Containment Spray Modeling using the Flow Regime of Viscous Flow and Transition Flow

Seung Chan Lee*, Je Joong Sung and Sang Yeol Kim
Korea Hydro Nuclear Power Electricity Co., KHNP Central Research Institute, Reactor Safety Laboratory, Yuseong-daero 1312-gil, Yuseong, Daejeon 305-343 Korea.
**Corresponding author: babel2lsc@khnp.co.kr*

1. Introduction

A spray model for removing fission products in the containment is developed using the Stokes Regime and the Reynolds numbers. A similar study was carried out by Lee et al. of the KHNP Central Research Institute in 2011 [1]. This study seeks to develop Lee's study by reducing the overall form. Additionally, a combination of Stokes and Reynolds numbers is used to improve the aerosol capture efficiency of the spray droplets. These results are compared with those of other studies.

2. Methodology

Given the introductions above, some fundamental forms are introduced to describe the nature of a spray droplet.

2.1 Phenomena of Spray droplet

Consider a sphere with a diameter $D_d(e)$ falling through space. After falling distance H, the droplet sphere will sweep out a volume of gas, which is given as the equation below.

$$\text{Volume} = \frac{\pi}{4} D_d(e)^2 H \quad (1)$$

If the gas contains a concentration of n(i) particles of diameter d_p(i), then, in the absence of hydrodynamic phenomena, the falling sphere would sweep out

$\frac{\pi}{4} D_d(e)^2 H$ of particles.

These experimental definitions were introduced by Pemberton[2].

Basic definition of the particle capture efficiency is the ratio of the actual number of particles of size $d_p(i)$ captured to the number of those captured in the impact and touch condition, as follows:

$$\epsilon\left(D_d(e), d_p(i)\right) = \frac{4\Delta N(i)}{\pi D_d(e) n(i)} H \quad (2)$$

Here
$\Delta N(i)$=the actual number of particles of diameter $d_p(i)$ at a fall distance of H. Therefore, equation (2) shows the capture efficiency of a droplet of diameter $D_d(e)$.
The aerosols capture efficiency depends on the nature of the flow around the droplet. Experimental results are, however, available for the combination of the limit of the viscous flow (Re→0) and of the potential flow (Re→∞).

2.2 Velocity in motion equation

Simplifying the classic Newtonian fluid mechanics formula, the drag force and the differential form of the motion equations are written as follows [1]:

$$m\frac{d\gamma}{dt} = F - k_1\gamma^1 - k_2\gamma^2 \ , \quad (3)$$

where

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

Equation (3) may be written as

$$\frac{d\gamma}{k_1\gamma^1 + k_2\gamma^2 - F} = -\frac{1}{m}dt \ . \quad (4)$$

According to Lee et al. [1], the integration of this equation gives

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

where γ is the velocity of a falling object.
In this work, to create a reduced form of equation (5), dimensionless parameters are selected from the first term and the second term. In the first term of equation (5), the dimensionless parameter φ is defined as

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

In equation (5), the terminal velocity of the first term is given by the following equation:

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

Applying the dimensionless parameter to the second term, the characteristic time τ is defined by

$$\tau = \frac{m}{\sqrt{k_1^2 + 4k_2F}} = \frac{m}{k_1\varphi} \quad (8)$$

where
k_1 : 0.2 ~ 1.8 (random number) (9)
φ : 1~200 (random number)
F : 1~6 (random number : log-normal distribution)(10)
M : 0.1 ~ 1.2(log-normal distribution) (11)

Applying the random numbers of (9), (10), and (11) into equations (7) and (8), the final random numbers are as follows:

γ_{ter} : 1~ 7.2 : (random number: log-normal distribution)
τ : 0.02 ~ 1.0(random number: log-normal distribution)

Therefore, the random parameters of the velocity can be reduced from four parameters to two parameters.
Finally, a very simple form of the droplet motion can be achieves as follows:

$$\gamma = \gamma_{ter}\left[\frac{1-\exp\left(\frac{-t}{\tau}\right)}{1+\frac{\varphi-1}{\varphi+1}\exp\left(\frac{-t}{\tau}\right)}\right] \quad (12)$$

2.3 Flow Regime

The flow regime around a falling object is expressed using a viscous and potential regime [3,4]. A combination of these terms is known as a transition flow regime. The format is the weighted form of a viscous and a potential term. The Reynolds numbers are as shown below,

$$Re = \frac{\gamma \times \rho_g \times E}{\mu_g} \quad (13)$$

$$Stk = \frac{{d_p}^2 \times \rho_g \times \gamma}{9 \times \mu_g \times D_d(e) \times E} \quad (14)$$

where
Re : Reynolds number
Stk : Stokes number
γ : Velocity of a water droplet (spray drop)
E : Eccentricity (random exponential distribution)
μ_g : Viscosity of a spray drop
d_p : Diameter of aerosol particles (fission product)
$D_d(e)$: Diameter of spray droplets

Here, the transition flow regime is introduced using Eqs. (13) and (14). The weighted factor can be referenced from the experimental results of Slinn's work. Hence, equation (15) is calculated by Eqs. (16) and (17)[3,4].

$$\text{Transition flow regime} = \frac{(Vft + Re \bullet Pft/59)}{(1+Re/59)} \quad (15)$$

where

$$\text{Potential term:} Pft = 6.43\left[\frac{Stk}{Stk+\delta}\right]^2 (Stk - 0.06) \quad (16)$$

$$\text{Viscous term : } Vft = \left[1 + \frac{0.8\ln(3Stk)}{(Stk-1.3)}\right]^{-2} \quad (17)$$

3. Results and Conclusions

Fig. 1 shows that the velocity of a falling object is calculated while considering the terminal velocity and characteristic time. Fig. 2 is the result of a droplet size distribution created by means of random generation. Equation (15) is used to calculate the fission product removal efficiency. Fig. 3 and Fig. 4 show the removal efficiency of fission products and the comparison with the results of other research, respectively. In conclusion, the development of the spray model was carried out using the flow regime and by reducing random parameters. The fission product removal rate is in good agreement with other experimental results (Fig. 4). The difference compared to other works is within 2%. In addition, this model provides a safety margin of more than 30 % against the NRC's model.

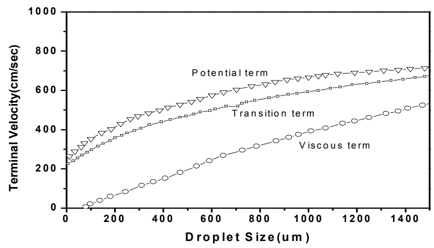

Fig. 1. Velocity of falling objects using the terminal velocity

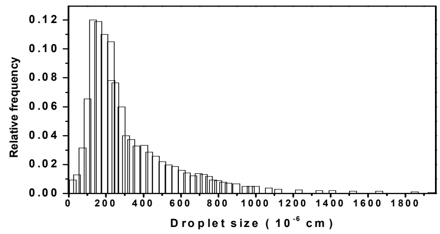

Fig. 2. Distribution of a spray droplet by a random generation

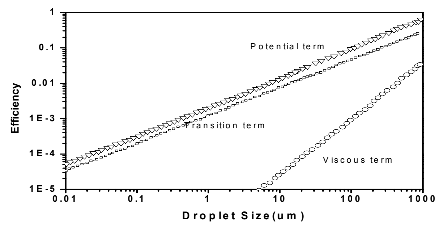

Fig. 3. Fission product removal efficiency by the weighted form of the viscous term and the potential term

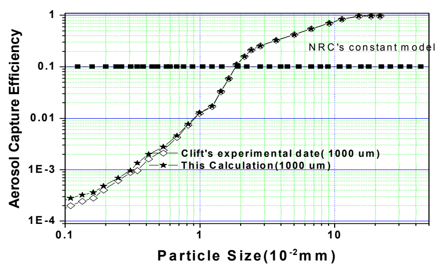

Fig. 4. Comparison with other works (Clift's study [geometric std : 1.690] , NRC(Nuclear Regulatory Commission) model[constant:0.1], this study [geometric std:1.677])

REFERENCES

[1] Seung Chan Lee and Sang Yeol Kim, "Determination of Fission Product Removal Rate in Containment Spray using Terminal Velocity and Reynolds Number", Korean Nuclear Society, Autumn Meeting, October 27-28, 2011.
[2] C.S. Pemberton, Journal of Air Pollution Vol 3, p.168, 1980.
[3] W.G. Slinn, "Precipitation scavenging" in U.S. Department of Energy, Washington D.C., 2000.
[4] R. Clift, J.R. Grace and M.E. Weber, "Bubbles Drops and Particles, Academic Press, New York, p.287, 1978.