Preliminary aerosol concentration effect modeling in pool scrubbing code

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1. Introduction

In the event of an accident at a nuclear power plant, pool scrubbing is one way to remove radioactive material and reduce emissions to the environment. The principle of pool scrubbing is to inject aerosol-type radioactive material into a water pool to keep the contaminant materials in water. To evaluate the effect pool scrubbing, pool scrubbing codes such as BUSCA, SPARC, and SUPRA have been developed, and these codes are used in severe accident analysis codes such as MELCOR. Many pools scrubbing experiments have been conducted to evaluate the pool scrubbing effect on various thermal-hydraulic conditions of water pool and injection gases, among which Hashimoto (1988) and Haomin Sun (2019) experimentally confirmed the pool scrubbing effect on aerosol concentration respectively [1][2]. Hashimoto confirmed that the lower the concentration of aerosol in a deep water pool condition, the higher the aerosol removal. Similarly, Haomin Sun also observed that aerosol concentration reduction enhances aerosol removal. However, despite the fact that the concentration of aerosol is an important factor in aerosol removal during the pool scrubbing process, the existing codes do not use aerosol concentration information as an input parameter. In this study, preliminary modeling was performed based on the Fuchs' model to take into account the aerosol concentration effects that do not exist in the existing codes.

2. Methods

In this section, the method used to model the aerosol concentration effects are described. This model is based on Fuchs' aerosol absorption model[3].

2.1 Effect of aerosol concentration on pool scrubbing

When a high concentration of aerosol is injected into a clean water pool, more contamination occurs than when a low concentration is injected. Contaminants in the water pool have a large effect on reducing the internal circulation of rising bubbles [2]. This is because contaminants present at the bubble interface interfere with the internal circulation. Therefore, the internal circulation is reduced more in the aerosol condition injected at a higher concentration. The main removal mechanism for aerosol in a relatively large particle area (>1 μm) in rising bubbles is impaction, as shown in Fig. 1 [4]. The source of impaction in ascending bubbles is the centrifugal force caused by internal circulation. However, due to contamination of the bubble interface, internal circulation is reduced or eliminated, impaction hardly occurs in the rising bubbles.

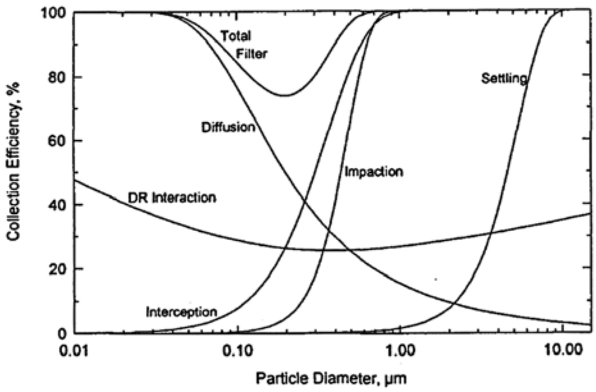

Fig. 1. Aerosol removal efficiency respect to particle size [4].

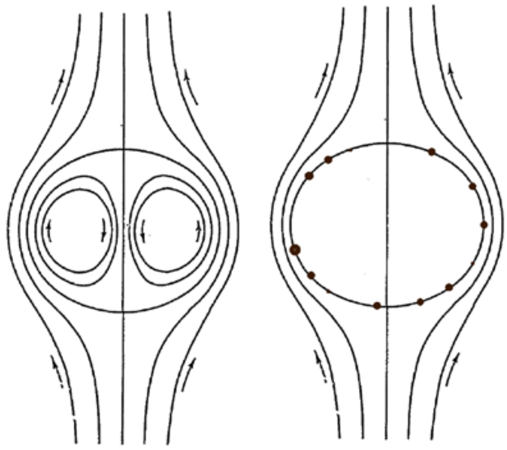

Fig. 2. Internal circulation in rising bubbles with or without contaminants [3].

2.2 The model of aerosol concentration effect

Fuchs assumed that aerosol removal occurred due to Brownian diffusion, gravitational sedimentation and inertial impaction, and some pool scrubbing codes even considered thermophoresis and diffusiophoresis. The deposition velocity due to these mechanisms are as follows [5].

$$U_g = \frac{\rho_p d_p^2 g Cn}{18\mu_g} \quad (1)$$

$$U_{imp} = \frac{9}{4}\frac{{U_B}^2 U_g \sin^2\theta}{R_c g} \quad (2)$$

$$U_{Brow} = 1.8\left(\frac{D_p U_B}{R_C^3}\right)^{0.5}\frac{V}{A_d} \quad (3)$$

$$U_{difph} = \frac{X_S}{X_S+\sum_{i\neq s}X_i\left(\frac{M_i}{M_S}\right)^{0.5}}\frac{-dm_S/dt}{m_S}\frac{V}{A} \quad (4)$$

$$U_{th} = \frac{3\mu_g}{2\rho_g T_B}\frac{k_h(T_B-T_p)Cn}{K_g}\frac{\frac{K_g}{K_p}+\frac{2.48\lambda_g}{r_p}}{\left(1+\frac{3\lambda_g}{r_p}\right)\left\{1+2\left(\frac{K_g}{K_p}+\frac{2.48\lambda_g}{r_p}\right)\right\}} \quad (5)$$

As the aerosol concentration increases, the internal circulation decreases, which results in a decrease in centrifugal velocity, and can be calculated by introducing the concept of aerosol concentration factor (ACF) as follows.

$$U_{imp,C} = U_{imp} \times ACF \quad (6)$$

ACF has a value of 0 to 1, depending on the concentration. It is assumed that when the aerosol concentration is high, the ACF approaches 0, and when the aerosol concentration is low, the ACF approaches 1. The total decontamination factor (DF) in rising bubbles can be calculated as follows.

$$DF_{rise} = \exp\left[\frac{1}{V_b}\int_0^{t_b}\int_A U_{net}\,dA\,dt\right] \quad (7)$$

where,

$$U_{net} = U_g\cos(\theta) + U_{imp,C} + U_{Brow} + U_{difth} + U_{th} \quad (8)$$

3. Results and discussion

DF calculations for various ACF values were performed to predict the change in DF for aerosol concentration variation. In addition, since impaction occurs well on relatively large particles, the effect of aerosol size was also considered to see the effect on small-sized particles. The calculation conditions are shown in Table 1.

Table 1. Calculation conditions

Pool temperature (°C)	20
Pool height (m)	2
Inlet gas flow (m^3/s)	0.001
Inlet steam mass fraction	0.5
Gas temperature (°C)	120
Orifice diameter (cm)	1
Composition	Nitrogen, Steam, SiO_2
Aerosol size (μm)	0.1, 0.5, 1.0, 5
ACF	0 ~ 1

The results of the DF calculation respect to the aerosol concentration factor are shown in Fig. 3. The effect of aerosol concentration can be predicted to occur well in large particles. In the case of 3 μm particle diameter, the variation of DF value respect to ACF is very large, but in the case of 0.1 μm particle diameter, it can be seen that it is hardly affected by ACF. The reason for this result is that, as shown in Fig. 1, particles larger than approximately 1 μm are most dominated by the impaction removal mechanisms. On the other hand, the particle size of about less than 0.1 μm is negligible by the impaction mechanism. As a result, when the aerosol concentration increased, the concept of ACF was introduced to take into account this effect, and it was confirmed that the removal of the aerosol decreased as the concentration increased. There are also areas that need further improvement in the future to apply the aerosol concentration effect to the pool scrubbing codes.

First, when the concentration of the aerosol is low, the amount of water vapor can be absorbed per aerosol particle can be relatively increased in the bubble. Due to this effect, when the concentration of the aerosol is low, the particle size may be larger, and removal of the aerosol may be better caused by gravitational sedimentation and inertial impaction. In addition, bubbles rising from the contaminated water have a slower rising velocity than clean water, as shown in Fig. 4, which causes the internal circulation to slow down. However, a decrease in the velocity of the rising bubble may increase the residence time of the bubble. Therefore, it is considered that a model that can consider all of these effects should be developed in the future.

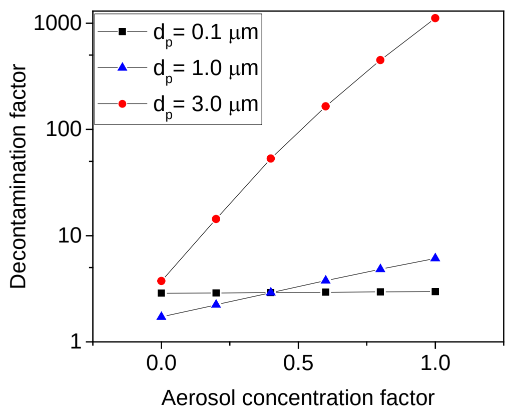

Fig. 3. DF calculation results for different ACF

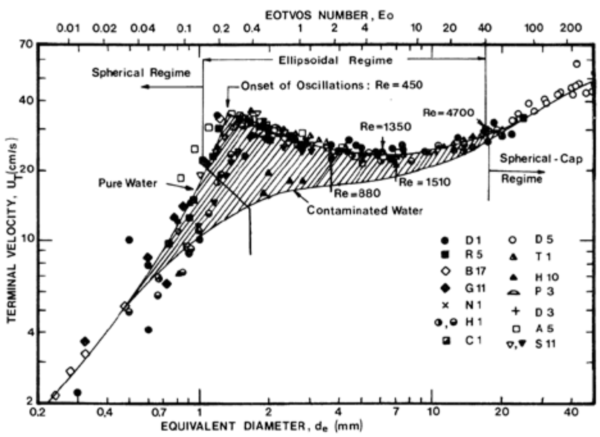

Fig. 4. Terminal velocity of clean water and contaminated water [6].

4. Conclusions

The concentration effect was considered preliminary in the pool scrubbing code. Existing experimental results showed that the increase in aerosol concentration tended to reduce aerosol removal. The code developed preliminary by introducing the concept of ACF showed a similar trend to the experimental results. In the future, it is necessary to supplement the parts that have not been considered about aerosol concentration effects.

Acknowledgments

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Nomenclature

A	surface area of a bubble	$[\mathrm{m}^2]$
Cn	Cunningham slip factor	$-$
D_p	particle diffusivity	m^2/s
d_p	Particle diameter	m
DF_{rise}	Bubble rise region DF	$-$
k_h	heat transfer coefficient	$\mathrm{W/m^2 \cdot K}$
k_g	bubble gas thermal conductivity	$\mathrm{W/m \cdot K}$
K_p	thermal conductivity of the particle	$\mathrm{W/m \cdot K}$
M_s, M_i	Molarcular mass of steam, i'th noncondensable gas	kg/mol
R_c	Radius of curvature	m
r_p	Particle radius	m
T_P, T_B	Pool, bubble temperature	℃
U_B	Bubble relative velocity	m/s
U_{Brow}	Brownian diffusion velocity	m/s
U_{imp}	Centrifugal velocity	m/s
U_{difph}	Diffusiophoresis velocity	m/s
U_g	Gravitational velocity	m/s
V	bubble volume	m^3
X_s	Steam mole fraction	$-$
X_i	mole fraction of non-condensable gas	$-$

Greek Letters

ρ_g	Gas density	$\mathrm{kg/m^3}$
ρ_p	Particle density	$\mathrm{kg/m^3}$
μ_g, μ_L	Gas, liquid viscosity	$\mathrm{kg/m \cdot s}$
λ_g	Molecular mean free path	m

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