The resolution and frame rate of the camera were 1024 × 1024 pixel and 3 kHz, respectively. The test facility was illuminated using constant diffusive light emitted from an LED panel with a luminous flux of 4300 lm. Because of the memory limitations of the camera, images could only be recorded only for 3s the maximum frame rate.

The WMS is an intrusive measurement instrument that determines the instant local void fraction distribution in a specified plane in a test channel. A WMS comprises two grids of parallel wires that generally span the flow area at an angle of 90°, as...
illustrated in Fig. 4. Further, the conductivity or capacitance (depending on the sensor design, fluid to be investigated, and data acquisition method) is measured to capture the volumetric content of a single-phase between the two layers. This is then converted to the local instantaneous void fraction. The sensor used in the test apparatus was used to measure the conductance. The wires of one layer acted as the transmitter electrodes, whereas those of the other layer acted as the receiver electrodes. In the test apparatus, two WMSs were mounted at an axial distance of 15 mm from each other. Each sensor had 120 measurement channels, resulting in a total of 28,800 measurement cells for the two sensors. The measurement frequency was 1024 Hz.

2.3. Data analysis and filtering

The raw data acquired by the WMS are described in Ref. [10]. The void fraction \( \alpha \) at point \( (i,j) \) and time \( k \) was calculated by interpolating the measured conductivity \( u_{ij,k} \) between the liquid and gaseous reference conductivity \( u_{ij,liq} \) and \( u_{ij,\text{gas}} \), respectively (Equation (1)) [9]:

\[
\alpha_{ij,k} = \frac{u_{ij,\text{liq}} - u_{ij,k}}{u_{ij,\text{liq}} - u_{ij,\text{gas}}} \quad (1)
\]

In this study, bubble recognition was performed using the bubble recognition algorithm developed by Prasser et al. [10]. A basic fill algorithm was used to recognize common void parts in the data until it reached a predefined threshold. This threshold was set independently for each measurement point in the test matrix, depending on the maximum and minimum voids in the entire data set. Next, the interface and volume were reconstructed by the arc reconstruction technique introduced by Betschart [9]. Through this, the two lateral distances were determined for each frame. To perform full reconstruction, the gas velocity should be known so that the axial information from the frames can be converted to spatial information. Unfortunately, the individual bubble velocity determined in this experiment was unreliable because of an unknown source of noise. Thus, the average gas velocity was calculated using the average void information. To obtain the average gas velocity \( v_{\text{ave,gas}} \), the gas flow rate \( Q_{\text{gas}} \) was divided by the flow area occupied by the gas phase \( \alpha \times A_{\text{channel}} \) (Equation (2)), [9]. The void fraction was averaged over the entire measurement window and all wire-mesh electrodes.

\[
v_{\text{ave,gas}} = \frac{Q_{\text{gas}}}{\alpha \times A_{\text{channel}}} \quad (2)
\]

Finally, the aforementioned information was used to obtain the average interfacial area distribution. In addition, the total reconstructed interfacial area was summed and divided by the total recorded volume.

The WMS is an analog measurement device based on electrical

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure above the pool</td>
<td>Ambient pressure</td>
</tr>
<tr>
<td>Water in the pool</td>
<td>Demineralized water</td>
</tr>
<tr>
<td>Injected gas (Pressure)</td>
<td>Pressurized air (1.3 bar)</td>
</tr>
<tr>
<td>Range of injected gas flow</td>
<td>100–210 kg/h</td>
</tr>
<tr>
<td>Water and gas temperature</td>
<td>35 °C</td>
</tr>
<tr>
<td>Measurement points</td>
<td>Seven points above the nozzle outlet (0.1, 0.2, 0.3, 0.4, 0.5, 1.25, 1.75 m)</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>Two wire mesh sensors (120 x 120 measurement points)</td>
</tr>
</tbody>
</table>

![Fig. 4. (a) Overview and (b) operational principle of the wire-mesh sensor in the test facility [9].](image)
conductivity; therefore, it is sensitive to electrical noise from the radio, WiFi, and other such signals. Therefore, the test facility channel was grounded to reduce as much noise as possible.

3. Results and discussion

3.1. Initial globule at the venturi nozzle outlet

A high-speed camera captured images of the gas flow emerging from the venturi nozzle. Fig. 5 shows images of the gas flow near the outlet of the venturi nozzle at different gas injection flow rates. The formation of initial globules at the outlet of the venturi nozzle is rare because gas flow with water bubbles inside the nozzle prevents the formation of an initial globule at the outlet. Furthermore, the venturi nozzle cap helps generate many small bubbles, thereby increasing the bubble surface area under high injection flow conditions. At the venturi nozzle outlet, flow is highly turbulent in all test cases. The identification of the pool condition with the injected gas flow is crucial for the design and operation of a pool scrubbing system with maximum efficiency. Wallis [11] proposed the condition for air-jet formation above a nozzle using the critical velocity at the nozzle. Zhao [12] and Sundar [13] presented the criteria for determining the bubble to the jet regime using the Weber number and Kutateladze number with the modified Froud number, respectively. In this study, the pool condition at the venturi nozzle outlet was the identified jet flow regime according to Zhao's idea [12]. Zhao expressed the transition criteria from the bubbling regime to jetting regime at the submerged orifice as shown in Equation (3).

\[
We \geq 10.5 \frac{\rho_f}{\rho_g} \sqrt{\frac{g}{r}}
\]  

In this work, the range of Weber numbers at the outlet of a venturi nozzle spanned from 8.84E3 to 3.90E4, which are considerably larger than the right-hand side criterion of Equation (3) formulated by the gas to water density ratio. Therefore, the probability of initial globule formation is exceptionally low. In addition, it was confirmed that bubble jets from the venturi nozzle hit the channel wall. This causes bubbles from the venturi nozzle to breakup into smaller sizes or deform upstream of the bubble flow path.

3.2. Void fraction

Fig. 6 shows the void fraction contours along the axial positions for different gas injection flow rates and Fig. 7 presents the quantitatively processed void fraction distributions giving more comparative point of view on the gas flow rates. To identify the void fraction according to the change in flow rates by the measurement position, the axial position, \( H = \frac{z}{D_h} \), is defined as the ratio of the axial distance above the venturi nozzle outlet to the hydraulic equivalent diameter of the rectangular channel pool. The time-averaged void fraction distribution with the gas injection flow rate is shown in Fig. 6. The x-axis and y-axis indicate the wire-mesh electrodes. Two gas streams are clearly formed near the venturi nozzle outlet because the exit of the venturi nozzle is divided into

![Fig. 5. Images of the outlet of the venturi nozzle at different gas flow injection rates: (a) 100, (b) 130, (c) 160, (d) 190, and (e) 210 kg/h.](image-url)
Fig. 6. Development of time-averaged void fraction distribution with axial position ($H$) for different gas flow injection rates: 100, 160, and 210 kg/h.
Fig. 7. Development of void profiles with axial position for different gas flow injection rates (kg/h).
two. At the axial position \( H = 0.2 \), two small central peaks are formed.

Despite the differences in the injection flow rate, when the gas reaches a higher axial position, the differences between the highest and the lowest void fraction values decrease. When the axial position is between 0.8 and 1.0, the interaction between the two streams and the wall and its flow increases, resulting in more chaotic conditions in the pool. The corresponding radial void profiles are shown in Fig. 7. As the distance from the venturi nozzle increases, the void fraction profiles flatten for the axial position of 0.2–1.0 and appears to reach a steady condition; however, a small peak in the center of a pool forms again, further from the venturi nozzle.

Fig. 8 shows the time and area-averaged void fractions with superficial gas velocity along with the axial position. Compared with Figs. 6 and 7, the void fraction in Fig. 8 is relatively small.

The one-dimensional (time and area-averaged) void fractions are considered to be the mean values in Fig. 8. These averaged void fractions generally increase with the increasing superficial gas velocity at the same axial position, whereas the averaged void fractions decrease along with the axial position. Owing to the injection of gas, many bubbles form near the outlet of the venturi nozzle, as shown by the highest averaged void fraction. As bubbles move upwards in the pool, bubbles mix well under the influence of strong turbulence in the pool, and the pool reaches a steady-state condition. Finally, the averaged void fractions decrease gradually owing to the bubble coalescence and breakup in the pool.

The void fraction is a crucial parameter that affects the flow behavior in the two-phase flow. To predict the void fraction values in a pool based on the experimental data, previous related studies are reviewed considering the experimental conditions of this study. Then, based on the time and area-averaged values of void fraction, the overall void fractions are calculated to neglect the axial distance from the venturi nozzle outlet for each injection condition. The circulation cycle of bubble formation, growth, breakup, and regrowth in the pool can be identified by reviewing the distribution of bubble size based on the distance from the venturi nozzle outlet for each injection flow rate. As shown in Fig. 10, the number of large bubbles reduces until the bubbles reach

\[
\alpha = 0.1161 \left( \frac{u_g}{\sigma} \right)^{0.578} \left( \frac{\mu_g \rho_f}{\mu_f \rho_g} \right)^{-0.131} \left( \frac{\rho_g}{\rho_f} \right)^{0.062} \left( \frac{\mu_g}{\mu_f} \right)^{0.107} \tag{4}
\]

### 3.3. Bubble size distribution

A discrete probability density function (PDF) was calculated to identify the bubble size distribution associated with the injection flow rates [10]. The volume PDF, \( P_v(D_i) \), is defined as

\[
P_v(D_i) = \frac{D_i^3 N_i}{\delta \sum_{j=1}^{N} D_j^3 N_j} \tag{5}
\]

In this work, many bubbles were generated in the water pool during experiments. They experienced various bubble dynamics such as growth, breakup, and coalescence. These effects can give deform the bubble shape. However, it is difficult to estimate the degree and quantity of bubble deformation under this experimental condition. Therefore, the shape of the bubbles was assumed to be spherical in this study. The bubble diameter was the same as the equivalent spherical diameter. The volumetric bubble size distributions are shown in Fig. 10; they indicate that there are significantly large bubbles in the pool. Around the venturi nozzle where the gas is injected, a jet flow forms (Section 3.1), which is a significant cause of the turbulence in the pool. Then, the bubbles generated by the injected gas travel to the top of the pool. These bubbles break into smaller bubbles or coalesce into larger bubbles as they collide with other bubbles. Consequently, relatively small bubbles may outnumber the large bubbles; however, the presence of large bubbles, which were observed in the experiments, is a key factor in reducing the scrubbing effect of bubbles in the pool. This is because large bubbles have a smaller surface area and greater terminal velocity in a pool than small bubbles under the same operating conditions. The circulation cycle of bubble formation, growth, breakup, and regrowth in the pool can be identified by reviewing the distribution of bubble size based on the distance from the venturi nozzle outlet for each injection flow rate. As shown in Fig. 10, the number of large bubbles reduces until the bubbles reach

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Fig. 8. Time and area-averaged void fraction according to superficial gas velocity along with the axial position.

Fig. 9. Overall void fraction with superficial gas velocity (m/s).
Fig. 10. Volumetric bubble size distribution for different gas flow injection rates (kg/h).
the axial position \( H = 2.5 \). Then, the number of large bubbles becomes increases again slightly at \( H = 3.5 \). Following the circulation cycle from bubble formation to breakup and regrowth, the large bubbles generated near the venturi nozzle breakup and grow with flow path. Finally, most large bubbles seem to breakup into smaller bubbles when they reach \( H = 2.5 \). Then, the bubbles increase again, as shown in Fig. 10. The breakup of large bubbles affects this tendency to a certain extent.

In this study, all bubbles were assumed to be spherical. Therefore, the sphericity of test data was reviewed. Bubble volume to surface area ratios are shown in Fig. 11. Regardless of the axial positions and gas injection flow rates, bubbles tend to be spherical for small surface areas and volumes. However, most bubble surface area to volume ratios lie close to the spherical line.

3.4. Prediction of bubble formation in the pool

The experimental results were analyzed to predict the average bubble size in the pool under the experimental conditions. Fig. 10 shows that the bubble sizes for different gas injection flow rates vary from a few millimeters to several hundred millimeters. However, to predict a more generalized bubble size under these conditions, the Sauter mean diameter (SMD) was applied, \( d_{32} \), which is defined as the ratio of bubble volume to surface area for the number of bubbles of diameter \( d_b \), \( N_i \),

\[
d_{32} = \frac{\sum_{i=1}^{N_i} (N_i d_i^3)}{\sum_{i=1}^{N_i} (N_i d_i^2)} \quad (6)
\]

Fig. 12 shows the average bubble sizes for various superficial gas velocities at all measurement locations. The average bubble sizes ranged from 20 to 40 mm under the experimental conditions. The average bubble sizes with respect to the measurement positions decreased with the increase in distance from the venturi nozzle after the gas was injected. As the bubbles generated by the injected gas rise to the top of the pool, the pool becomes more turbulent, and the bubbles are more likely to be broken into smaller bubbles. In contrast, in most cases, the average bubble sizes tend to increase as the flow rates of the injected gas increase at the same axial position. As the gas injection flow rate increases, the pool conditions become more turbulent. Therefore, the collision probability increases between bubbles at the same axial position. Accordingly, the bubble size may increase due to an increase in bubble aggregation. However, the variation in bubble size with increasing gas flow injection at the same axial position is small compared with the variation in bubble size with increasing axial position. In some cases, a degree of abnormality is also observed in Fig. 12. Therefore, the effect of bubble size considering the change in gas injection flow rate at the same axial position cannot be determined from the experimental results.

The main factors affecting bubble sizes in the pool are the size and configuration of the injection nozzle, physical properties of the liquid, and gas injected into the pool. Davidson [15] concluded that the influence of injection nozzle diameter on the bubble sizes was negligible if the injection flow rates were sufficiently large and the bubble size, \( d_b \), is correlated with the gas injection flow rates, \( Q \) (Equation (7)):

\[
d_b = \left( 1.138 \times \frac{6}{\pi} \times \frac{Q_k}{g} \right)^{1/3} \quad (7)
\]

Similarly, based on extensive research and experiments, Akita et al. [16] and Gaddis et al. [17] developed bubble size prediction models, expressed as Equations (8) and (9), respectively, which fit well for a wide range of inputs.

\[
d_b = 1.88 \times d_N \times \left( \frac{u_g}{\sqrt{g d_N}} \right)^{1/3} \quad (8)
\]

\[
d_b = \left[ \left( \frac{6 \rho_d a}{\rho g} \right)^{1/3} + \frac{135Q_k^2}{4 \pi g^2} \right] \left( \frac{135Q_k^2}{4 \pi g^2} \right)^{1/4} \quad (9)
\]

Jamialahmadi et al. [18] proposed a nonlinear correlation for estimating bubble size by applying a neural network:

\[
d_b = 19.54 + 1.28 u_g + 16.78 \alpha \quad (11)
\]

The void fraction was obtained using Equation (4) to estimate the bubble sizes.

Fig. 13 compares the results of the proposed correlations obtained from Equation (11) with the existing correlations. Each correlation is plotted within its valid allowable range of superficial gas velocity. The influence of the injection nozzle size is also reflected in the correlations. Although all correlations indicate an increase in bubble size as the gas injection flow rate increases, the estimates of Equation (11) are considerably lower than those of the other correlations. The Davidson correlation (Equation (7)), which is applicable to this experimental range, calculates the bubble sizes considering the experimental range in Fig. 13. Equations (8)–(10) generally exhibit a good fit when predicting bubble sizes in a pool with the nozzle diameters up to 6 mm. However, the venturi nozzle hydraulic diameter used in this study was 106 mm, which is large compared with those considered in the other correlations. Furthermore, the bubble volume increases with the gas injection flow rate for nozzles with large diameters. Therefore, the effect of the nozzle diameter is an important parameter when estimating bubble sizes. However, Davidson’s correlation can predict bubble sizes only for small nozzles because it does not consider the effect of the nozzle size. This explains why other correlations generate significantly larger values.

In addition, the experimental conditions of this study are similar to those in bubble column reactors [19]. According to the flow regime of gas velocity and test channel diameter for bubble column reactors, the flow regime of the pool in this experiment was classified as churn-turbulent flow (gas velocity was greater than 2.4 m/s and the pool diameter was 0.5 m), which is considerably more intensive than the flow regime of the other correlations. Therefore, the proposed correlation and the previous correlations mentioned above are not directly comparable because of the considerable differences in experimental conditions, especially flow condition, nozzle diameter, and nozzle configuration. Although most previous models were developed based on experiments performed on air-water systems, they are mainly focused on the physical properties of the liquid such as surface tension and density, rather than nozzle design and operation conditions. In other words, Equation (11) is the dedicated experimental correlation that predicts the bubble sizes according to gas injection flow rates in a water pool with a
large diameter venturi nozzle.

It is noteworthy that the proposed correlation was deduced from the test conditions similar to the actual operating conditions during severe accidents at an NPP.

4. Conclusion

This study investigated the hydrodynamic characteristics of bubbles generated in a pool due to gas injection with a submerged
venturi nozzle using WMSs and a high-speed camera. The pool was filled with water, and air at the same temperature as the water pool was injected. Void fraction and bubble size distribution information were acquired for various injection flow rates. Based on the obtained data, averaged bubble sizes were calculated. Additionally, a previous empirical correlation from the literature was modified to predict the void fraction. The predictions of void fraction showed deviations of 4.3% compared with the experimental data. Finally, an empirical model for predicting bubble sizes using the void fraction and flow rates of the injected gas was derived.

In general, all models showed a similar trend of predicting an increase in bubble size with increasing gas flow rate; however, existing models gave significantly larger values for the bubble diameter than the proposed model for a large venturi nozzle diameter. In other words, previous models seemed to excessively over-estimate bubble sizes as the nozzle diameter increased.

However, the proposed model can predict the bubble behavior and the pool scrubbing effect caused by actual CFVS nozzles. The proposed model can be used to predict bubble sizes for venturi nozzles with large diameters.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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Nomenclature

\[ a_{i,j,k} \] void fraction at point \((i,j)\) and time \(k\)
\[ u_{i,j,k} \] measured conductivity at point \((i,j)\) and time \(k\)
\[ u_{i,j,liq} \] liquid reference conductivity
\[ u_{i,j,gas} \] gaseous reference conductivity
\[ u_{avg,gas} \] average gas velocity
\[ Q_{gas} \] gas flow rate
\[ \alpha \] average void fraction
\[ A_{channel} \] area of channel
\[ H \] axial position, dimensionless
\[ z \] axial distance above the nozzle outlet
\[ D_h \] hydraulic equivalent diameter of the rectangular channel pool
\[ g \] gravitational acceleration
\[ u_g \] nozzle superficial gas velocity
\[ \rho_f \] density of water
\[ \rho_g \] density of air
\[ \mu_f \] viscosity of water
\[ \mu_g \] viscosity of air
\[ \sigma \] surface tension
\[ P_v(D_i) \] volume probability density function (PDF) of bubble diameter \(D_i\)
\[ D_i \] bubble diameter within the range of the bubble size class \(i\)
\[ \delta_i \] width of the bubble size class bin
\[ N_i \] number of bubbles
\[ \nu_f \] kinematic viscosity of water
\[ d_{32} \] Sauter mean diameter (SMD)
\[ d_b \] bubble diameter
\[ d_N \] nozzle diameter
\[ Bd \] Bond number \(= \frac{\rho_g u_g^2}{\sigma}\), dimensionless
\[ Fr \] Froude number \(= \frac{u_g^2}{g d_b}\), dimensionless
\[ Ga \] Galileo number \(= \frac{\rho_g u_g^2 d_b}{\mu_g}\), dimensionless
\[ We \] Weber number \(= \frac{d_b u_g^2}{\sigma}\), dimensionless

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