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Improvement and Validation of an Aerosol Deposition Model in the GAMMA-FP, a Fission Product Analysis Module for VHTRs

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1. Introduction

As a part of the Nuclear Hydrogen Development and Demonstration (NHDD) program in Korea, the Korea Atomic Energy Research Institute (KAERI) has developed a computer software to analyze the behaviors of the fission products (FP) circulating in the primary coolant loop and in the containment for very high temperature gas-cooled reactors (VHTR's). This software, named GAMMA-FP (GAs Multicomponent Mixture Analysis-Fission Products module), consists of gaseous and aerosol fission product analysis modules. The aerosol FP module adopts a multi-component and multi-sectional aerosol analysis model that has been developed based on the MAEROS model [1].

For the first work of FP module development, the MAEROS model has been implemented and examined against some analytic solutions and experimental data by Yoo et al. [2] An aerosol transport model was developed and implemented in the GAMMA-FP code, and verified. [3] In this study, the aerosol deposition model in the GAMMA-FP code was improved by adopting recent achievements, and was validated against an experimental data available.

2. Improvement of the Deposition Model

In VHTR's, aerosol deposition into the surrounding walls is mainly caused by thermophoresis, eddy impaction, and gravitational settling. The equation sets of aerosol deposition mechanisms for the previously implemented MAEROS model [1] and for the more recent model from the VICTORIA code [4] are described in this section.

2.1 MAEROS Model

The deposition rates, S, in s^{-1} are multipliers to the aerosol concentration in kg/m^3 to produce the removal terms in the aerosol balance equations. Negative signs represent the removal of aerosols. A definition of the deposition velocity, U [m/s], is introduced with the surrounding wall area, A_{wall} [m^2], and the chamber volume, V_{chamber} [m^3], as in eq. (1). Therefore, the thermophoretic deposition velocity is expressed as,

$$S = -\frac{A_{wall}U}{V_{chamber}} \qquad (1)$$

$$\text{where} \quad U = \frac{3\eta Cn\left(c_t Kn + k_f / k_s\right)\nabla T}{2\chi\rho_g T\left(1+3c_m Kn\right)\left(1+2c_t Kn+2k_f / k_s\right)}$$

Here, Cn is Cunningham slip correction, Kn is the particle Knudsen number, and χ is the dynamic shape factor. c_s, c_t, and c_m are dimensionless constants. More details on these nomenclatures can be found in reference [1].

The gravitational settling(terminal) velocity, V_T [m/s], is expressed as below.

$$S = -\frac{A_{floor}V_T}{V_{chamber}} \quad \text{with} \quad V_T = \frac{2\rho_p(\text{grav.})r^2 Cn}{9\eta\chi} \qquad (2)$$

Here, ρ_p is the aerosol particle density in kg/m^3, r is the particle diameter in meters, and η is the carrier gas viscosity in kg/m/s.

The deposition by diffusion is expressed as follows.

$$S = -\frac{DA_{wall}}{V_{chamber}\Delta} \qquad (3)$$

Here, D is the particle diffusivity in m^2/s, and Δ is the diffusion boundary layer thickness in meters.

2.2 VICTORIA Model

Brock [5] proposed the most reliable formula for thermophoretic deposition velocity, as eq. (4).

$$U = \frac{-2c_s\left(k_f / k_s + c_t Kn\right)\dfrac{\mu Cn}{\rho}\dfrac{T_f - T_s}{T_f\delta_T}}{\left(1+3c_m Kn\right)\left(1+2c_t Kn+2k_f / k_s\right)} \qquad (4)$$

Here, δ_T is thermal boundary layer thickness in meters. The values of constants c_s, c_t, and c_m were also changed.

For turbulent deposition, two separate correlations are used: one for submicron particles (r < 10^{-6} m) and the other for supermicron particles (r > 10^{-6} m). The former correlation was derived by Sehmel [6].

$$U = 1.47\cdot 10^{-16}\left(\frac{\rho_a}{1000}\right)^{1.01}\left(\frac{2\cdot 10^4 r_a}{D_h}\right)\text{Re}^{3.02}\,\overline{v}, \quad \overline{v} = \text{friction velocity} \qquad (5)$$

In addition, the latter correlation was modeled from the theoretical model of Davies [7].

$$U = \frac{Sc^{-2/3}\overline{v}}{14.5\left\{\dfrac{1}{6}\ln\left[\dfrac{(1+\varphi)^2}{1-\varphi+\varphi^2}\right]+\dfrac{1}{\sqrt{3}}\text{atan}\left[\dfrac{2\varphi\text{-}1}{\sqrt{3}}\right]+\dfrac{\pi}{\sqrt{3}}\right\}} \qquad (6)$$

3. Validation against STORM SR-11 Test

The STORM SR-11 experiment is a separate effect test for aerosol deposition (Phase 1) and resuspension (Phase 2) in a circular pipe. Figure 1 shows a schematic view of the STORM experimental facility. In phase 1, the test section is a 5.0055 meter long straight pipe with a 63 mm internal diameter [8]. The aerosols used were of tin oxide (SnO_2), and the carrier gas was a mixture of nitrogen and steam, plus the argon, helium, and air. The total mass flow rate of the carrier gas was estimated to be $3.5975*10^{-2}$ kg/s.

For the GAMMA-FP simulation of the deposition test, the test section was modeled as a 10-cell fluid block connected to the IN and OUT boundary volumes. A steady-state GAMMA+ simulation was performed to produce a similar initial condition to the thermal-fluidic condition of the experiment.

The aerosol source rates in 20 aerosol size bins were computed with the parameters of 0.43 μm geometric mean diameter and 1.7 geometric standard deviation. The transient calculation for the 9,000 second Phase 1 test was performed on a PC with 3.47GHz Intel Xeon X5690 CPU. The total CPU time was 88h 47m 32s.

The mass of the aerosols deposited in the test pipe alone during the deposition phase was calculated to be 189.8 grams, while the measured value was 162 grams. The spatial distribution of deposition at 9,000 s is shown in Fig. 2. The GAMMA-FP calculation predicted the thermophoresis to be the dominant deposition mechanism, with 98% of the total deposition. (Fig. 3)

Compared to the previous results of the ISP (International Standard Problem)-40 Meeting [8], it was proven that the current simulation gives the most well matched results with the experimental data.

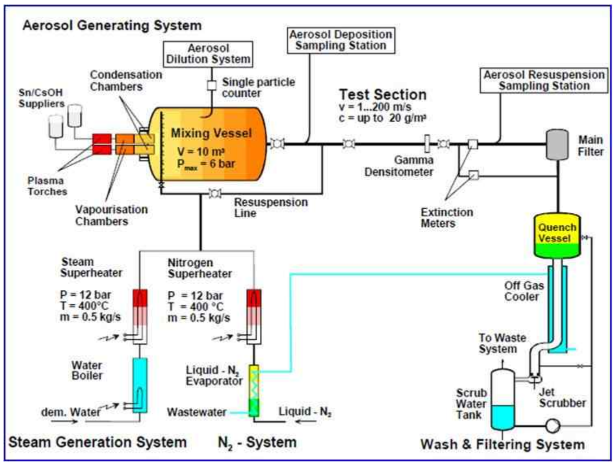

Fig. 1. The STORM experimental facility.

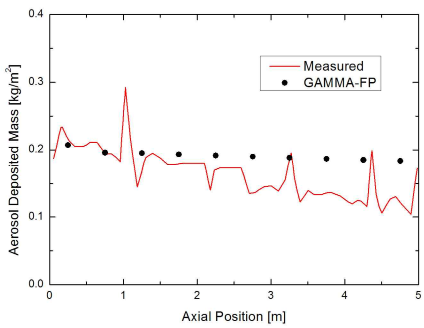

Fig. 2. Aerosol deposition along the test pipe.

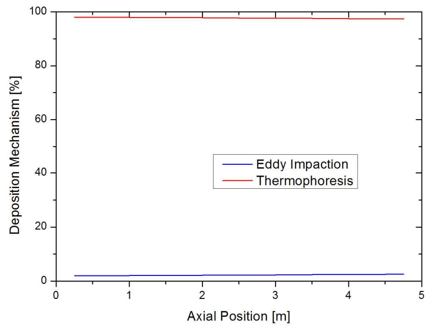

Fig. 3. Deposition mechanisms along the test pipe.

4. Conclusions

The aerosol deposition model in the GAMMA-FP code has been improved and successfully validated against the STORM SR-11 deposition test. The simulation with the improved deposition model predicted the matched results with the experimental data well. For future studies, the aerosol deposition model by flow irregularities will be implemented and validated against the TRANSAT bend effect test.

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