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Evaluation of Decontamination Factor of Aerosol in Pool Scrubber according to Bubble Shape and Size

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1. Introduction

If a severe accident occurs in a nuclear power plant (NPP), the aerosol and gaseous fission products might be produced in the reactor vessel, and then released to the environment after the containment failure [1]. FCVS (Filtered Containment Venting System) is one of the severe accident mitigation systems for retaining the containment integrity by discharging the high-temperature and high-pressure fission products to the environment after passing through the filtration system.

In general, the FCVS is categorized into two types, wet and dry types. A conceptual schematic of wet type FCVS is shown in Fig. 1. The scrubbing pool could play an important role in the wet type FCVS because a large amount of aerosol is captured in the water pool [2]. The pool scrubbing phenomena have been modelled and embedded in several computer codes, such as SPARC (Suppression Pool Aerosol Removal Code), BUSCA (BUbble Scrubbing Algorithm) and SUPRA (Suppression Pool Retention Analysis) [3]. These codes aim at simulating the pool scrubbing process and estimating the decontamination factors (DFs) of the radioactive aerosol and iodine gas in the water pool, which is defined as the ratio of initial mass of the specific radioactive material to final massy after passing through the water pool.

The pool scrubbing models were reviewed and an aerosol scrubbing code has been prepared to calculate decontamination factor through the pool. The developed code has been verified using the experimental results and evaluated parametrically on the input variables.

2. Pool scrubbing phenomena and modeling

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Phenomena and decontamination factor of injection zone was pointed out in the previous studies[4]. In this paper, the aerosol removals and hydrodynamics models are focused on the rise zone.

2.1 Hydrodynamics at rise zone

Figure 2 shows the typical configurations of a water pool during pool scrubbing. When the gases including radioactive aerosols enter the pool through a vent, the gases leaving the vent form large globules that break up into a swarm of small bubbles. It is called to rise zone where the bubble exists in region. The hydrodynamics associated with rise zone are discussed in this section.

The stable bubble swarm has a bubble size distribution

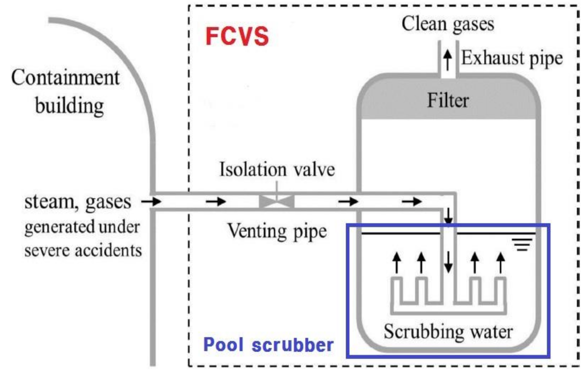

Fig.1. A conceptual schematic of the wet type FCVS [2]

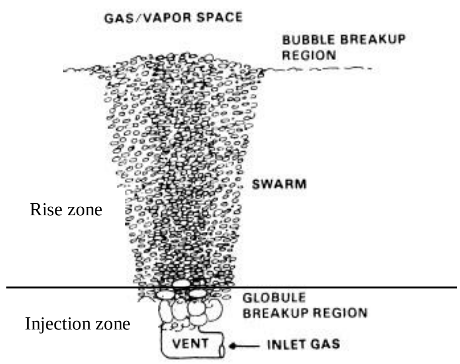

Fig.2. A schematic of water pool during scrubbing of inlet gas [5]

that is essentially lognormal.

To represent the series of stable bubbles, the single diameter is obtained as volume mean diameter (d_{vm}) and calculated by Eq.(1)[6].

$$d_{vm} = 0.684\exp(2.303(-0.2265 + \sqrt{0.0203 + 0.0313x_{nc}}) \quad (1)$$

All the rising bubbles are considered to be equal in size, and sphere or oblate ellipsoid shape is assumed; the relationship between the major/minor axes is calculated on the basis of the following Eq.(2)[5].

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$$\frac{a}{b} = 0.84107 + 1.13466d_{vm} - 0.3795d_{vm}^2 \quad (2)$$

(If the bubble shape is sphere, $\frac{a}{b}$ is equal to 1.)

The aerosol removal mechanisms can occur during the bubble rises by pool surface, so that the relative velocity of the rising velocity is very important parameter. The bubble rising velocity depends on the volume mean

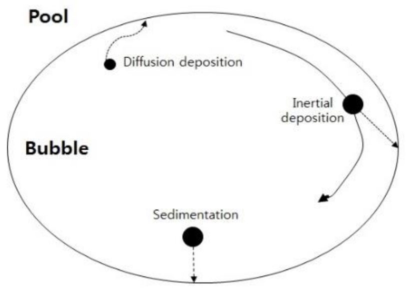

Fig.3. Aerosol dynamics within bubble

diameter, and is based on the Haberman data and following Eq.(3)[5].

$$d_{vm} < 0.5\ cm, \qquad v_r = 7.876(\frac{\sigma_p}{\rho_p})^{\frac{1}{4}}$$
$$d_{vm} > 0.5\ cm, \ v_r = 1.40713 d_{vm}^{0.49275} 7.876(\frac{\sigma_p}{\rho_p})^{\frac{1}{4}} \qquad (3)$$

The residence time of the bubble in the pool is function of rising velocity.

$$t_r = \frac{h_p}{u_r} \qquad (4)$$

2.2 Aerosol removal mechanisms at rise zone

Several physical processes are involved in transporting aerosol to the liquid-gas interface (equal bubble surface) when steam/gas mixtures are bubbled through a water pool such as gravity settling, centrifugal force and diffusion[7]. Fig. 3 shows aerosol behavior within bubble.

The large aerosols over 1μm are removed by gravity settling mechanism. The Stokes' law is the determination of the velocity of aerosol gravity settling by Eq.(5).

$$v_g = \frac{\rho_a d_a^2 g C_c}{18 \mu_g} \qquad (5)$$
$$C_c = 1 + (2.493 \frac{\lambda_g}{d_a} + 0.84 \frac{\lambda_g}{d_a} \exp\left(-0.435 \frac{d_a}{\lambda_g}\right)) \ [8] \qquad (6)$$

The small aerosol under 0.1μm are removed by diffusive deposition. The diffusion velocity from Brownian diffusion can be estimated by Eq.(7)[5].

$$v_d = \sqrt{\frac{D}{\pi t_e}} \qquad (7)$$
$$\mathrm{D} = \mathrm{k} T_b B \qquad (8)$$
$$t_e = \frac{a}{v_r} \qquad (9)$$

2.3 Decontamination factor at rise zone

The net local deposition velocity at finite surface area from all forces is the vector sum deposition velocities[5]. This net deposition velocity can be used to define the decontamination factor for the aerosol removal mechanisms. The code has not yet considered all aerosol removal mechanisms. The diffusion deposition velocity is integrated over the whole bubble surface area and gravity settling deposition velocity is integrate over the cross section of the bubble and over the bubble residence time.

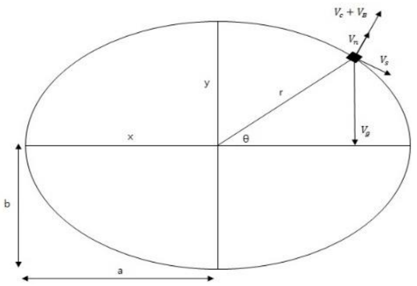

Fig.4. Net deposition velocity at local surface of bubble

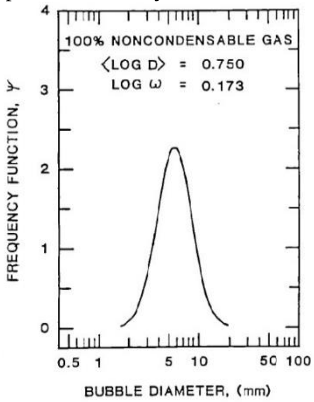

Fig.5. Bubble size distribution in pool[5]

$$\mathrm{DF(rise)} = \exp(\frac{t_r}{Vol_b}\left(\int v_d dA + v_g \pi ab\right)) \qquad (10)$$

In the codes, the decontamination factor of aerosols is calculated in two regions: gas injection and bubble rising regions. The total decontamination factor is obtained by a product of the values calculated in those regions.

$$DF = DF_{(injection)} \times DF_{(rise)} \qquad (11)$$

2.1 Log-normal distribution model

Generally, the aerosol size are described by the log-normal size distribution[8]. As evaluation of decontamination factor of aerosol in pool scrubber, aerosol size distribution has to be considered, because radioactive aerosol was released at sever accident has the log-normal size distribution as following Eq.(12)[9].

$$\mathrm{dN} = \frac{N}{\sqrt{2\pi} ln\sigma_a} \exp(-\frac{(lnd_a - lnd_g)^2}{2ln^2\sigma_a} d(lnd_a)) \qquad (12)$$

Either the aerosol size or bubble size have the log-normal distribution as shown a Fig. 5. It is necessary to develop the model can consider the bubble size distribution[6].

3. Results and discussion

3.1 Comparison to reference experimental data (LACE-ESPANA experiment)

An aerosol scrubbing code was prepared to calculate decontamination factor through the pool by C++ language. LACE-ESPANA experimental results were simulated to the verify aerosol scrubbing code. The LACE-ESPANA experimental conditions are tabulated

Table I: The common parameters of LACE-ESPANA[10]

Pool		Gas	
Temperature	110 ℃	Temperature	150 ℃
Depth	2.5 m	Composition	N_2, Steam CsI(g)
Absolute pressure	3 bar	Inlet pressure	3.25 bar
Vent type	horizontal	Orifice diameter	1 cm

Table II: The variable parameters of LACE-ESPANA[10]

Case	Steam fraction	Aerosol diameter(μm)	GSD
1	0.11	3.0	2.3
2	0.38	0.55	1.6
3	0.58	3.4	5.4
4	0.90	3.4	2.6
5	0.15	5.8	3.5
6	0.35	7.2	1.6
7	0.56	4.2	3.3
8	0.87	5.0	3.8

in Tables I and II, that is, common and variable parameters. In this case, condensation of hygroscopic aerosol wasn't considered.

Fig. 6 were shown to results to compare to the aerosol decontamination factor of experiment, BUSCA, SPARC and developed the code. The code has tendency as like BUSCA. The reason why difference occur between experiment and code seems as centrifugal deposition to be excepted for code.

The bubble has variety shape like sphere, ellipsoid and cap in pool. Considering to bubble shape, carried out to compare to decontamination factor according to bubble aspect ratio as shown in Fig. 7. As shown to Fig. 7, the decontamination factor of ellipsoid bubble are larger than sphere bubble. It seems that the ellipsoid bubble have larger cross section area than sphere bubble.

Either the bubble has variety shape or size. As shown in Fig. 8, the decontamination factor changes according to bubble diameter. The decontamination factor was in inverse proportion to the bubble diameter. Especially, the bubble size was smaller, the decontamination was changed.

Actually, the bubble has the log-normal size distribution in pool. Fig. 9 was shown that to compare to decontamination factor in bubble single size and log-normal size distribution. As shown in Fig. 9, the bubble size distribution is affected on the decontamination factor. Especially, geometry standard deviation of distribution were more increase, the decontamination factor were higher.

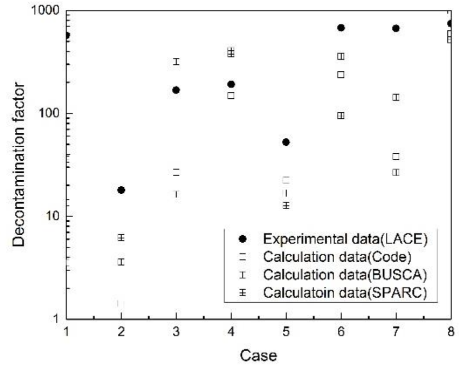

Fig. 6 Comparing to experimental data and calculation data of pool scrubbing codes

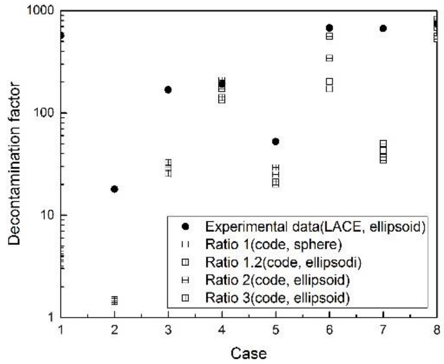

Fig. 7 Comparing to calculation results of code according to bubble aspect ratio

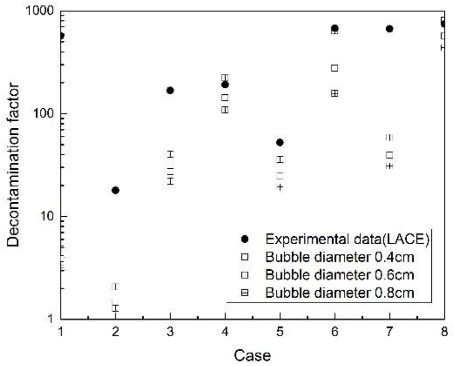

Fig. 8 Comparing to calculation results of code according to bubble diameter.

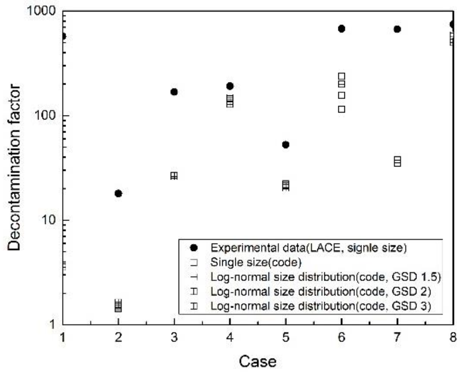

Fig. 9 comparing to calculation results of code according to bubble size distribution.

4. Conclusion

The pool scrubbing models in rise zone were reviewed and an aerosol scrubbing code has been prepared to calculate decontamination factor through the pool. The developed code has been verified using the experimental results and parametric studies the decontamination factor according to bubble shape and size.

To evaluate the decontamination factor more accurate whole pool scrubber phenomena, the code was improved to consider the variety shape and size of bubbles.

The decontamination factor were largely evaluated in ellipsoid bubble rather than in sphere bubble. And bubble log-normal size distribution was affected to the decontamination factor, because the decontamination factor were changed rapidly according to bubble diameter as shown in Fig. 8.

The pool scrubbing models will be enhanced to apply more various model such as aerosol condensation of hygroscopic. And, it is need to experiment to measure to bubble shape and size distribution in pool to improve bubble model.

NOMENCLATURE

a major axis of ellipsoid
b minor axis of ellipsoid
B aerosol mobility
C_c cunningham slip correction factor
d_a aerosol diameter
d_g geometric diameter
d_{vm} bubble volumetric mean diameter
D diffusion coefficient of aerosol.
g gravity constant
h_p pool depth
K boltzmann's constant
t_e exposure time
t_r residence time
T_b, bubble temperature
V_d diffusion aerosol deposition velocity
V_g gravitational aerosol deposition velocity
V_n net local deposition velocity
V_r bubble rising velocity
Vol_b globule volume
χ_{nc} the mole fraction of non-condensable gas in inlet gas.
ρ_a aerosol of density
μ_g gas viscosity;
σ_a geometry standard deviation in log-normal size distribution.
λ_g mean free path in air
*DF(injection)*decontamination factor at injection zone.
DF(rise) decontamination factor at rise zone.

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