Verification of a Fission Product Analysis Module in the GAMMA+ Code

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1. Introduction

Very High Temperature Gas Cooled Reactor (VHTR) has been selected and researched as a high energy heat source for a nuclear hydrogen production. For thermal-fluid analysis of a VHTR, the GAMMA(GAs Multicomponent Mixture Analysis) code had been developed under I-NERI project during years of 2002-2005. The GAMMA+[1], an improved version of the GAMMA, is now under development and distinguished from its origin by integrated multidimensional feature, modular structures, capability of coupled calculation with a neutronic code, and inclusion of two-phase modules and FP(fission product)/Dust/Tritium modules.

The MAEROS[2] model is the multicomponent aerosol module of the CONTAIN code, and has been widely used for aerosol behavior analysis. For the first work of FP module development, the MAEROS model had been implemented as an independent module and examined against some analytic solutions and experimental data by Yoo et al.[3] In this study, the implemented MAEROS model was additionally verified by a conceptual problem and qualified for FP analysis of VHTR.

2. Methods and Results

2.1 Governing Equations

Fission products released from various plant conditions are mainly in a form of aerosol, which means suspensions of small solid or liquid particles in gases except some gaseous radionuclide. Aerosol dynamics for assessing health consequences account for two important parameters, particle size and chemical species. Particle size is the most important variable characterizing the respirability of an aerosol, and different substances(chemicals) do not have similar biological effects. Assuming that coagulation and condensation occurs in series and that any two mechanisms cannot occur simultaneously, eq. (1) is the governing equation for aerosol dynamics with sectional subscripts *l* and component identifier *k*. [4]

$$\frac{dQ_{l,k}}{dt} = \frac{1}{2}\sum_{i=1}^{l-1}\sum_{j=1}^{l-1}\left[{}^{1a}\bar{\beta}_{i,j,l}Q_{j,k}Q_i + {}^{1b}\bar{\beta}_{i,j,l}Q_{i,k}Q_j\right] - \sum_{i=1}^{l-1}\left[{}^{2a}\bar{\beta}_{i,l}Q_iQ_{l,k} - {}^{2b}\bar{\beta}_{i,l}Q_iQ_{l,k}\right]$$
$$-\frac{1}{2}{}^{3}\bar{\beta}_{l,l}Q_lQ_{l,k} - Q_{l,k}\sum_{i=l+1}^{m}{}^{4}\bar{\beta}_{i,l}Q_i + \bar{F}_{l,k}Q_l + {}^{1}\bar{G}_{l,k}Q_l$$
$$-\sum_{i=1}^{s}\left[{}^{2}\bar{G}_{l,i}Q_{l,k} - {}^{2}\bar{G}_{l-1,i}Q_{l-1,k}\right] + {}^{3}\bar{G}_{l-1,k}Q_{l-1} + \bar{S}_{l,k} - \bar{R}_{l,k} \qquad (1)$$

Here, $Q_{l,k}(t)$ is the total mass of aerosol component *k* per unit volume of fluid in section *l* at time t, $\bar{\beta}$'s are sectional coagulation coefficients, $\bar{F}$ is sectional coefficient for intra-particle chemical reaction, $\bar{G}$'s are sectional growth coefficients due to gas-to-particle conversion, $\bar{S}$ is a source and $\bar{R}$ is a removal rate. Therefore, the first and second terms represent the mass flux of component *k* into section *l* from the lower sections. The third and fourth terms are removing and remaining flux of component *k* due to collision of particles in section *l* and section *l*-1, respectively. The fifth term is removing flux of intrasectional coagulation and the sixth term is removing flux due to coagulation of particles in section *l* and a higher section. The eighth and ninth are mass formation and removing rate due to condensation and dissolution. The tenth and eleventh are mass fluxes from lower section by condensation and dissolution.

2.2 Solving Mechanism

After defining a problem by setting variables and sectional boundaries, initializing and checking the input parameters are performed in MAEROS algorithm. The coagulation coefficients are calculated by summing three coefficients for each mechanism of Brownian motion, turbulence and gravitation. The deposition coefficients are considered for aerosol removal by three mechanisms such as gravitational settling, diffusive wall deposition and thermophoretic wall deposition. Condensation of a vapor on to a particle results in particle growth. The growth coefficients are calculated from an isothermal condensation correlation. For sectional coefficients, the obtained coagulation, deposition, and growth coefficients are integrated over sections by the two-point Gauss-Legendre quadrature formula. By this point, every terms of eq. (1) are composed to form an ordinary differential equation, which will be now solved by the fourth-fifth order Runge-Kutta-Fehlberg Method. Before print the output, the value of $Q_{l,k}(t)$ is linearly interpolated in temperature and pressure.

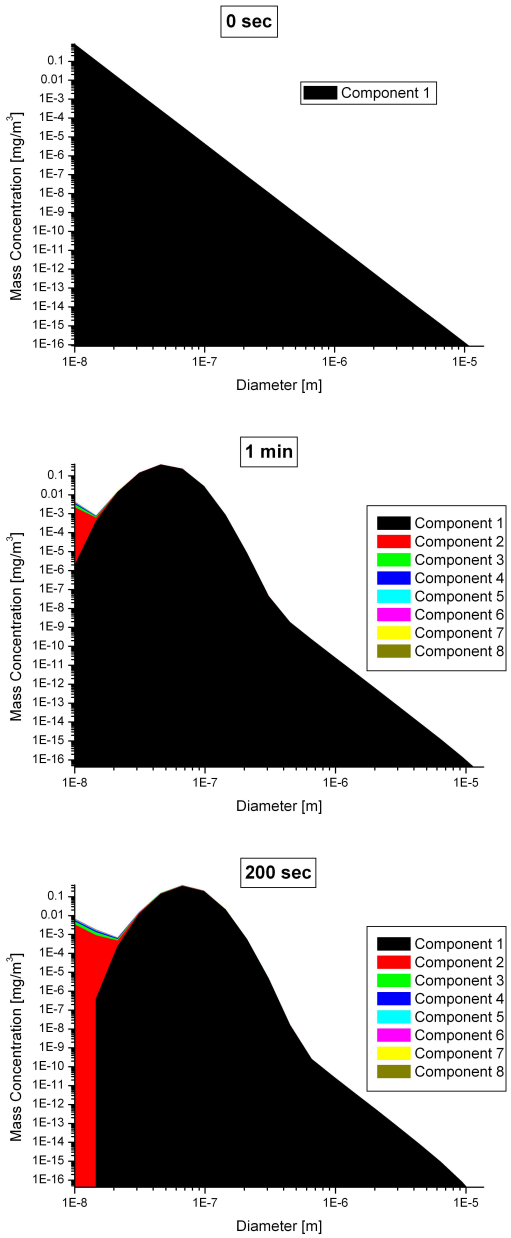

Fig. 1. Aerosol mass concentrations of 8 components over particle sizes at selected times.

2.3 Conceptual Problem

A conceptual problem was chosen from the MAEROS manual[2], and the results by GAMMA+ was compared with the original MAEROS results for verifying the implementation. In this problem, there are 20 sections logarithmically spaced in particle diameter from 0.01 to 20 microns. The initial aerosol is composed entirely of component 1, for which the aerosolized mass concentrations in section I are expressed as follows:

$$Q(\text{section } I) = 1.0\times10^{-6}\exp\left(-\frac{8(\mathrm{I}-1)+1}{4}\right) \quad [kg/m^3]$$

The other 7 components are not contained in the initial aerosol. Components 2 through 7 are generated in section 1 at a rate of $1.0\text{x}10^{-9}/I^2$ kg/m^3, where I is the component number. This choice of initial mass concentration and source generation rate is arbitrary.

2.4 Results

Figure 1 shows the aerosol mass concentrations after 1, 60, and 200 seconds of the simulation. Because there is no source of component 1, the total suspended and deposited mass of component 1 is equal to the initial suspended mass of component 1 during the transient. Due to condensational growth and scavenging by coagulation, all the mass of component 1 has been removed from section 1 after 200 seconds. Finally note that the total suspended and deposited masses of components 2 to 7 are equal to the generation rate of that component multiplied by time and the chamber volume. These results and observations are exactly matched with the test with the MAEROS code, and reasonably explained. Therefore it is concluded that the implementation of MAEROS module into the GAMMA+ code was successful.

3. Conclusions

The implemented aerosol module of the GAMMA+ code was additionally verified by a conceptual problem in this study. The results of the implemented aerosol module and the original MAEROS code are well matched together. Thus, it is concluded that the new 1-dimensional multicomponent aerosol module is qualified for FP analysis of VHTR.

Acknowledgement

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST). (Grant code: 2009-006258)

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