Transactions of the Korean Nuclear Society Autumn Meeting
Goyang, Korea, October 24-25, 2019

Effect of Bubble Size Distribution in Retention of Aerosol Particles during Pool Scrubbing − Part I: Sensitivity Studies on Retention Mechanisms of Aerosol Particles and Various Bubble Size Distributions

Yoonhee Lee1)*, Yong Jin Cho1), and Inchul Ryu2)
1) Korea Institute of Nuclear Safety
62 Gwahak-ro, Yuseong-gu, Daejeon, Korea 34142
2) KEPCO Engineering & Construction Company Inc.
269 Hyeoksin-ro, Gimcheon-si Gyeongsangbuk-do, Korea 39660
**Corresponding author: yooney@kins.re.kr*

1. Introduction

Main mechanisms of the retention of fission products (FPs) during the pool scrubbing are centrifugal deposition, Brownian diffusion, gravitational settling, and etc. [1]. The amount of FPs released after the aforementioned processes is expressed by the decontamination factor (DF), ratio of the mass of FPs entering the water pool volume to the mass released from the surface of the pool.

From the understanding on the numerous experiments on the pool scrubbing, e.g., EPRI experiments [2], LACE-ESPAÑA [3], and etc., computer codes such as SPARC-90 [4], MELCOR [5], and etc. were developed to analyze the pool scrubbing phenomena. According to comparative studies on the various parameters in pool scrubbing[6, 7], the average equivalent diameter of the bubble, one of the most critical points for calculation of the DFs, was selected to provide conservative results.

The results of EPRI experiments [2], however, showed that bubbles during the pool scrubbing have size distributions. Deposition velocities on the aforementioned mechanisms, therefore, should also be dependent on the size distributions since they are function of the size of bubbles. This results in bubble-size-dependent DFs.

In addition, according to legislation on severe accidents in Korea, there is a quantitative safety goal of new and/or operating nuclear power plants in terms of the amount of FPs released checked by a best-estimate methodology [8]. It is, therefore, essential to consider the size distributions of the bubbles for realistic analyses on amount of the FPs released.

This study consists of two parts. The first part of the study focuses on a calculational procedure for the bubble-size-dependent DFs and sensitivity studies on the bubble sizes on the aforementioned retention mechanisms and the various size distributions of the bubbles. The other part of the study [9] focuses on the validation of the calculational procedure via application to analyses on LACE-ESPAÑA experiments.

2. Derivation and Calculational Procedure of the Bubble-Size-Dependent DFs

2.1 Funtionalization of DF on the size of bubbles during bubble rise

The gravitational settling velocity $v_g(d_i)$, is expressed as

$$v_g\left(d_i\right)=\frac{1}{18\mu}\rho_p\cdot d_i^2\cdot g\cdot Cn_i, \tag{1}$$

where
d_i : equivalent diameter of aerosol particle in section i,
Cn_i : Cunningham slip correction factor for aerosol particle with d_i,
μ : viscosity of carrier gas.

The centrifugal deposition occurs due to surface circulation as the bubble rise through the liquid surface when the size of bubble is greater than the critical size [4]. The deposition velocity is expressed as

$$v_c\left(\phi_j,\theta,d_i\right)=\frac{v_s^2\left(\phi_j,\theta\right)v_g\left(d_i\right)}{r_c\left(\phi_j,\theta\right)g}, \tag{2}$$

where
ϕ_i : equivalent diameter of the bubbles in section j,
θ : cylindrical polar coordinate on the local surface of the bubble,
$v_s(\phi_i , \theta)$: local surface velocity on the surface of bubble with ϕ_i.

Deposition due to Brownian diffusion is done by diffusion of aerosol particles within a bubble. The velocity is expressed as

$$v_B\left(\phi_j,\theta,d_i\right)=\left(\frac{D\left(d_i\right)}{\pi t_e\left(\phi_j,\theta\right)}\right)^{1/2}, \tag{3}$$

where
$D(d_i)$: diffusion coefficient for the aerosol particles with d_i,
$t_e\ (\phi_i , \theta)$: exposure time of the surface of the bubble with ϕ_i,

With Eqs. (1)~(3) and the vapor velocity, $v_v(\phi_i)$, the net deposition velocity of an aerosol particle with d_i on the surface of θ of a bubble with ϕ_i is expressed as

$$\begin{aligned}v_n\left(\phi_j,\theta,d_i\right)=&\,v_c\left(\phi_j,\theta,d_i\right)+v_B\left(\phi_j,\theta,d_i\right)+v_g\left(d_i\right)\cos\theta\\&+v_v\left(\phi_j\right),\end{aligned} \tag{4}$$

and the relationship between the each mechanism of retention is shown in Fig. 1.

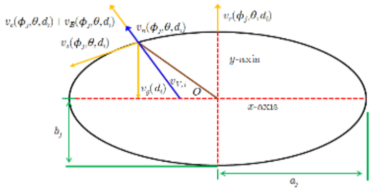

Fig. 1. Rising bubble with various retention mechanisms of aerosol particles

With the functionalized deposition velocity, i.e., Eq. (4), the bubble-size-dependent DF is expressed as

$$DF\left(\phi_j, d_i\right) = \exp\left\{ \frac{1}{\pi a_j^{\,2} b_j} \int_0^{t_{b,j}} \int_{A_j} v_n\left(\phi_j, \theta, d_i\right) dA dt \right\}, \qquad (5)$$

where
a_j : length of major axis of the bubble with ϕ_i,
b_j : length of minor axis of the bubble with ϕ_i,
A_j : surface area of bubble with ϕ_i,
$t_{b,j}$: rise time of bubble with ϕ_i.

Then, the DF during bubble rise can be calculated by the following:

$$DF_{br} = \frac{1}{\sum_j \sum_i \frac{N_{Fr}\left(\phi_j\right) \cdot M_{Fr}\left(d_j\right)}{DF\left(\phi_j, d_i\right)}}, \qquad (6)$$

where
$M_{Fr}(d_i)$: mass fraction of aerosol particles with d_i,
$N_{Fr}(\phi_i)$: number fraction of bubbles with ϕ_i.

2.2 Calculational procedure for the bubble-size-dependent DFs

In the calculation of the DF, bubble-hydrodynamics is required to calculate velocities and volume fraction of the globules and bubbles. Bubble-thermodynamics is required to calculate pressures and temperatures of the bubbles. In I-COSTA, in which the aforementioned bubble-size-dependent DF is implemented, calculational modules of the bubble-hydrodynamics and bubble-thermodynamics are based on those used in SPARC-90 [4].

For the rise of a bubble, the first step is to calculate the volume fraction of the globule and bubbles. Then, for each section of the bubbles, surface temperatures of the bubbles are calculated to obtain the saturation ratio which is used to solve Mason Equation.

The next step is to calculate the internal energy of a bubble with consideration of the heat added to the bubble and the work of expansion done by the bubble from pressure drop, vapor production, and temperature change. The internal energy is also calculated by considering the thermodynamics state of the bubble. The two aforementioned internal energies are calculated iteratively until the surface temperatures of the bubbles from the two internal energies are converged. The calculational procedure is shown in Fig. 2.

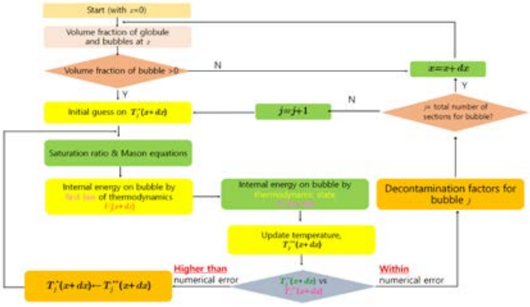

Fig. 2. Calculational procedure for bubble-size-dependent DF

3. Numerical Results

3.1 Sensitivity Analyses on Retention Mechanisms of Aerosol Particles

I-COSTA is applied to sensitivity analyses on the various mechanisms of aerosol retention during the pool scrubbing. The geometric and thermophysical condition of the pool are based on the RT-SB-12/13 test in LACE-ESPAÑA experiments [3]. The area at the exit of the nozzle is 7.854E-05m^2, equivalent to the exit diameter of the nozzle of 9.9 mm. CsI aerosol particles with an average equivalent diameter of 3.0E-06 m and a geometric standard deviation of 2.3 are injected at a rate of 5.0E-06 kg/sec. The size distribution of the aerosol particles and bubbles are shown in Figs. 3 and 4, respectively.

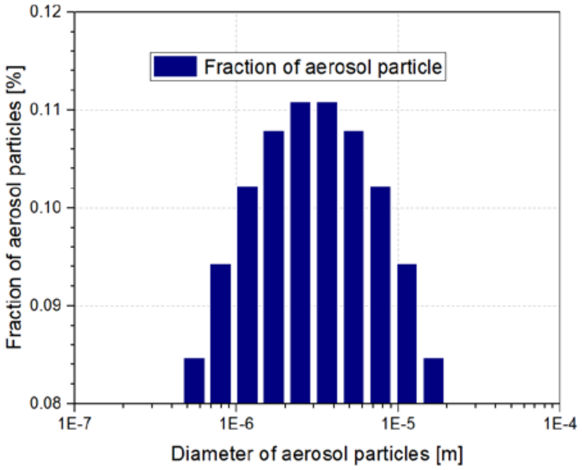

Fig. 3. Distribution of the aerosol particles considered in the sensitivity analyses

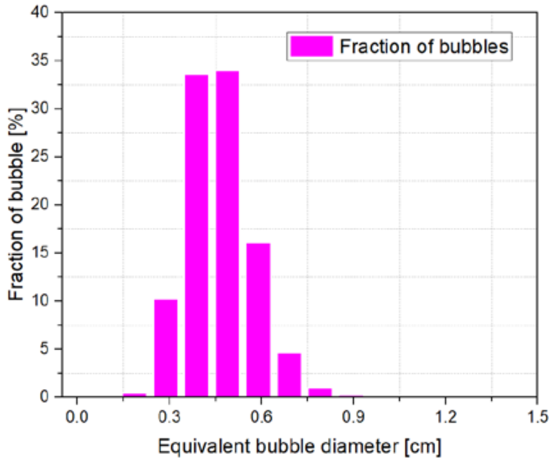

Fig. 4. Distribution of the bubbles considered in the sensitivity analyses

The net deposition velocities are compared with the deposition velocities according to the various retention mechanisms for the various bubble equivalent diameters in Fig. 5. Note that the velocities in Fig. 5 are average values considering the size distributions of the aerosol particles.

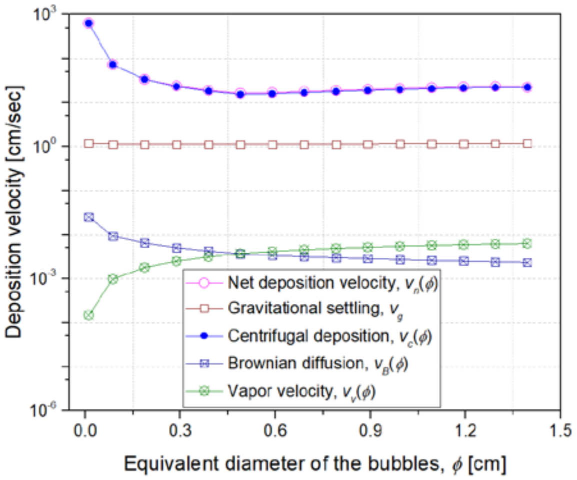

Fig. 5. Comparison of net deposition velocities to the deposition velocities of the various retention mechanisms

As shown in Fig. 5, the net deposition velocity of a bubble with an equivalent diameter of 0.01 cm is ~650cm/sec and it decreases rapidly as the bubble equivalent diameter increases. The value is saturated at ~20/cm sec when the bubble equivalent diameter is ~0.7 cm. Such changes are consistent with the change of the DFs over bubble equivalent diameter reported in Ref. 6.

From the comparison of the deposition velocities for each retention mechanism with the net deposition velocities in Fig. 5, we find that the centrifugal deposition is the dominant mechanism of the aerosol retention in the bubbles, i.e., ~90% of net deposition velocity comes from the centrifugal deposition. It is also the most sensitive mechanism to the change of the bubble equivalent diameters. We, therefore, can conclude that the centrifugal deposition is the most important mechanism of retention in the calculation of the bubble-size-dependent DFs.

3.2 Sensitivity Analyses on Retention Mechanisms of Aerosol Particles

In the analyses, I-COSTA is applied to sensitivity analyses on the various size distribution of the bubbles. For the sensitivity analyses, we consider three cases: effect of diameter at nozzle exit (Case 1), effect of molecular weight of non-condensable gas (Case 2), and steam fraction (Case 3). The geometric and thermo-physical conditions used in the analyses are the same as those in the previous section. The average equivalent diameters and the geometric standard deviations of the bubble size distributions for three cases are listed in Table 1. Changes of the DFs according to the distance from the nozzle exit for the three cases are shown in Figs. 6~8.

Table 1. Size distribution of the bubbles

Parameter		**Data**	
		Avg. [cm]	**Log (Std.)**
Reference case (9.9 mm, Nitrogen, 0.07)		0.564	0.172
Case 1	12.7 mm	0.554	0.199
	20.2 mm	0.589	0.191
Case 2	Hydrogen	0.562	0.193
	Helium	0.466	0.200
Case 3	0.25	0.578	0.181
	0.50	0.545	0.183
	0.75	0.467	0.189
	0.95	0.361	0.163

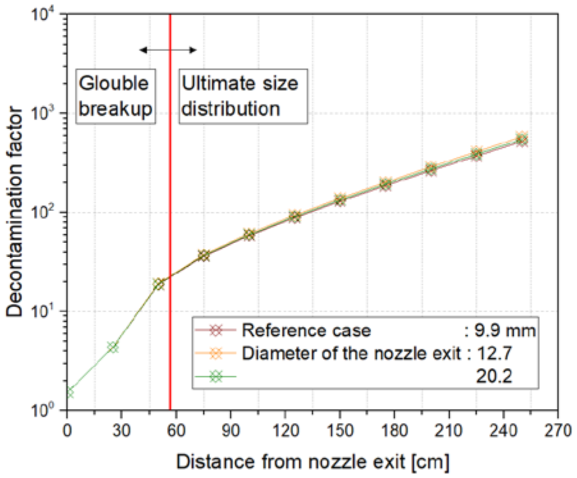

Fig. 6. Comparison of DFs for various diameters of the nozzle exit

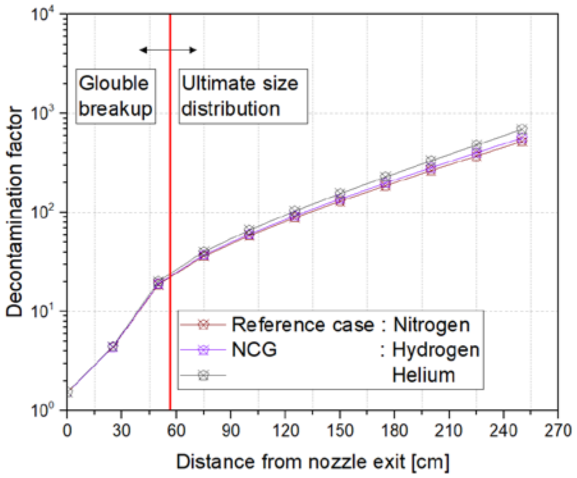

Fig. 7. Comparison of DFs for various molecular weights of non-condensable gases

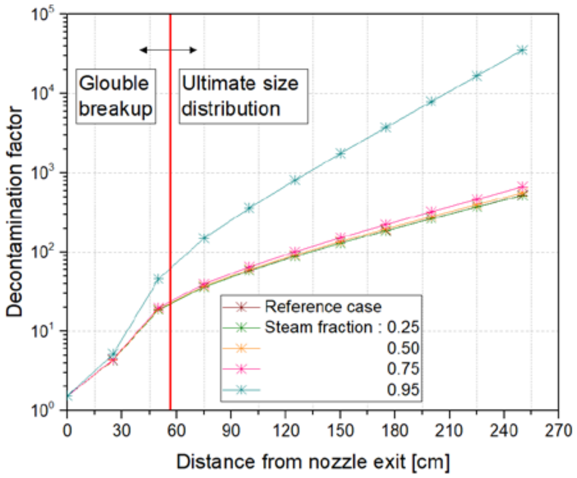

Fig. 8. Comparison of DFs for various steam fractions

As shown in Figs 6 and 7, the differences in the change of the DFs as the bubbles rise are less than 40 % compared to those in the reference case. These results are attributed to the small effect that injector diameters and the molecular weight of non-condensable gases, respectively have on the ultimate size distributions of the bubbles.

For case 3, when the steam fraction increases higher than 0.95, the differences in the change of DFs as the bubbles rise become 680 % compared to those in the reference case. These results are ascribed to that most steam condenses before the globule completely breaks up into small bubbles. We, therefore can conclude that the steam fraction is the most important factor in the calculation of the bubble-size-dependent DFs.

4. Conclusions

In the first part of this study, we proposed a calculational procedure for the bubble-size-dependent DFs in order to analyze the amount of FPs released during the pool scrubbing more realistically. The bubble-size-dependent DFs were derived from the deposition velocities which are functionalized over the size of bubbles. The calculational procedure for the bubble-size-dependent DF was implemented in I-COSTA coupling with the bubble-hydrodynamics and bubble-thermodynamics to obtain the thermophysical conditions, i.e., pressures, temperatures, and velocities of the bubbles.

With I-COSTA, we performed two sensitivity analyses: one was on the various retention mechanisms of the aerosol particles in order to find the dominant mechanism of the retention as the bubble size changes, the other was on the various size distributions of the bubbles in order to find the most important factor in the bubble-size-dependent DFs.

From the sensitivity analyses on the various retention mechanisms, we found that the net deposition velocities decreased rapidly as the bubble equivalent diameter increases. We also found that ~90 % of the net deposition velocities came from the centrifugal deposition. Therefore, the centrifugal deposition is the most dominant retention mechanism. It is also the most sensitive mechanism to the change of the bubble size.

In the sensitivity analyses on the various size distributions of the bubbles, we found that the steam fraction is the most important factor in the calculation of the bubble size-dependent DFs. As the steam fraction was higher than 0.95, the difference in the DFs as the bubbles rise become 680 % compared to those in the reference case. These results were attributed to that most steam condenses before the globule completely breaks up into small bubbles. For the other cases, there were small effects the injector diameters and the molecular weights respectively have on the ultimate size distributions of the bubbles.

In the second part of this study, we will apply I-COSTA to analyze LACE-ESPAÑA experiments for validation of the calculational procedure.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using financial resources granted by Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805001).

REFERENCES

[1] M. Escudero et al., State-of-the-art review on fission products aerosol pool scrubbing under severe accident conditions In: Nuclear Science and Technology, European Commission Report, EUR 16241 Brussels, Belgium, 1995.

[2] D. D. Paul et al., Radionuclide Scrubbing in Water Pools Volume 1 : Gas-Liquid Hydrodynamics, NP-4154, EPRI, Palo Alto, CA.

[3] M. J. Marcos et al., LACE-ESPAÑA Experimental Programme on the Retention of Aerosols in Water Pool, Final Reports, ITN/TS-08/DP-93, CIEMAT, Madrid, Spain, 1994.

[4] P. C. Owczarski and K. W. Burk, SPARC-90: A Code for Calculating Fission Product Capture in Supression Pools, NUREC/CR-5765, U.S NRC, Washington, DC. 1991.

[5] R, O. Gaunnt et al., MELCOR Computer Code Manuals Vol. 1: Primer and Users' Guide, Version 1.8.6 Sandia National Laboratories, Albuquerque, NM, 2005.

[6] L. E. Herranz et al., Review and assessment of pool scrubbing models, ISSN 1135-9420, CIEMAT, Madrid, Spain, 1996.

[7] H-J Jo et al., "Evaluation of Decontamination Factor of Aerosol in Pool Scrubber according to Bubble Shape and Size," In : *Trans. Kor. Nucl. Soc.*, *Autumn Meeting*, Goyang, Korea, May. 12-13, 2016.

[8] Nuclear Safety Act in Korea, https://elaw.klri.re.kr/kor_mobile/viewer.do?hseq=45486&type=sogan&key=61 , 2017 (Accessed on July 11, 2019).

[9] Y. Lee et al., "Effect of Bubble Size Distribution in Retention of Aerosol Particles during Pool Scrubbing – Part II : Applications to LACE-ESPAÑA experiments," In : *Trans. Kor. Nucl. Soc.*, *Autumn Meeting*, Goyang, Korea, Oct. 24-25, 2019.