# Improvement of Swarm Rise Region Modelling in SPARC-90 Pool Scrubbing Code

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## 1. Introduction

Pool scrubbing is an important safety measure for mitigating severe accidents in nuclear reactors, including Small Modular Reactors (SMRs). This process involves complex interactions between hydrodynamic, thermal, and chemical processes. As gas bubbles containing fission products move through a water pool, radioactive substances are effectively trapped, preventing their release. However, current pool scrubbing codes such as SPARC-90, BUSCA, and PIAERO [1-3] have limitations due to simplifying empirical assumptions, which can lead to underestimation of the Decontamination Factor (DF), a measure of the process effectiveness. One major limitation is the inadequate representation of bubble dynamics, where codes use a constant bubble diameter in the swarm rise region, despite the DF depending on the surface area-to-volume ratio of the bubbles. Additionally, factors such as the effective residence time of aerosols and net deposition velocities are also influenced by the size of individual oblate bubbles.

To address these limitations, a new bubble size model has been proposed for the rise region, using a mean bubble diameter correlation to calculate the average bubble size at any height along the region. This model has been implemented into the SPARC-90 pool scrubbing code, resulting in a more mechanistic model that can be adopted by other pool scrubbing codes.

## 2. Methodology and Results

A new correlation for mean bubble size, presented in Eq. (1), is developed by Bicer et al. [4]. This correlation differs from existing ones by depending only on inlet conditions, offering a wide range of applicability, reducing the need for additional parameters, and incorporating the reduction in bubble diameter along the flow direction [4]. The present correlation accounts for the majority of the globule regime in pool scrubbing conditions by predicting bubble size based on the Injector Weber Number ($WE_o$), Turbulent Intensity ($TI_o$), and the Aspect Ratio of the submergence ($AR_z$) as given in Eq. (1)

$$d_m = 0.715 \cdot D_{d,max} \left[\frac{\rho_L U_o^2 d_o}{\sigma}\right]^{-0.014} \left[\frac{k_o^{1/2}}{U_o}\right]^{-0.032} \left[\frac{H(z)}{D_h}\right]^{-0.063}$$
$$d_m = 0.715 \cdot D_{d,max} \, [WE_o]^{-0.014} \, [TI_o]^{-0.032} \, [AR_z]^{-0.063} \qquad (1)$$

$$3.325 \cdot 10^2 < WE_o < 9.887 \cdot 10^4 \text{ (-)}$$
$$0.09 < TI_o < 5.0 \text{ (\%)}$$
$$0.1 < H(z) < 2.5 \text{ (m)}$$

### *2.1 The Current Modelling*

To determine the overall DF in SPARC-90, the DF of various retention mechanisms must be determined for both the vent exit and swarm rise regions. The general calculation approach for the overall DF is illustrated in Fig. (1). According to the procedure, the overall DF ($DF_{OV,i}$) is calculated as the product of the steam condensation ($DF_{EC}$), inertial impaction ($DF_{II,i}$), exit region particle deposition ($DF_{ER,i}$), and swarm rise ($DF_{SR,i}$) for each particle size, *i*.

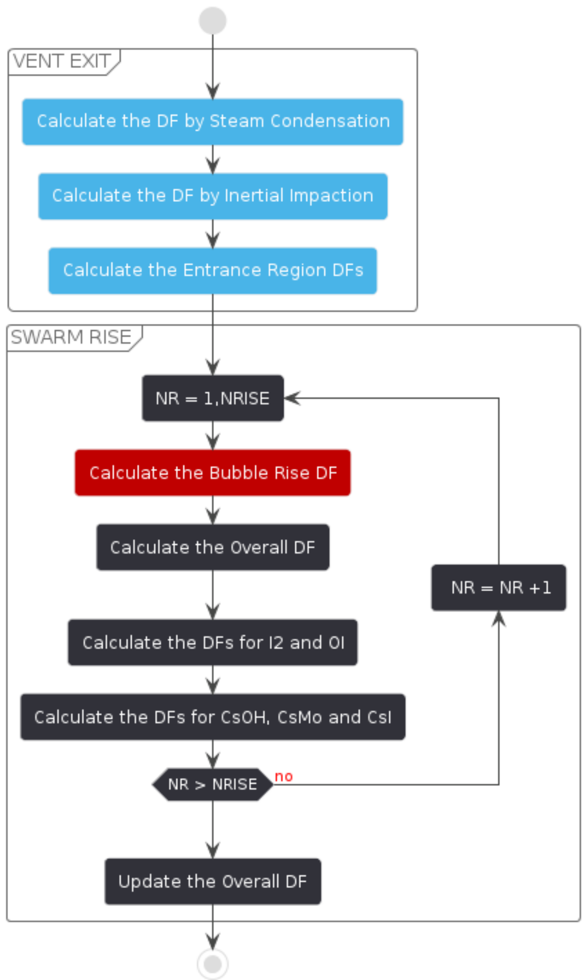


Fig. 1. The current DF calculation procedure in SPARC-90

In the current SPARC-90 model, gas bubbles are represented as stable 7 mm diameter bubbles rising in discrete sections from the nozzle to the top of the liquid. This model assumes constant bubble size along the rise region [1]. However, experiments and numerical analyses show that bubble size decreases during ascent, impacting the overall DF [4]. Thus a more mechanistic bubble size model is needed for the swarm rise region.

*2.2 The Proposed Modelling*

The new model, shown on the right side of Fig. (2), takes into account the average diameter of bubbles at each section where the bubbles rise together. The selected correlation in Eq. (1) can predict the average bubble diameter at each section in the area where the bubbles rise based only on the flow conditions. All the necessary parameters for the input variables of the correlation are already available. However, an initial iterative calculation is necessary to estimate the $T_i$ before calculating the average bubble diameter at each section.

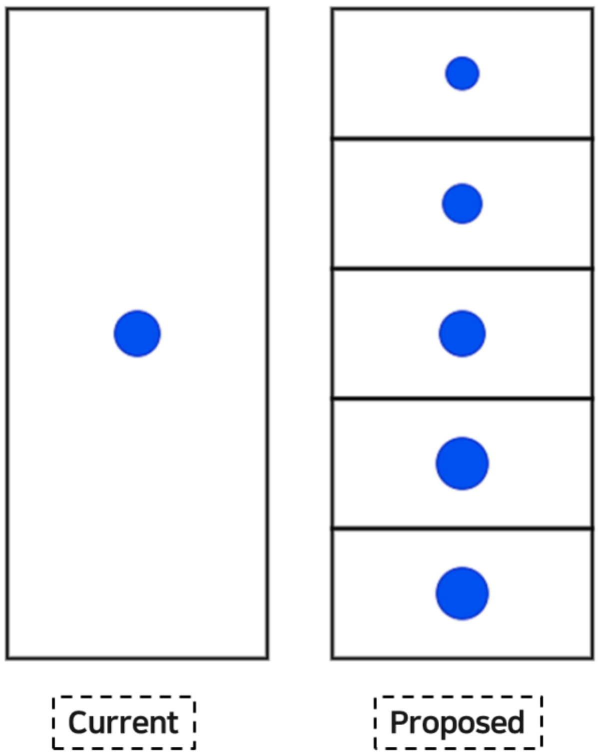


Fig. 2. The current and proposed models for the swarm region

*2.3 The Implementation Methodology*

The process in SPARC-90 begins by reading the constant bubble diameter (7 mm) in the default model before entering the bubble rise loop. The corrected bubble diameter is then calculated, taking into account the steam content of the injected gas. This corrected diameter becomes the assigned constant bubble diameter used to compute the elliptical ratio and other parameters for the oblate spheroid bubble. Finally, the constant bubble diameter is assigned and fixed as a reference diameter for subsequent calculations.

The swarm rise region calculations involve a bubble rise loop, where the following calculations are performed at each section during bubble rise. Firstly, the pressure at the current depth is calculated, and based on this pressure, the new bubble diameter is determined by calculating the bubble volume using the ideal gas law. This diameter is then used to compute the volumetric expansion ratio, which quantifies the relative change in bubble size as the bubble rises. The results of this calculation are used to update the condensed, non-condensed, and total gas moles in the bubble. Finally, the loop returns the bubble size to the original diameter and resets the related parameters for the next step.

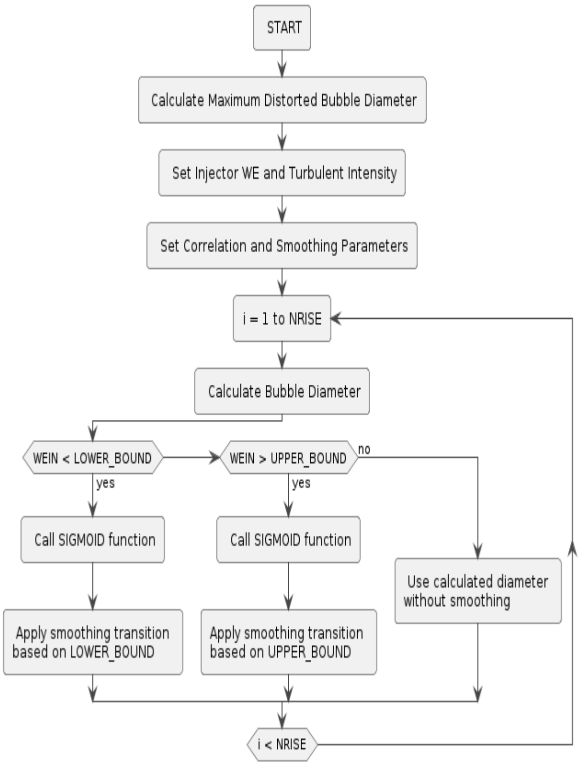


Fig. 3. Correlation implementation

The proposed model for calculating bubble sizes in the swarm rise region is illustrated in Fig. (3). In the modified model, a new array named *DIAMCOR(NRISE)* needs to be declared with the size of sections for the swarm rise region. This array will store the calculated mean bubble diameters for each section. *NRISE* represents the number of sections in the swarm region. Following the declaration, the maximum distorted bubble diameter is calculated to ensure that the bubble size does not exceed the bubble flow limits. The turbulent intensity now needs to be calculated, and the mean bubble diameter can be calculated for each section using all the calculated parameters. After all the diameters are calculated and stored, the first section bubble diameter is assigned to continue with the calculations.

All the preceding steps are performed before entering the bubble rise loop. Once inside the loop, the volumetric expansion ratio is recalculated at the current depth (i.e., section), and related calculations are performed. Instead of returning the fixed constant bubble diameter, the new model now returns the correct diameter at the current depth using the *DIAMCOR* array. This adjustment allows for the modification of the bubble number density with varying bubble diameters, rather than using a constant bubble diameter as was previously done. The implementation of the proposed correlation requires additional considerations. While the current correlation is applicable for the majority of the globule regime, as given in Eq. (1), the entire range must be considered for code stability. As a result, a sigmoid smoothing function (Han and Moraga 1995 [5]) is used to accommodate bubble diameters outside the correlation within the globule regime.

$$\sigma(x) = \frac{1}{1 + e^{-k(x - x_0)}} \qquad (2)$$

The sigmoid function is a mathematical function characterized by an "S"-shaped curve, typically defined as shown in Eq. (2). It maps any real-valued number to a range between 0 and 1, making it useful for applications requiring smooth transitions. In this implementation, the sigmoid function will ensure that the bubble diameter smoothly returns to the default constant bubble diameter value if the injector Weber number in the calculation is not within the applicable range of the correlation. In Eq. (2), $x$ represents the input value (the calculated bubble diameter in this case), $x_o$ is the transition point (7 mm), and $k$ is the steepness. The steepness of the transition can be determined through a parametric test. Considering the lower and upper bounds of the correlation, the applicability ranges of the smoothing are limited; therefore, a moderate $k$ value (0.98) is selected for use in this research.

*2.4 Validation and Results*

The new model needs to be evaluated by comparing the default and modified SPARC-90 codes using pool scrubbing experiments with the selected correlation. The figure-of-merit is DF in pool scrubbing analyses, and it is expected to improve compared to the experimental data. The assessment of the analysis is measured by the Underestimation Factor (UF) introduced by the developers of the SPARC-90 pool scrubbing code [1]. The UF, which is provided in Eq. (3), gives a quantitative assessment of model accuracy by comparing the calculated DF with the measured one. Considering the operational range in Fig. (4) and data availability, this research will use three pool scrubbing experiments (Crespo et al., 1994 [6]; Jung et al., 2022 [7]; Kadoma et al., 2022 [8]), referred to as LACE, FNC, and KAD from now on, to assess the proposed model.

$$\mathrm{MD} = \frac{\sum_{j=1}^{n} [\log_{10}\, DF_{\mathrm{m}} - \log_{10}\, DF_{\mathrm{c}}]_j}{n}$$
$$\mathrm{UF} = \log_{10}^{-1}(MD) \qquad (3)$$

Before comparing the default and modified models, it is important to validate the default model. To achieve this, the results of the SPARC-90 default model are cross-validated with the results of Lee et al. (2021) [9] for the same LACE experiment tests. The comparison results are presented in Fig. 5 and indicate that the results of the default bubble size model align well with those of Lee et al. (2021) [9], validating that any improvement in the DF calculation would be attributed to model enhancements rather than overestimated results from the default model.

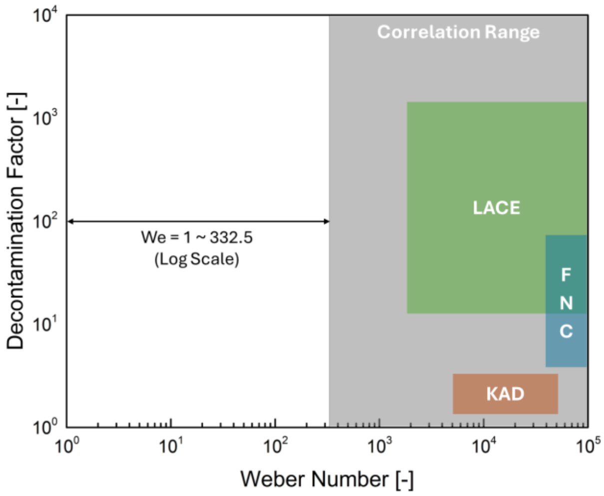


Fig. 4. The selected experiments for DF analyses

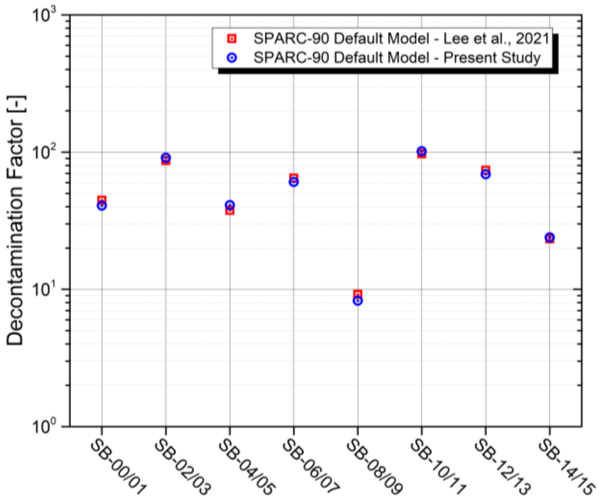


Fig. 5. The selected experiments for DF analyses

According to the DF analysis results given in Fig. (6), the average percent increase in DF estimations varies among different experiments: approximately 44.83% for the LACE experiments, 12.06% for the FNC experiments, and 28.63% for the KAD experiments, leading to an overall average percent increase of about

35.89%. Additionally, the overall UF in DF estimations decreased from 5.07 to 3.55, representing an approximate 30% reduction in under-prediction.

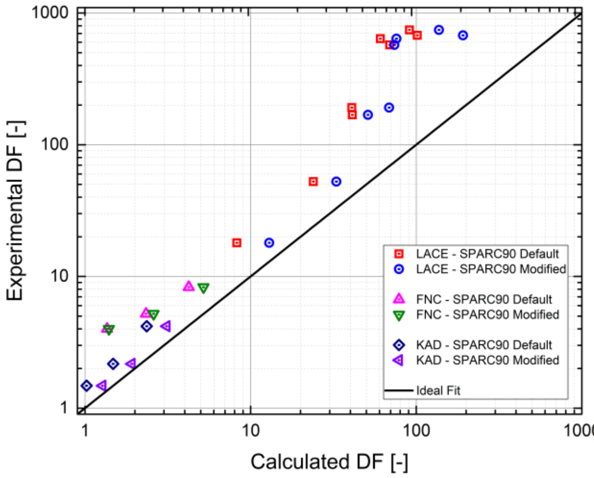


Fig. 6. DF estimation improvement results of all experiments

## 3. Conclusions

A new bubble size correlation has been incorporated into the SPARC-90 pool scrubbing code through the introduction of an updated bubble size model. This model enhances the prediction capability of the SPARC-90 pool scrubbing code in the swarm rise region by accounting for the variation in bubble size along this region. By incorporating this model, the SPARC-90 code now provides a more accurate representation of bubble size, which directly influences the computation of bubble-related parameters including bubble surface area, bubble aspect ratio, bubble rise velocity, effective residence time, and effective deposition velocity. In the previous model, all the aforementioned parameters were used as constants because the bubble size was assumed to be constant regardless of the flow conditions. However, in the current model, all these parameters will be dynamically calculated at each section of the domain due to dynamic bubble diameter calculation.

The new model has been validated using experimental data from a range of pool scrubbing experiments. These validations show improvements in the calculation of DF across all test cases. The consistent improvement in DF estimation results across various conditions indicates that the new bubble size model enhances the predictive accuracy of DF estimations in SPARC-90. The proposed bubble size model offers a more mechanistic approach compared to the previous model that used a constant bubble diameter assumption for the swarm rise region. This methodology not only refines the SPARC-90 code but also has the potential to benefit other pool-scrubbing codes that rely on similar empirical assumptions.

In summary, this study introduces models and practices to improve the capabilities of pool scrubbing codes by proposing a new bubble size model for the swarm rise region.

## ACKNOWLEDGMENT

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