Code Development of Radioactive Aerosol Scrubbing in Pool – Injection Zone

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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 injection zone. 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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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. 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 [4].

In the SPARC 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.

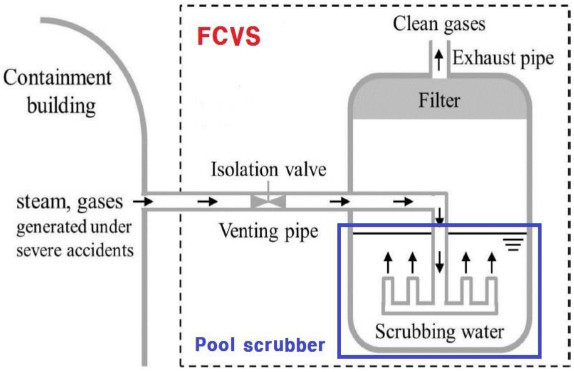

Fig.1. A conceptual schematic of the wet type FCVS [2]

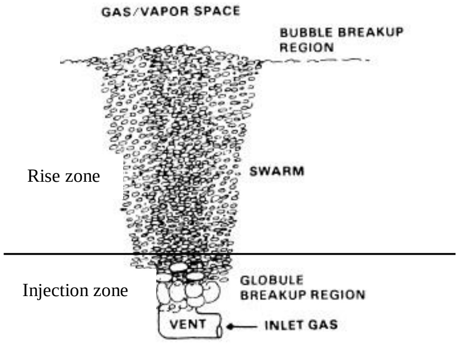

Fig.2. A schematic of water pool during scrubbing of inlet gas [5]

In the injection zone, aerosol removal occurs by following mechanisms [4].

- Stefan flow from steam condensation during gas equilibration to pool conditions. This effect is named initial steam condensation.
- Inertial impaction of aerosol in rapidly decreased gas velocity
- Centrifugal, diffusional and gravitational aerosol deposition during gas injection through small orifice, multi-hole vents.

In the rise zone, aerosol removal occurs by centrifugal, diffusional, and gravitational aerosol deposition within a bubble.

In SPARC code, the overall DF in the injection zone and in the rise zone can be calculated separately, and then the total DF can be obtained by multiplying this two DFs. In this paper, the aerosol removals and hydrodynamics models are focused on the injection zone.

2.1 Hydrodynamics at injection zone

When gas is injected from a vent into a water pool, large gas bubbles are formed initially and called globule. The injection zone is defined as the globule existing region.

Before decontamination factor is calculated at injection zone, an initial globule diameter should be obtained by aerosol removal model equations based on the input values. The initial globule diameter can be obtained by equation (1).

$$D_{\mathrm{g}} = \left(\frac{3}{2} V_{\mathrm{n}} D_0^2 \sqrt{\frac{\sigma}{\rho_{\mathrm{p}} g}} \right)^{1/3} \tag{1}$$

$$V_{\mathrm{n}} = a\mathrm{We}^b \tag{2}$$

$$\mathrm{We} = \frac{\rho_{\mathrm{p}} D_0 V_0^2}{\sigma} \tag{3}$$

$$\mathrm{Q} = \frac{\pi}{4} V_o D_o^2 \tag{4}$$

The initial globule diameter in SPRAC is assumed that the inlet gas is only non-condensable gas. Therefore, it is need to revision to equation when gas is mixture non/condensable gas.

Considering the mole fraction of the non-condensable (χ_n) gas in inlet gas, equations (5) and (6) can be used to get the initial globule diameter.

$$V_o = \frac{4Q_v \chi_n}{\pi D_{on}^2} \tag{5}$$

$$D_{on} = D_o \times \chi_n \tag{6}$$

2.2 Aerosol removal mechanisms at injection zone

In the injection zone, aerosols are removed by an initial steam condensation, impaction, gravity settling, and centrifugal, Brownian diffusion deposition at vent exit.

2.2.1 Initial steam condensation

If inlet gas contains steam, the condensation of the steam occurs around the injection point. Aerosols in the steam are trapped in the condensed water and finally eliminated in the pool. The aerosol removal by this process is called an initial steam condensation effect [6]. The decontamination factor due to this process is expressed as follows:

$$\mathrm{DF(ec)} = 3\frac{X_o}{X_i} \tag{7}$$

$$X_o = 1 - \frac{P_{sat}(T_p)}{P_s + \rho_p g h_p} \tag{8}$$

In the module, the saturation vapor pressure was calculated by using Antonie's equation.

If $0℃ \le T_p < 100℃$

$$P_{sat}(T_p) = 10^{8.07131 - (\frac{1730.63}{T_p + 233.426})} \div 760 \times 1013000 \tag{9-1}$$

If $100℃ \le T_p < 374℃$

$$P_{sat}(T_p) = 10^{8.14019 - (\frac{1810.94}{T_p + 244.485})} \div 760 \times 1013000 \tag{9-2}$$

2.2.2 Impaction

When the gas is injected into the pool, some particulate can be removed close to the orifice due to inertial impaction. At high flow rates and low steam mole fractions, this effect dominates comparing the other removal mechanisms which occur as the bubble rises to the surface.

The decontamination factor by impaction can be calculated by using alpha (α) which is a function of the Stokes' number of aerosol [7].

$$\mathrm{DF(impact)} = \frac{1}{1-\alpha} \tag{10}$$

$$\mathrm{Stk} = \frac{\rho_a V_o d_a^2}{9\mu_g D_o} \tag{11}$$

If $0 < \mathrm{stk} \le 0.65868$ (12)

$$\alpha = 1.79182(3.347 \times 10^{-11})^{(5.9244\times10^{-3})^{\sqrt{stk}}}$$

If $0.65868 < \mathrm{stk} \le 1.4$

$$\alpha = 1.13893(1.4173 \times 10^{-6})^{(4.25973\times10^{-3})^{\sqrt{stk}}}$$

If $\alpha = 0.9$, DF(impact) = 1

2.2.3 Gravity settling, centrifugal and Brownian diffusion deposition

It is assumed that the final detached globule is spherical of diameter, and that the forming globule is elongated with a hemispherical front of diameter equal orifice diameter [5]. The cumulative DF at vent exit is named DF(vent exit) and obtained by multiplying each DF.

$$\mathrm{DF}(\mathrm{C_{inject}}) = \exp(\frac{V_c}{V_{inlte}}) \tag{13}$$

$$\mathrm{DF}(C_{detach}) = \exp(\frac{V_{inlet} V_g \rho_g}{9D_o f g \rho_p}) \tag{14}$$

$$\mathrm{DF}(D_{inject}) = \exp(\frac{16\tau_{fill}}{3D_0}) \sqrt{\frac{D}{\pi\tau_{fill}}} \tag{15}$$

$$\mathrm{DF}(D_{detach}) = \exp(\frac{12\tau_{stop}}{D_0}) \sqrt{\frac{V_{inlet} D}{\pi D_o}} \tag{16}$$

$$\mathrm{DF}(\mathrm{G_{inject}}) = \exp(\frac{A_s V_g \tau_{fill}}{Vol_g}) \tag{17}$$

$$\mathrm{DF}(\mathrm{G_{detach}}) = \exp(\frac{3V_g(\tau_{stop})}{2D_g}) \tag{18}$$

$$\tau_{fill} = \frac{2D_g^3}{3D_0^2 V_{inlet}} \tag{19}$$

$$\tau_{stop} = \frac{4\rho_g D_g}{3f\rho_p V_{inlt}} \tag{20}$$

$$A_s = \frac{2D_o^3}{3D_o} + D_o^2(\frac{\pi}{8} - \frac{1}{3}) \tag{21}$$

2.2.4 Decontamination factor at injection zone

The decontamination factors of the removal processes in the injection zone, that is, impaction, sedimentation, diffusion, centrifugal impaction, and condensation, were multiplied to get the overall DF.

$$DF_{(injection)} = DF_{(ec)} \times DF_{(impact)} \times DF_{(vent\ exit)} \tag{22}$$

3. Results and discussion

3.1 Comparison to LACE-ESPANA

An aerosol scrubbing code was prepared to calculate decontamination factor through the injection zone by C++ language. LACE-ESPANA experimental results were simulated to verify the aerosol scrubbing code. The LACE-ESPANA experimental conditions are tabulated in Tables I and II, that is, common and variable parameters.

The Table III shows the calculation results of the decontamination factors by the aerosol removal mechanisms in the injection zone.

Table I: The common parameters of LACE-ESPANA[8]

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[8]

Case	Steam fraction	Aerosol diameter
1	0.11	0.3μm
2	0.38	0.3μm
3	0.58	0.3μm
4	0.9	0.3μm
5	0.15	2μm
6	0.35	2μm
7	0.56	2μm
8	0.87	2μm

Table III: Decontamination factor at injection zone

	DF (initial steam condensation)	DF (impact)	DF (vent exit)	DF (injection)
1	1.00	1.00	1.0047	1.0047
2	1.00	1.00	1.0040	1.0040
3	3.93	1.00	1.0037	3.9500
4	16.53	1.00	1.0031	16.600
5	1.00	1.00	1.0033	1.0033
6	1.00	1.00	1.0031	1.0031
7	3.75	1.00	1.0027	3.7650
8	12.89	1.00	1.0017	12.950

3.2 Parametric studies

Parametric studies were also performed to evaluate the influence of selected parameters on the decontamination factor. The following parameters were selected: steam fraction in inlet gas, aerosol size, and injected gas volumetric flow. The common and variable parameters for parametric studies are listed in Table IV~V.

Table IV: The common parameters for parametric studies

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

Table V: The variable parameters for parametric studies

Variable parameter	Unit	values
Steam fraction		0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Aerosol diameter	μm	100, 200, 300, 400, 500, 600, 800, 1000, 2000, 3000
Gas volumetric flow rate	cm^3/s	0.7, 1, 2, 3, 4, 5, 6, 7, 10, 20
Orifice diameter	cm	0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5
Pool temperature	℃	20, 40, 50, 60, 80, 100, 110, 120, 130

- Steam fraction

Figure 3 shows that the calculated results on the decontamination factor of each mechanism according to the stream fraction. As shown in Fig. 3, the steam fraction is highly affected on the decontamination factor by initial steam condensation.

- Aerosol size

Figure 4 shows that the calculated results on the decontamination factor of each mechanism according to the aerosol size. As shown in Fig. 4, the aerosol size in 0.7μm to 20μm range is less affected on the decontamination factor in the injection zone.

- Gas volumetric flow rate

Figure 5 shows that the calculated results on the decontamination factor of each mechanism according to the injected gas volume flow rate. As shown in Fig. 5, the injected gas volume flow rate is less affected on the decontamination factor in the injection zone.

- Orifice diameter

Figure 6 shows that the calculated results on the decontamination factor of each mechanism according to the vent orifice diameter. As shown in Fig. 6, the vent orifice diameter is less affected on the decontamination factor in the injection zone. It is expected that the vent type might be more affected on DF compared with the orifice diameter.

- Pool temperature

Figure 7 shows that the calculated results on the decontamination factor of each mechanism according to the pool temperature. As shown in Fig. 7, the decontamination factor by initial steam condensation decreases as the pool temperature increases. This is why the pool saturation pressure increases as the pool temperature increases. There are no DF variations if the pool temperature is larger than 110℃.

4. Conclusion

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

In injection zone, the initial steam condensation was most effective mechanism for the aerosol removal, and the steam fraction and pool temperature were highly affected on the decontamination factor by initial steam condensation.

The aerosol scrubbing code will be updated to evaluate the decontamination factor at rise zone and finally whole pool scrubber phenomena. And the pool scrubbing models will be enhanced to apply more various conditions such as multi-aerosol sizes and multi-bubble sizes.

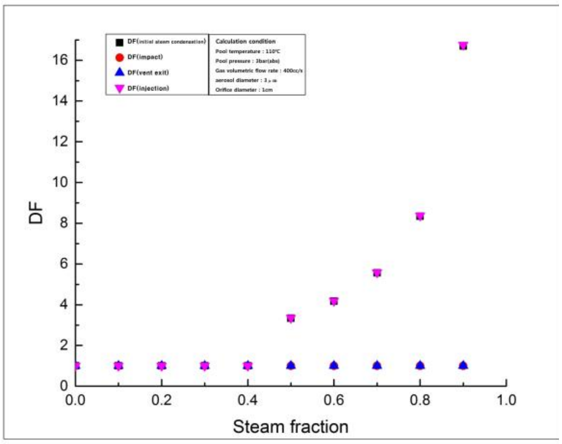

Fig. 3. DF according to steam fraction

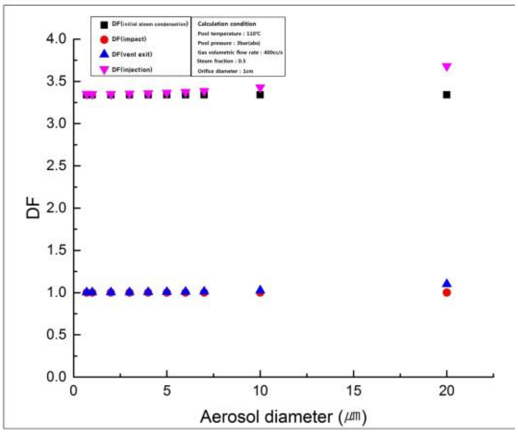

Fig. 4. DF according to aerosol diameter

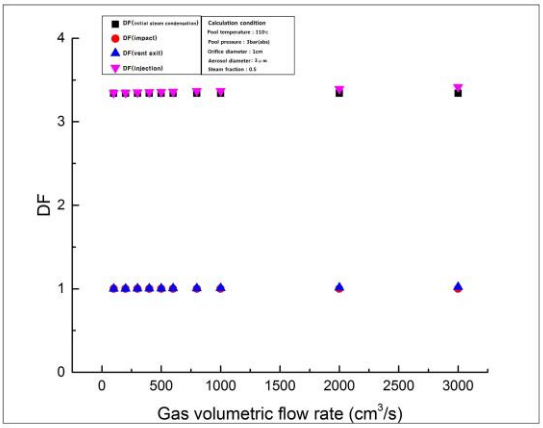

Fig. 5. DF according to gas volumetric flow rate

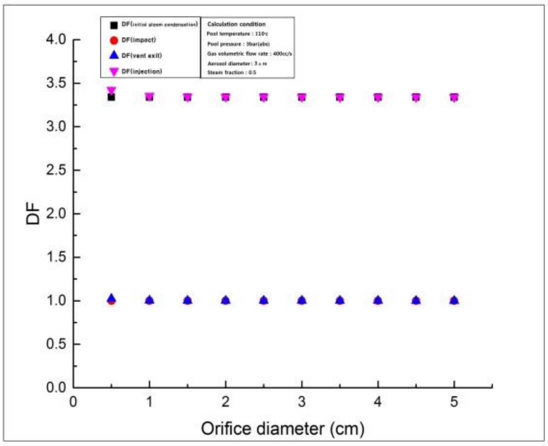

Fig. 6. DF according to orifice diameter

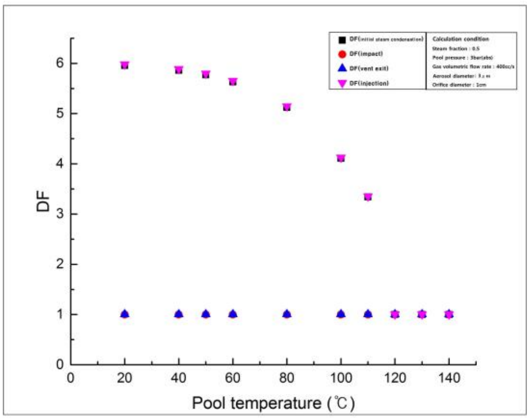

Fig. 7. DF according to pool temperature

NOMENCLATURE

A_s	globule surface area of bottom
a	0.857 at a horizontal vent coefficient
b	0.73 at a horizontal vent coefficient
d_a	aerosol diameter
D_g	initial globule diameter
D_0	vent diameter
D_{on}	modified orifice diameter
D	diffusion coefficient of aerosol
f	friction factor 0.2
h_p	pool depth
P_s	pool pressure
Q	gas volumetric flow rate at the vent in equilibrium with the pool conditions at the vent depth
T_p	pool temperature
V_c	centrifugal aerosol deposition velocity
V_g	gravitational aerosol deposition velocity
V_{inlte}	gas inlet velocity
V_o	exit gas velocity
Vol_g	globule volume
χ_n	mole fraction of non-condensable gas in inlet gas
X_o	mole fraction of non-condensable gas in the gas after equilibration
X_i	mole fraction of noncondensible gas
ρ_a	aerosol of density
ρ_g	gas density
ρ_p	pool liquid density
σ	pool liquid surface tension
μ_g	gas viscosity
τ_{fill}	time to fill the globule
τ_{stop}	characteristic stopping time
DF(ec)	decontamination factor due to initial steam condensation
DF(impact)	decontamination factor due to inertial impaction
$DF_{(C_{inject})}$	decontamination factor due to centrifugal deposition during the injection
$DF_{(C_{detach})}$	decontamination factor due to centrifugal during detached globule
$DF_{(D_{inject})}$	decontamination factor due to diffusion deposition during the injection
$DF_{(D_{detach})}$	decontamination factor due to diffusion deposition during detached globule
$DF_{(G_{inject})}$	decontamination factor due to diffusion deposition during the injection
$DF_{(G_{detach})}$	decontamination factor due to diffusion deposition during detached globule
$DF_{(vent\ exit)}$	decontamination factor at injection point multiplied each DF

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