Development of a Mean Bubble Size Correlation under Pool Scrubbing Conditions

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1. Introduction

There is a growing demand for clean and sustainable energy, which has led to renewed interest in nuclear power. However, to ensure that nuclear designs are safer, there is a need for the development of Passive Containment Cooling Systems (PCCSs) such as the Containment Pressure and Radiation Suppression System (CPRSS). These systems use pool scrubbing to mitigate any potential consequences of nuclear accidents.

Although pool scrubbing is a critical safety measure, current pool scrubbing codes have some uncertainties, particularly regarding bubble dynamics in the swarm region. Existing models oversimplify bubble behavior by assuming a constant diameter throughout, which can lead to inaccuracies in calculating the Decontamination Factor (DF). While there are some correlations for bubble diameter in the literature, they are often based on idealized flow conditions with low inlet velocities.

The objective of this study is to propose a new correlation for mean bubble size variation in the swarm region. This correlation will be informed by recent experimental data, Abe et al. [1], Fujiwara et al. [2], and Behzadipour et al. [3], and will utilize Computational Fluid Dynamics (CFD) techniques.

2. Methodology and Results

A comprehensive survey of past studies shown in Table I on bubble dynamics across different configurations of bubble columns reveals several key correlations for predicting bubble characteristics. However, there is not a strong agreement among these correlations for the given parameters. Furthermore, the validity of these correlations is limited, particularly concerning the superficial gas velocity and hydraulic diameter ranges. A new correlation is needed for the pool scrubbing operating conditions, as the understanding of the parameters affecting mean bubble diameter is limited, and relevant correlations are scarce.

Table I: Effect of parameters on mean bubble diameter

Year	Author	D_h	D_o	D_i	U_o	ε	U_r	α	σ	ρ_L	ρ_G	ν_L	μ_L	μ_G	g
1974	Akita and Yoshida	−	×		−				+	−		+	+		−
1976	Kumar et al.		+		±				+		±			±	−
2002	Hibiki and Ishii	+				−			−	+	+	+			+
2005	Pohorecki et al.				−				+	−			−		
2018	Jamshidi and Mostoufi	−			+				+	−			+		−
2018	Kanaris et al.	+	+		+				−	+			−		−
2019	Azizi et al.	+		+	+				+	+			−		−
2020	Bak et al.					+	−	+	+	−		+			+
2023	Azimi et al.				−										

2.1 Experiments and the CFD Model

Selecting appropriate experiments for pool scrubbing is a challenging task because the conditions in a pool are unique compared to conventional pipe flow. Pool scrubbing occurs in large bodies of water with low aspect ratios, which makes fully developed flow assumptions invalid. This study will model two-phase flow in three recent experiments conducted by Abe et al. [1], Fujiwara et al. [2], and Behzadipour et al. [3], referred to as ABE, FUJ, and BEH from now on, respectively. Despite the challenges in conducting pool scrubbing experiments, the experimental facilities shown in Fig. (1) provide valuable insights.

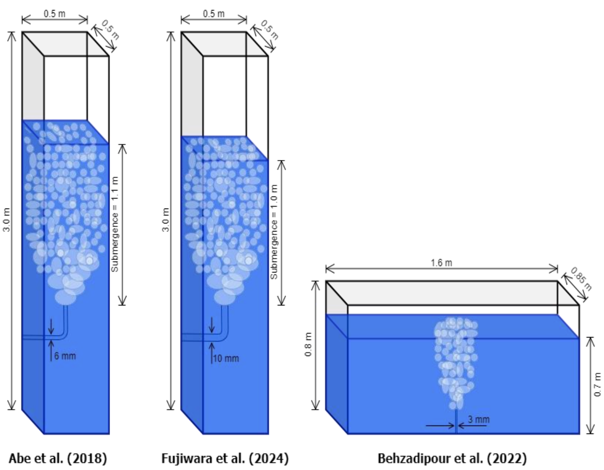

Fig. 1. Experimental Setups

The recirculation flow and intense bubble interaction in the swarm region necessitate a three-dimensional simulation to resolve the size of liquid eddies caused by gas motion. Conventional turbulence models focusing solely on the liquid phase may fall short in two-phase flow modeling at pool scrubbing conditions. Therefore, this study utilizes three-dimensional CFD to accurately predict flow behavior in gas-liquid simulations. Specifically, the Eulerian-Eulerian approach in OpenFOAM-V11 is employed, utilizing the *multiphaseEuler* solver capable of handling multiple interpenetrating fluid phases in Bubble Column Reactor (BCR) simulations. This approach compensates for unresolved flow structures introduced by averaging flow variables in the conservation equations of the two-fluid model by modeling turbulence and phase interactions.

Accurately modeling turbulence in pool scrubbing processes is essential due to its complex nature. This study employs the *mixtureKEpsilon* model in OpenFOAM, known for capturing diverse turbulence characteristics in multiphase flows. Traditional definitions of turbulence intensity may lead to inaccurate estimations, potentially causing numerical instabilities. Therefore, an iterative approach is proposed to constrain the turbulent viscosity within the range of molecular viscosity at the inlet. Additionally, the *mixtureKEpsilon* model is modified to account for Bubble Induced Turbulence (BIT) effects using the Lahey model [4] in OpenFOAM. Additionally, the *mixtureKEpsilon* model introduces unique coefficients, C_p and α_p (both set at 0.25) for bubble-generated turbulence and controlling gas phase inclusion based on void fraction avoiding unnecessary turbulence in high void regions, respectively.

The drag, lift, turbulent dispersion, and virtual mass forces are used for interphase modeling. The details can be found in our previous work [5].

Accurate modeling of bubble diameters is crucial for predicting reactor performance and hydrodynamics in two-phase flow simulations. In this study, the one-group Interfacial Area Transport Equation (IATE) model is used since it offers a balance between accuracy and computational cost, making it suitable for simulating bubble dynamics in BCRs. The one-group IATE model, as described in Eq. (1), focuses on spherical/distorted bubbles in the swarm region of BCRs. It includes terms for bubble breakage caused by Turbulent Impact (TI), binary bubble coalescence driven by Random Collisions (RC), and Wake Entrainment (WE). Model coefficients, such as CTI, CRC, and CWE, reflect experimental conditions, while parameters like We_{cr} and α_{max} influence calculations.

$$\begin{aligned}\frac{\partial a_i}{\partial t} + \nabla\cdot(a_i v_i) &= \frac{2}{3}\left(\frac{a_i}{\alpha}\right)\left(\frac{\partial\alpha}{\partial t}+\nabla\cdot\alpha v_g\right)\\ &+\left[C_{TI}\frac{1}{18}\left(\frac{a_i^2}{\alpha}u_t\right)\sqrt{1-\frac{We_{cr}}{We}}\exp\left(-\frac{We_{cr}}{We}\right)\right]\\ &-\left[C_{RC}\frac{1}{3\pi}\frac{a_i^2 u_t}{\alpha_{\max}^{1/3}(\alpha_{\max}^{1/3}-\alpha^{1/3})}\left[1-\exp\left(-C\frac{\alpha_{\max}^{1/3}\alpha^{1/3}}{\alpha_{\max}^{1/3}-\alpha^{1/3}}\right)\right]\right]\\ &-\left[C_{WE}C_D^{1/3}\frac{1}{3\pi}a_i^2 u_r\right]+\pi D_{bc}^2 R_{ph}\end{aligned} \quad (1)$$

In this study, We_{cr} is set to 2 based on the literature review [5], considering the nature of gas flow in a pool. Eq. (1), coupled with the field equations of the two-fluid model, will be used to solve for Interfacial Area Concentration (a_i) in pool scrubbing experiments. To estimate an average bubble diameter streamwise, Eq. (2) is utilized, which includes area averaging of the time-averaged void fraction and IAC from the IATE model. The resulting averaged Sauter Mean Diameter $\langle d_{\mathrm{sm}}\rangle$represents the characteristic bubble length scale at the height of averaging. The one-group IATE focused on spherical/distorted bubbles constrained by the predefined maximum distorted bubble diameter, $D_{d,max} = 4\sqrt{\sigma/g\Delta\rho}$.

$$\begin{aligned}\text{Area-Averaged Void Fraction: } \langle\alpha\rangle &\equiv \frac{1}{A}\int_A \alpha(r)\mathrm{d}A\\ \text{Area-Averaged IAC: } \langle a_{\mathrm{i}}\rangle &\equiv \frac{1}{A}\int_A a_{\mathrm{i}}(r)\mathrm{d}A\\ \text{Averaged SMD: } \langle d_{\mathrm{sm}}\rangle &\equiv \frac{6\langle\alpha\rangle}{\langle a_{\mathrm{i}}\rangle}\end{aligned} \quad (2)$$

To account for the latent heat, porosity, and natural convection effects, appropriate volume source terms for the governing equations must be introduced as given in Eq. (1).

2.2 Simulation of Pool Scrubbing Experiments

The eligible experiments for two-phase flow simulations were selected based on criteria including a Weber number less than 10^5 and operating in the bubble flow regime near the inlet region by setting the centerline (maximum) void fraction at 0.25. Modeling practices were consistent across all geometries, with the inlet boundary modeled as a square patch at the channel center to replicate the cylindrical nozzle. Simulations were conducted in parallel on multiple processors using OpenFOAM, with decomposition utilizing the hierarchical method. The simulations ran for 30 seconds with a maximum Courant number criterion set to 0.5.

The time-averaged void fraction and gas velocities of the ABE experiment, compared to the experimental results at various heights shown in Fig. 2, indicate that the proposed model captured the major flow variables well. The flow variables of FUJ were captured by the model, whereas BEH did not report them, similar to ABE.

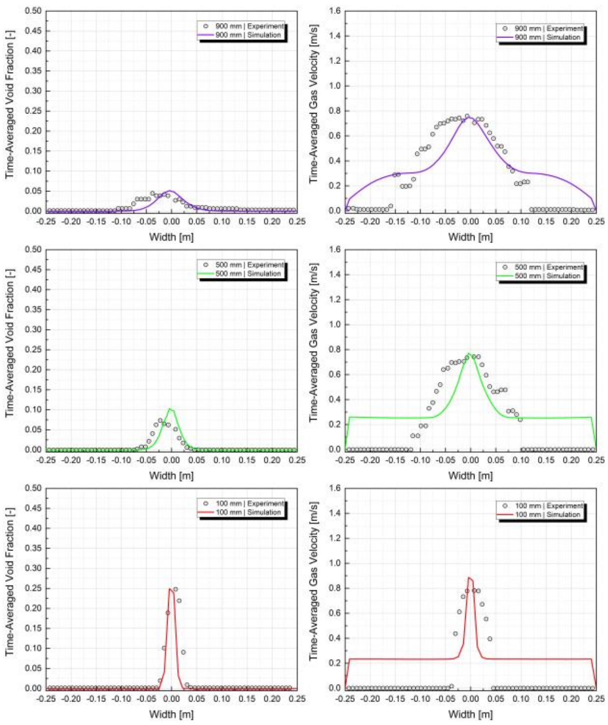

Fig. 2. Void Fraction and Gas Velocity Comparisons of ABE

Comparing BSDs from ABE, FUJ, and BEH experiments with simulations in Fig. (3) shows that the model captured the experimental data well. Though ABE's BSDs weren't reported, similarities in geometry and flow conditions suggest comparable results to FUJ. Thus, FUJ's BSD results can validate ABE's simulations, given the reasonable capture of flow variables in Fig. (2). Overall, the successful capture of flow variables and BSDs across experiments confirms the effectiveness of the proposed two-phase flow model with IATE for accurately estimating average bubble diameter in the swarm region during pool scrubbing conditions.

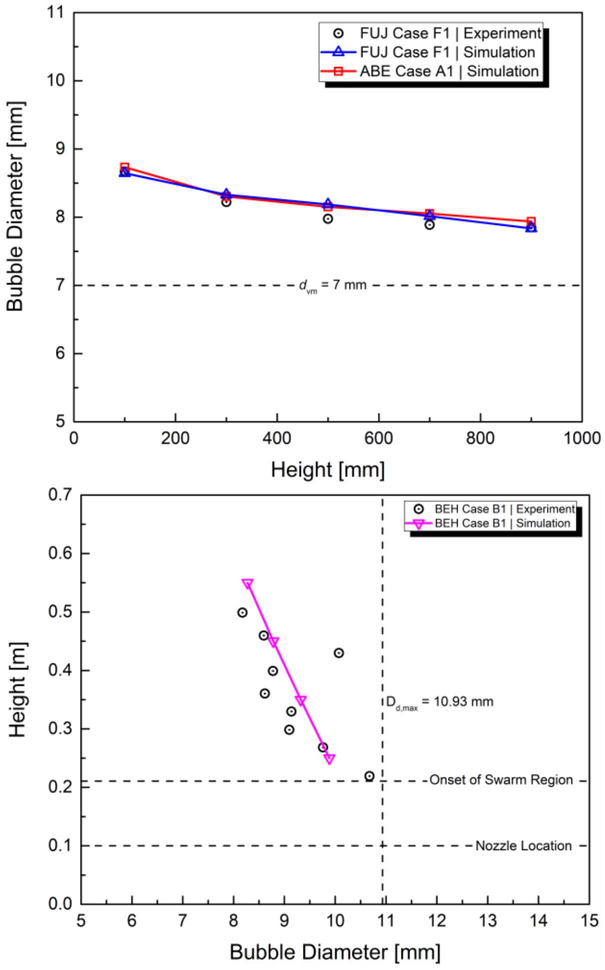

Fig. 3. Bubble Diameter Comparisons of ABE, FUJ, and BEH

2.3 Mean Bubble Diameter Correlation

The existing mean bubble diameter correlations are often restricted to low inlet velocities and provide conflicting results on the same parameters. While turbulence parameters are crucial, they are not frequently considered. A new correlation in Eq. 3 is proposed considering the sensitivity analysis findings and interface structure length scale requirements. The equation includes the injector Weber number (We_o) for space probability, Turbulent Intensity (T_i) for the parameter characterizing the flow in the domain, and the Aspect Ratio (AR_z) for the system length scale. Experimental data from ABE (A1), FUJ (F1), and BEH (B1~B4) have been used along with the CFD (S-A1 ~ S-A6) by varying the inlet velocity and inlet turbulent intensity to account for missing experiment data and to expand the applicability range of the experiment.

$$\frac{d_m}{D_{d,\max}} = f[WE_o, TI_o, AR_z]$$
$$\frac{d_m}{D_{d,\max}} = a[WE_o]^b[TI_o]^c[AR_z]^d \qquad (3)$$
$$\frac{d_m}{D_{d,\max}} = a\left[\frac{\rho_L U_o^2 d_o}{\sigma}\right]^b \left[\frac{k_o^{1/2}}{U_o}\right]^c \left[\frac{H(z)}{D_h}\right]^d$$

Regression analysis using experimental and simulation data yields Eq. (4), showing a negative relationship between mean bubble diameter and all variables. The applicability range of the correlation is also given in Eq. (4) where D_i, is the initial globule diameter and H_o is the submergence height up to 1.1 m in the current experiments.

$$d_m = 0.715 \cdot D_{d,max}\left[\frac{\rho_L U_o^2 d_o}{\sigma}\right]^{-0.014}\left[\frac{k_o^{1/2}}{U_o}\right]^{-0.032}\left[\frac{H(z)}{D_h}\right]^{-0.063}$$
$$d_m = 0.715 \cdot D_{d,max}\,[WE_o]^{-0.014}\,[TI_o]^{-0.032}\,[AR_z]^{-0.063} \qquad (4)$$
$$3.325 \cdot 10^2 < We_o < 9.887 \cdot 10^4 \text{ (-)}$$
$$0.09 < T_i < 5.0 \text{ (\%)}$$
$$12 \cdot D_i < H(z) < H_o \text{ (m)}$$

According to the results in Fig. (4), the correlation predicts the mean bubble diameter variation more accurately for ABE and FUJ compared to bubble diameters that are close to the maximum bubble diameter in BEH experiments, likely due to turbulence and geometrical effects in larger-scale facilities. Regression analysis results indicate an average error of 3.31% and a maximum error of 14.12%.

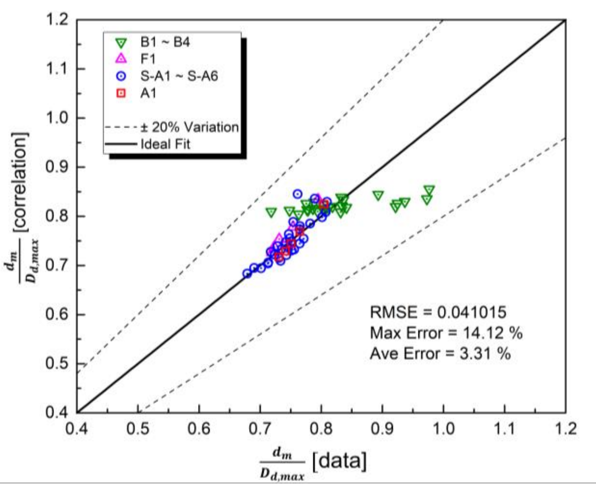

Fig. 4. Regression Analysis Results

2.4 Validation and Results

The proposed model effectively captures flow variables in ABE and FUJ experiments. Additionally, it confirms BEH experiment operates in the bubbly flow regime and accurately predicts bubble diameters for all cases. The proposed mean bubble diameter correlation was evaluated by using the experimental data from the FUJ, BEH, and Azimi et al. [6] experiments, referred to as AZI from now on, and validated by comparing it with the correlations by Hibiki and Ishii [7] and AZI. It should be added that the testing of the present correlation includes predicting the cases of FUJ and AZI that were not used in the development of the correlation.

The current correlation and AZI are easily computable for all data, requiring minimal flow information, however, Hibiki and Ishii's [7] correlation needs detailed flow parameters obtained from the CFD simulations. The comparison results in Fig. (5) reveal that the present correlation performs more accurately than Hibiki and Ishii's [7] and AZI correlations. However, discrepancies occur near the maximum distorted bubble diameter limit of the AZI experiment, likely due to the limitations of the one-group IATE model.

Assessment of prediction errors using the absolute average error method revealed that the present correlation showed excellent agreement with an average error of about 5.07%. In contrast, Hibiki and Ishii's [7] and AZI correlations exhibit higher average errors of approximately 15.23% and 17.95%, respectively. While the AZI correlation performs better for its dataset and BEH experiment, it struggles with higher regions of the FUJ experiment likely due to differing aspect ratios. The correlation by Hibiki and Ishii [7] was evaluated on a limited dataset reflecting its restricted applicability range which is primarily based on fully developed pipe flow experiments rather than pool scrubbing conditions.

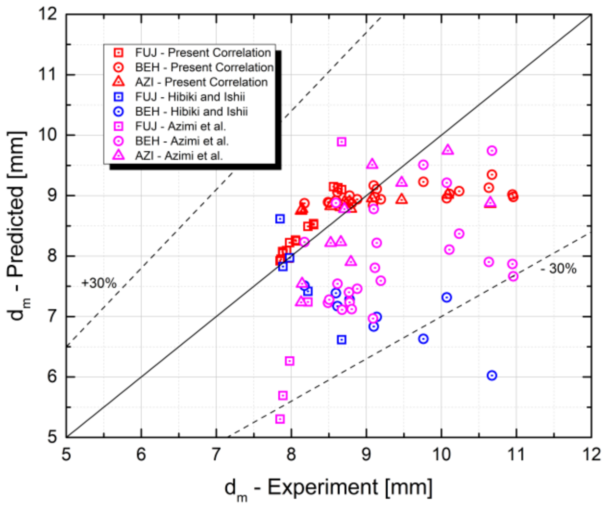

Fig. 5. Bubble Size Correlation Validation Results

3. Conclusions

This study aimed to investigate two-phase flow dynamics, particularly bubble size variation in the swarm region under pool scrubbing conditions, using a comprehensive modeling approach. A two-fluid model, coupled with the IATE was employed to accurately represent bubble sizes based on recent BCR experiments. The IATE model was tailored to suit pool scrubbing conditions, accurately predicting flow variables and bubble size variations. It is found that injector Weber Number, Turbulent Intensity at the inlet, and distance from the nozzle have a significant impact on the mean bubble size.

A new correlation was proposed, relying solely on inlet conditions, developed through non-linear regression using experimental and simulation data. This correlation exhibited a negative relationship between mean bubble size and the variables. The correlation's availability covered a wide range of conditions, validated against experimental data from various facilities, showing excellent predictive accuracy with an absolute average error of approximately 5.07%.

Overall, this study provides a robust framework for accurate mean bubble diameter predictions under pool scrubbing conditions, offering insights for the optimization and design of pool scrubbing systems.

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