Monte-Carlo Strategy of Spray Droplet for LOCA Dose Estimation by Decontamination Factor

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1. INTRODUCTION

As part of the system of fission product decontamination, the containment spray system is very important in NPP (Nuclear Power Plants). The fission product's removal efficiency is affected by the spray droplet behavior. In this study, some parameters of the efficiency are introduced and the relation between the parameters are evaluated. In order to derivate the spray removal phenomena, the only one water drop is used in modeling in the first step. And then the water drop model is extended to spray droplets behavior [1-2]. In this study, for LOCA dose calculation and the comparison with other experiment study, Lee's study of KHNP-CRI is recalculated and re-simulated [2]. In addition, to obtain the spray removal modeling results, as a part of some parameters, terminal velocity and Reynolds number are carried out by simplifying and recalculating. In this study, in order to get the fission product removal efficiency, the Monte-Carlo simulation is applied using the parameters such as the simplified terminal velocity, Reynold's number and the eccentricity of spray droplet [2]. The calculation results are reviewed and compared with the other studies of Slinn's study and NRC fission product removal constant [1-5]. From these results, LOCA dose estimation is carried out and compared with other experiment work.

2. METHODOLOGY

In this study, Monte-Carlo simulation strategy is needed for making some equations to the droplet motion modeling. Newtonian fluid motion equation is simplified changing the terminal velocity's various parameters into the reduced 3-parameter. As shown in chapter 2.1, in order to apply the Monte-Carlo strategy, some processes are introduced. Here, Monte-Carlo simulation methodology is mainly introduced in case of the terminal velocity, Reynolds number and fission products removal efficiency. They are used to calculate the LOCA dose and DF.

2.1 Monte-Carlo Strategy

- Newtonian dynamics equation modeling.
- Random number generation and random parameters.
- Determination of Terminal velocity and Reynolds number.
- Monte-Carlo calculation application
- Comparison between this study and other work
- Application as LOCA dose input for Monte-Carlo simulation results

2.2 Monte-Carlo Modeling of Newtonian Fluid Equation and Terminal Velocity

In this study, the motion equation for Monte-Carlo simulation is derivate using Newtonian fluid mechanics. Here, terminal velocity is achieved by simplifying the classic Newtonian fluid mechanics formula. The water drop fallen equation is written as the differential motion equation as equation (1) below [1,2].

$$m\frac{d\alpha}{dt} = NF - k_1\alpha^1 - k_2\alpha^2 \tag{1}$$

where
NF(Net Force) = the difference between gravity force and drag force.

α = terminal velocity, m = water drop's mass
(Here, terminal velocity is falling velocity when droplet reached on the maximum falling height)

from equation (1), integration process is carried out and changed into terminal velocity term as equation (2) below (See "Appendix A" about the detailed process) [2]:

$$\alpha = \frac{2NF}{k_1+\sqrt{k_1^2 + 4k_2NF}} \times \left[\frac{1-\exp\left(\frac{-\sqrt{k_1^2 + 4k_2NF}}{m}t\right)}{1-\frac{k_1-\sqrt{k_1^2 + 4k_2NF}}{k_1+\sqrt{k_1^2 + 4k_2NF}}\exp\left(\frac{-\sqrt{k_1^2 + 4k_2NF}}{m}t\right)}\right] \tag{2}$$

which describes the velocity of the object in the fluid as a function of time. From equation (2), a dimensionless parameter φ is defined as

$$\varphi = \sqrt{1 + \frac{4k_2NF^2}{k_1^2}} \tag{3}$$

In equation (2), the terminal velocity is given by

$$\alpha_{ter} = \frac{2NF}{k_1+\sqrt{k_1^2 + 4k_2NF}} = \frac{2NF}{k_1(1+\varphi)}, \tag{4}$$

where
k_1 : 0.2 ~ 1.8 (random number)
φ : 1~220 (random number)
NF : 1~6 (random number : log-normal distribution)

2.3 Reynolds Number Determination

In the previous section, terminal velocity is used for calculating the terminal Reynolds number. According to Clift's study[3], the Reynolds number of a water droplet is given by

$$R = \frac{\alpha_{ter} \times \rho_g \times \text{Eccentricity}}{\mu_g} \qquad (5)$$

where

R: Reynolds numbers at the terminal velocity of spray droplet

α_{ter} : Spray droplet's terminal velocity

Eccentricity : random exponential distribution

μ_g : Viscosity of a spray droplet

Generally, Reynolds number is defined as the ratio between a fluid material's density and a fluid material's viscosity. The value is proportional to the interaction between the spray droplet and an aerosol particle.

2.4 Fission Product Removal Efficiency

The fission product removal efficiency includes various motion phenomena such as Brownian diffusion, interception, and inertia impaction.
In this study, Slinn's experimental equation [4] can be used to simulate the removal process behavior. The equation is written by equation (6).
From previous chapters, fission products removal efficiency is written as below:

$$\text{Removal efficiency} = \frac{4}{R}[1 + 0.4R^{1/2}\,\alpha_{ter}{}^{2/3} + 0.16R^{1/2}\,\alpha_{ter}{}^{1/2}] + 4 \bullet \text{Eccentricity}[1 + 2R^{1/2} \bullet \text{Eccentricity}]$$
(6)

Finally, fission products removal efficiency of equation (6) is calculated by equation (4) and equation (5) in using Monte-Carlo simulation.

2.5 LOCA Dose Estimation

LOCA dose estimation is carried out by modeling some volumes and pathways as shown Fig. 1 concept.
Fig.1 shows the frame of LOCA modeling for dose estimation.
The compartments of LOCA model include the unsprayed and sprayed region including some sub volumes, sump volumes and other volumes.
The fission products removal efficiency is used to calculate the LOCA dose as input material.
Dotted lines show for the sump leakage concept and containment purge leakage concept. Solid lines show the containment leakage concept.
In the outside of containment, the environment component of Fig.1 is located.
In the environment, the fission-product is diffused and goes to the dose estimation position by offsite atmosphere dispersion factor simulation. This diffusion behavior can be simulated by PAVAN code.

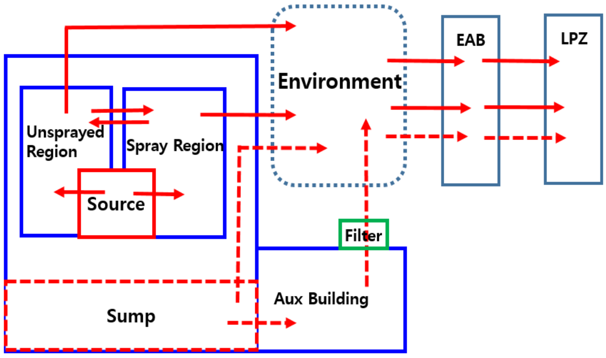

Fig. 1 LOCA modeling concept in RADTRAD code

3. RESULTS AND DISCUSSIONS

3.1 Monte-Carlo Simulation Results.

In order to calculate the fission product removal efficiency, Reynolds number is simulated for equation (5) by Monte Carlo simulation. During the simulation, random parameters are terminal velocity and eccentricity.
Monte-Carlo simulation results of equation (4) are shown in Fig. 2.
In Reynolds numbers calculation, the eccentricity is depend on the water droplet shape. Generally speaking, the water droplet or the spray droplet is governed by three dimensional ellipsoid functions. This value is simulated as random number by exponential random distribution (Fig.3). The variable range is from 1 to 1.8.

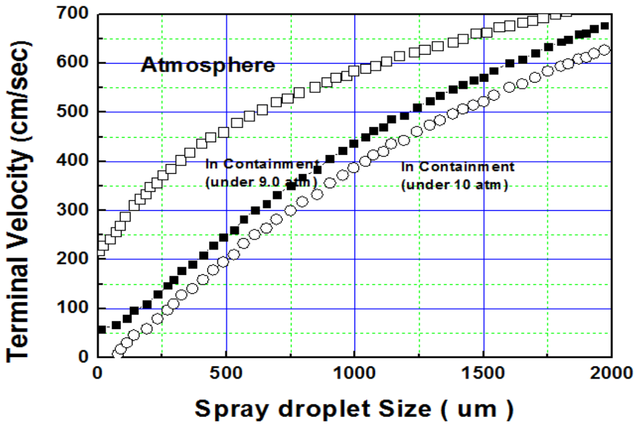

Fig. 2. Monte-Carlo simulation of terminal velocity

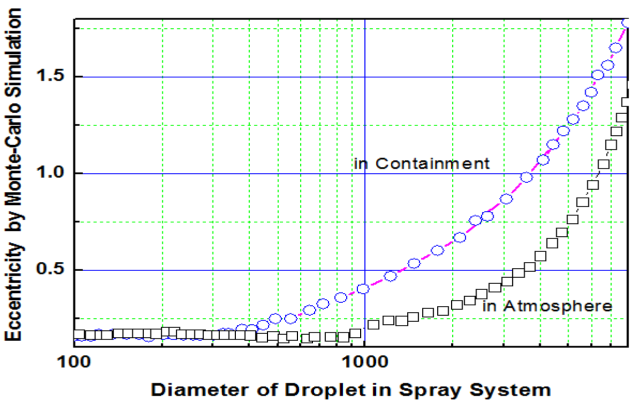

Fig. 3. Eccentricity related to spray droplet size by Monte-

Carlo simulation

3.2 Fission Products Removal Efficiency

Using Monte-Carlo simulation of equation (4) and equation (5), the fission product removal efficiency is calculated from equation (6).

Fig. 4 shows the fission product removal efficiency results. In the bigger droplet size, the fission products removal efficiency is better than the small one.

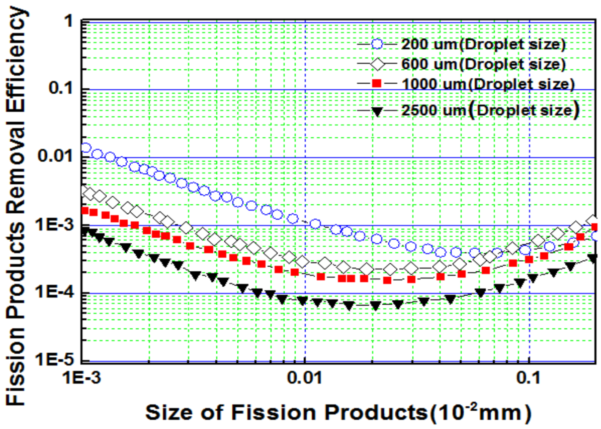

Fig. 4. Fission product removal efficiency by equations (4), (5), (6).

3.3 Comparison Results

Fig.5 shows the comparison between this study and Slinn's study.

This study work is in good agreement with Slinn's experimental study. The difference between them is less than 1.2%. In addition, Fig.5 show this work result is very useful to get the safety margin compared with NRC's constant removal model.

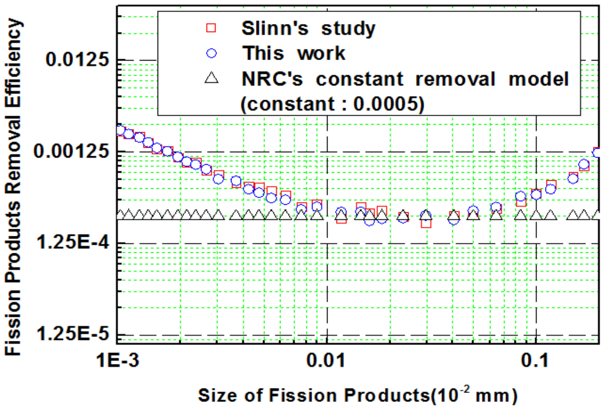

Fig. 5. Comparison between this work and other study (Slinn's work[geometric std : 1.637], this work[geometric std:1.690])

3.4 LOCA Dose Estimation

From the results of Fig. 5, LOCA dose estimation is carried out. Table1 shows the key parameters of LOCA dose. In using the Monte-Carlo simulation results, Westinghouse type LOCA dose is calculated. Table2 is the LOCA dose results in this study. Table3 is the LOCA dose results used as the input of Slinn's experimental value.

Table1. Key parameters for LOCA dose calculation

Input	Calculated results
Containment leakage flow rate (Vol% per day)	Containment leakage - 0 ~ 24 hours : 0.1 - 24 ~ 720 hours : 0.05
Removal rate or Decontamination Factors	Natural deposition removal rate - Unsprayed region : 5.50 - Sprayed region : 12.5 Iodine Decontamination Factor - Iodine by deposition : 100
Offsite Dispersion Factors (sec/cubic meter)	EAB : 4.661e-04 (0~2hours) LPZ : 3.211e-05(0~8hours) 2.007e-05(8~24hours) 1.011e-05(24~96hours) 3.3337-06(96~720hours)
Iodine removal efficiency(This work, Monte-Carlo simulation)	Removal Efficiency : 0.001 ~0.15 Eccentricity : 0.3 ~ 1.2

Table2. Calculation results of LOCA dose (This work)

Location	Results of LOCA analysis
EAB : TEDE (rem)	Containment leakage model :10.9 Purge leakage : 0.5 Sump leakage : 2.7 Total : 14.1
LPZ : TEDE (rem)	Containment leakage model :8.8 Purge leakage : 0.22 Sump leakage : 2.3 Total : 11.32
Dose Criteria : TEDE(RG 1.183) (rem)	EAB & LPZ : 25

Table3. Calculation results of LOCA dose (used as the input of Slinn's experimental value)

Location	Results of LOCA analysis
EAB : TEDE (rem)	Containment leakage model :11.0 Purge leakage : 0.5 Sump leakage : 2.8 Total : 14.3
LPZ : TEDE (rem)	Containment leakage model :8.8 Purge leakage : 0.22 Sump leakage : 2.35 Total : 11.325
Dose Criteria : TEDE(RG 1.183) (rem)	EAB & LPZ : 25

From Table 2 and Table 3, Monte Carlo results are used as input to calculate LOCA dose. In comparing this work with Slinn's experimental results, Monte-Carlo simulation of this work is in good agreement with

Slinn's experimental results. And also LOCA dose estimation is in good agreement with each other.
In LOCA dose of EAB, this work is 14.1 rem and the Slinn's experiment result is 14.3 rem. In LOCA dose of LPZ, this work is 11.32 rem and the Slinn's experiment result is 11.325 rem. In NRC's constant model, EAB and LPZ are 22 rem and 16.7 rem respectively. In comparing with NRC's constant model, the Monte-Carlo simulation of this work have safety margin more than 50%. And the LOCA dose calculation is in good agreement with other study.

4. CONCLUSIONS

Using the fission product removal efficiency is calculated by Monte-Carlo simulation. The simulation process is carried out by terminal velocity and Reynolds numbers. Fission products removal efficiency is calculated and other study. And also LOCA dose is estimated and compared with other study.

From these works, some conclusions are shown as below:

a. Monte-Carlo simulation of this work is in good agreement with other study in the fission product removal efficiency and the LOCA dose.
b. The difference between this work and Slinn's experimental value is within 1.0 %
c. The safety margin of this work is more than 50% in comparing with NRC's constant removal model.0%.
d. In LOCA dose of EAB, this work and Slinn's experimental value are 14.1 rem and 14.3 rem respectively.
e. In LPZ, this work and Slinn's experimental value are 11.3 rem and 11.325 rem respectively.

From these conclusions, this work is in good agreement with other study.

REFERENCES

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[3] C.S. Pemberton, Journal of Air Pollution Vol 3, p.168, 1980.
[4] R.Clift, J.R. Grace and M.E. Weber, "Bubbles Drops and Particles, Academic Press, New York, p.287, 1978.
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Appendix A

The equation derivation for Monte-Carlo simulation is introduced in detail as below:

$$m\frac{d\alpha}{dt} = NF - k_1\alpha^1 - k_2\alpha^2 \quad , \quad (1)$$

where F_b is buoyancy force or drag force and F is written as below:

$$NF = \begin{cases} F_b - mg, & mg < F_b \\ mg - F_b, & mg \geq F_b \end{cases}$$

$$\alpha = \text{velocity},\ m = \text{water drop's mass}$$

Equation (1) may be written as

$$\frac{d\alpha}{k_1\alpha^1 + k_2\alpha^2 - NF} = -\frac{1}{m}dt\ . \quad (2)$$

Integration of this equation gives

$$\frac{1}{\sqrt{k_1^2 + 4k_2NF}}\ln\left(\frac{2k_2\alpha + k_1 - \sqrt{k_1^2 + 4k_2NF}}{2k_2\alpha + k_1 + \sqrt{k_1^2 + 4k_2NF}}\right) = -\frac{t}{m} + C_1 \quad (3),$$

where C_1 is the integration constant. This equation easily reduces to

$$\frac{2k_2\alpha + k_1 - \sqrt{k_1^2 + 4k_2NF}}{2k_2\alpha + k_1 + \sqrt{k_1^2 + 4k_2NF}} = C_1^{'}\exp\left(\frac{-\sqrt{k_1^2 + 4k_2NF}}{m}t\right) \quad (4),$$

where $C_1^{'}$ is a new constant that is related to C_1. Evaluating $C_1^{'}$ using the initial condition $\gamma(0)$ = 0 and solving (4) for α, the result is

$$\alpha = \frac{2NF}{k_1 + \sqrt{k_1^2 + 4k_2NF}} \times \left[\frac{1 - \exp\left(\frac{-\sqrt{k_1^2 + 4k_2NF}}{m}t\right)}{1 - \frac{k_1 - \sqrt{k_1^2 + 4k_2NF}}{k_1 + \sqrt{k_1^2 + 4k_2NF}}\exp\left(\frac{-\sqrt{k_1^2 + 4k_2NF}}{m}t\right)}\right] \quad (5)$$

which describes the velocity of the object in the fluid as a function of time. From equation (5), a dimensionless parameter φ is defined as

$$\varphi = \sqrt{1 + \frac{4k_2NF^2}{k_1^2}} \quad (6)$$

In equation (5), the terminal velocity is given by

$$\alpha_{ter} = \frac{2NF}{k_1 + \sqrt{k_1^2 + 4k_2NF}} = \frac{2NF}{k_1(1+\varphi)}\ , \quad (7)$$