Determination of Fission Product Removal Rate in Containment Spray using Terminal Velocity and Reynolds Number

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1. Introduction

As part of the development of a Westinghouse type spray model for removing fission products in containment, a study of the terminal velocity and terminal Reynolds number is carried out using the classic Newtonian fluid model. In order to illustrate the spray removal model, the spray droplet is replaced with a water droplet. Furthermore, to obtain a better understanding of the spray removal model, the terminal velocity is simplified. The simplified terminal velocity is applied for determining the Reynolds number and fission product removal efficiency (aerosol capture efficiency). The obtained results are compared with the findings of other studies such as Slinn's work and NRC's constant model.

2. Methods and Results

Some equations are simplified to perform Monte Carlo calculations. If the motion equation is simplified, various parameters of the terminal velocity can be simply reduced to 3 parameters.

2.1 Study Frame

Step 1 : Simplifying Terminal Velocity.
Step 2 : Calculation of Terminal Velocity.
Step 3 : Determination of Reynolds number.
Step4 : Fission Products Removal Rate Calculation
Step5 : Comparison between this study and other work

2.2 Terminal Velocity

New development of terminal velocity is achieved by simplifying the classic Newtonian fluid mechanics formula. For a drag force governed by equation (1), the differential equation of the motion[1,2] is

$$m\frac{d\gamma}{dt} = F - k_1\gamma^1 - k_2\gamma^2 \quad , \qquad (1)$$

where

$$F = \begin{cases} F_b - mg, & mg < F_b \\ mg - F_b, & mg \geq F_b \end{cases}$$
$\gamma = \text{velocity}, \ m = \text{water drop's mass}$

Equation (1) may be written as

$$\frac{d\gamma}{k_1\gamma^1 + k_2\gamma^2 - F} = -\frac{1}{m}dt\,. \qquad (2)$$

Integration of this equation gives

$$\frac{1}{\sqrt{k_1^2 + 4k_2F}}\ln\left(\frac{2k_2\gamma + k_1 - \sqrt{k_1^2 + 4k_2F}}{2k_2\gamma + k_1 + \sqrt{k_1^2 + 4k_2F}}\right) = -\frac{t}{m} + C_1 \qquad (3),$$

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

$$\frac{2k_2\gamma + k_1 - \sqrt{k_1^2 + 4k_2F}}{2k_2\gamma + k_1 + \sqrt{k_1^2 + 4k_2F}} = C_1' \exp\left(\frac{-\sqrt{k_1^2 + 4k_2F}}{m}t\right) \qquad (4),$$

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 γ, the result is

$$\gamma = \frac{2F}{k_1 + \sqrt{k_1^2 + 4k_2F}} \times \left[\frac{1 - \exp\left(\frac{-\sqrt{k_1^2 + 4k_2F}}{m}t\right)}{1 - \frac{k_1 - \sqrt{k_1^2 + 4k_2F}}{k_1 + \sqrt{k_1^2 + 4k_2F}}\exp\left(\frac{-\sqrt{k_1^2 + 4k_2F}}{m}t\right)}\right] \qquad (5)$$

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

$$\varphi = \sqrt{1 + \frac{4k_2F^2}{k_1^2}} \qquad (6)$$

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

$$\gamma_{ter} = \frac{2F}{k_1 + \sqrt{k_1^2 + 4k_2F}} = \frac{2F}{k_1(1+\varphi)}\,, \qquad (7)$$

where
k_1 : 0.2 ~ 1.8 (random number)
φ : 1~200 (random number)
F : 1~6 (random number : log-normal distribution)

2.3 Reynolds Number

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

$$ReT = \frac{\gamma_{ter} \times \rho_g \times E}{\mu_g} \qquad (8)$$

where
ReT: Terminal Reynolds number

γ_{ter} : Terminal Velocity of water droplet (spray drop)
E : Eccentricity (random exponential distribution)
μ_g : Viscosity of a spray drop

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.
In order to calculate the fission product removal efficiency, ReT is simulated using the Monte Carlo method. Here, random parameters are the terminal velocity and eccentricity.
Terminal velocity is simulated by equation (7) and the results are shown in Fig. 1.
Eccentricity is used to estimate the shape of the water droplet (the water droplet is assumed to be an ellipsoid). This value is a random number ranging from 1 to 1.8, which is characterized by an exponential random distribution (Fig. 2).

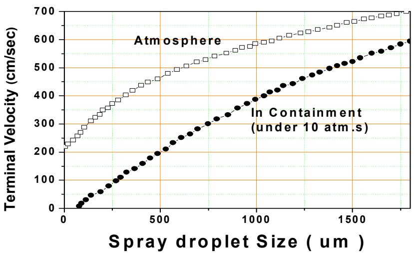

Fig. 1. Terminal velocity using MC calculation.

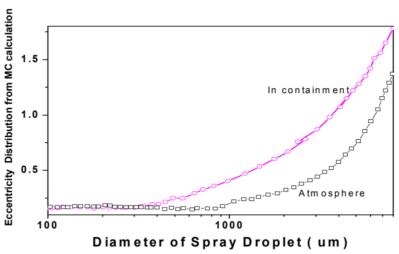

Fig. 2. Distribution of eccentricity using MC calculation.

2.4 Fission Product Removal Efficiency

The fission product capture process is expressed using Brownian diffusion, interception, and inertia impaction. In this study, the inertia impaction term is excluded due to its very small contribution to the aerosol capture process (fission product removal process). Considering Brownian diffusion and interception, Slinn's equation[4] can be used to represent the behavior of the removal process. The equation is represented by equation (9).

$$\text{Capture eff} = \frac{4}{\text{ReT}}\left[1 + 0.4\text{ReT}^{1/2}\,\gamma_{ter}{}^{2/3} + 0.16\text{ReT}^{1/2}\,\gamma_{ter}{}^{1/2}\right] + 4E\left[1 + 2\text{ReT}^{1/2}E\right] \quad (9)$$

Here, equation (9) shows the aerosol capture efficiency (fission products removal efficiency) and can be calculated using the results from equation (7) and equation (8). Fig. 3 shows the fission product removal efficiency using the simulation of equation (9).

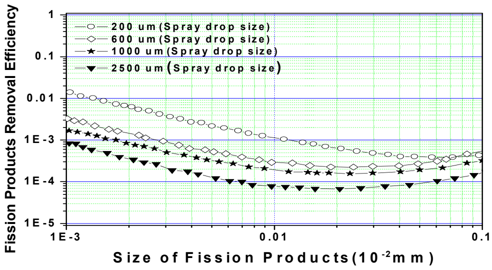

Fig. 3. Fission product removal efficiency (aerosol capture efficiency) using the terminal velocity and Reynolds number.

2.5 Comparison

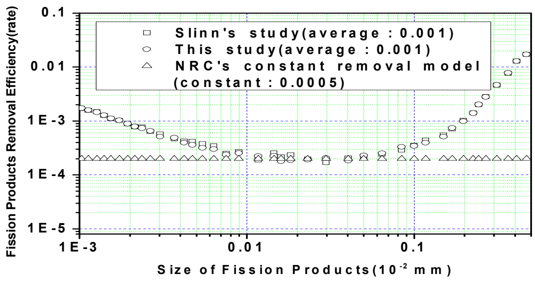

Fig. 4. Comparison of Slinn's work and NRC's constant conservative model (Slinn's study[geometric std : 1.637] with the present study [geometric std:1.690])

Fig.4 presents a comparison of the results of this study with Slinn's study under the same conditions. The difference between graphic lines is due to the exclusion of the inertia impact component in this study. The difference between this study and Slinn's study is within 5% in comparison with the geometric standard. Also, the results of Fig.4 show that the results are very useful to obtain more than a two-fold greater safety margin relative to the safety margin of NRC's constant removal model.

3. Conclusions

The fission product removal model of Westinghouse type spray is calculated using the terminal velocity and terminal Reynolds number. The terminal velocity is simplified, and the aerosol capture efficiency is comprehensively calculated through Monte Carlo calculations. The difference between this study and Slinn's work is within 5%. In comparison with NRC's constant model, the obtained result provides more than a twofold greater safety margin.

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