An Evaluation of a Hygroscopic Model in the SIRIUS Code

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) developed a computational code, Simulation of Radioactive nuclides Interaction Under Severe accidents (SIRIUS), for predicting a radioactive material behavior in the reactor coolant system (RCS) in a nuclear power plant during a severe accident [1,2]. The SIRIUS code has a hygroscopic model to simulate the growth of the hygroscopic aerosols such as cesium hydroxide (CsOH), cesium iodide (CsI), and sodium hydroxide (NaOH) in a humid condition during the severe accidents. The growth of hygroscopic aerosols significantly can increase the settling rate resulted from the gravitational force when the relative humidity (RH) condition is higher than 90% [3]. To evaluate the hygroscopic model in SIRIUS, a numerical analysis was performed using the test conducted in the aerosol and heat transfer measurement device (AHMED) facility [4,5].

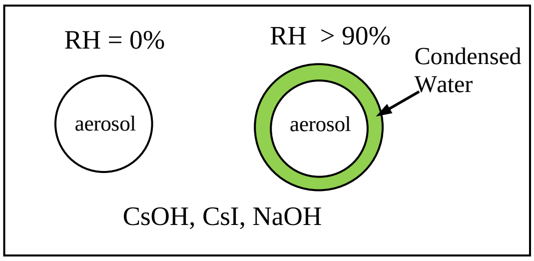

Fig. 1. Growth of hygroscopic aerosols in a humid condition

2. Hygroscopic Models in the SIRIUS Code

An equilibrium radius (R_{eq}) of the hygroscopic aerosol in the humid condition is calculated through solving a fourth-order equation (Eqs. (1) and (2)) which assumes that the saturation ratio at the aerosol surface (Eq. (3)) may be equal to the atmospheric RH during the condensation process from the water vapor to the aerosol [1,3,6]. The water mass on aerosol (M_{aw}) is calculated by Eq. (4) where V_{wet} is the volume of the hygroscopic aerosol and ρ_w is the water density.

$$(\emptyset - 1)r^4 - \frac{2\sigma}{\rho_w R_w T R_0} r^3 + \left(1 - \emptyset + \frac{M_w \rho_a}{M_a \rho_w}\right) + \frac{2\sigma}{\rho_w R_w T R_0} = 0 \quad (1)$$

$$r = \frac{R_{eq}}{R_0} \quad (2)$$

$$\emptyset = \frac{P_{st}}{P_{sat}} \quad (3)$$

$$M_{aw} = (V_{wet}\,\rho_W)(r^3 - 1) \quad (4)$$

where,

M_w : Molecular weight of water
M_a : Molecular weight of aerosol
P_{st} : Water vapor pressure at the aerosol surface
P_{sat} : Saturated water vapor pressure at the particle surface temperature
R_o : Minimum radius of aerosol

The hygroscopic aerosol with the condensed water on its surface can affect the gravitational settling (λ_{sed}) and the inertia deposition (λ_{imp}) of the aerosol removal rate (Eqs. (5) and (6)) during the aerosol transport phenomenon [1,7]. In Eq. (5), i means the aerosol phases of the *i*-group.

$$\frac{dm_{a,i}^n}{dt} = \dot{m}_{a,i,in}^n - \dot{m}_{a,i,out}^n - \lambda_{t,i}^n m_{a,i}^n + \dot{G}_{a,i}^n \quad (5)$$

$$\lambda_t = \lambda_{sed} + \lambda_{imp} + \lambda_{diff} + \lambda_{th} + \lambda_{tub} \quad (6)$$

3. SIRIUS Analysis for the Hygroscopic Aerosol

3.1 AHMED Test [4,5]

A hygroscopic aerosol test using the NaOH aerosol was conducted at the AHMED facility (Fig. 2) by VTT (Technical Research Center of Finland). The AHMED facility consisted of a cylindrical vessel (volume 1.81 m^3, radius 0.635 m, sedimentation area 1.27 m^2), measuring devices, and wall heating system. The NaOH aerosol with the particle size of 2.4 μm was injected into the vessel for setting the initial mass concentration at the constant relative humidity as shown in Table 1. The pressure in the vessel was maintained as 1.013×10^5 Pa during the test period. Mass and number concentrations of the aerosol in the vessel were measured at different heights in the vessel.

Fig. 2. AHMED test facility [5]

Table 1: AHMED test condition [5]

	Relative Humidity (%)	Temperature (K)	Initial Mass Concentration (mg/m^3)
RH22	22	323.15	112
RH82	82	300.15	208
RH96	96	296.15	218

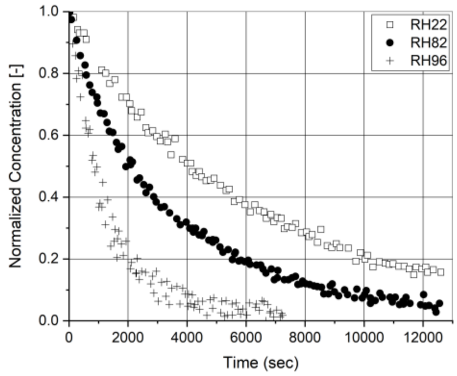

Fig.3. Normalized airborne NaOH concentrations [5]

The measured data of the normalized airborne NaOH concentration (Fig. 2) shows that the aerosol concentration at higher RH conditions decreases faster than those at lower RH conditions. This means that the NaOH at higher RH conditions increased its size through a strong coagulation due to the hygroscopic process and quickly settled downward in the vessel.

3.2 SIRIUS Calculation

The SIRIUS calculation was performed to predict the gravitational settling of the NaOH aerosol at various RH conditions in the AHMED test. A nodalization for the SIRIUS calculation was constructed with a single cell with specifying the volume and sedimentation area of the test vessel. The initial mass concentration of the NaOH aerosol, as shown in Table 1, was achieved using the aerosol source model in the SIRIUS code [1]. The thermal hydraulic conditions of pressure, temperature, relative humidity according to RH22, RH82, and RH96 in the test were given to the single cell using the input data of the SIRIUS code. The aerosol removal model applied for this SIRIUS calculation was only the gravitational settling (λ_{sed}) rate using the increased aerosol mass through the hygroscopic growth process. The SIRIUS calculation was performed as a transient case for 13,000 s with a time step size of 1 s.

The SIRIUS results (Fig. 4) show that the calculated normalized aerosol concentrations according to the different RH conditions accurately predict the phenomenon, a faster concentration decrease at higher humid condition, in the test results. However, the SIRIUS results simulated much faster decrease of the aerosol concentration than the test results for all cases. This may mean that the hygroscopic growth of the NaOH aerosol predicted by SIRIUS was greatly increased in a short time when compared to the results. This result may be explained by the fact that the SIRIUS code considers the aerosol removal process based on the aerosol mass, whereas the hygroscopic aerosol growth generally dependent on the aerosol size [4]. Therefore, it is necessary to implement the model of the aerosol size distribution into the SIRIUS code for accurate simulating the hygroscopic aerosol behavior.

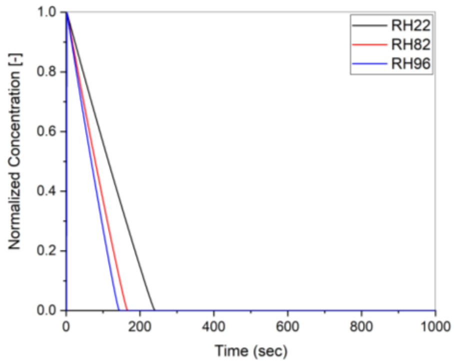

Fig. 4. SIRIUS results for the AHMED test

4. Conclusions and Further Work

A numerical analysis for evaluating a hygroscopic aerosol model in the SIRIUS code was performed using the AHMED test results. The SIRIUS results accurately predicted the faster decrease of the aerosol airborne concentration as the relative humidity increases in the test. However, the SIRIUS results did not simulate the time used for hygroscopic aerosol settling when compared to the test data. To improve this difference, the aerosol size distribution model should be implement to the SIRIUS code because the hygroscopic aerosol growth is generally dependent of the aerosol size.

ACKNOWLEDGMENTS

This work was financially supported by the Nuclear and Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (Ministry of Trade, Industry and Energy) (No. 20181510102400).

REFERENCES

[1] K. S. Ha, S. I. Kim, H. S. Kang, and D. H. Kim, "SIRIUS : A Code on Fission Product Behavior under Severe Accident," *Proc. of KNS Spring Meeting*, Jeju, Korea, May 18-19 (2017).

[2] H. S. Kang, B. W. Rhee, and D. H. Kim, "Development of a Fission Product Transport Module Predicting the Behavior of Radiological Materials during Severe Accidents in a Nuclear Power Plant," *J. of Radiation Protection and Research*, 41, No 3, pp.237-244 (2016).

[3] Jorma Jokiniemi, "The Growth of Hygroscopic Particles During Severe Core Melt Accidents," *Nuclear Tech.*, Vol. 83, pp.16-23 (1988).

[4] Jouni Makyuen and Jorma Jokiniemi, AHMED Code Comparison Exercise, Technical Report, NEA/CSNI/R(95)23, OECD/NEA (1995).

[5] L. L. Humphries, et al., MELCOR Computer Code Manuals Vol, 3: MELCOR Assessment Problems, Technical Report, SAND2015-6693 R, U.S.NRC (2015).

[6] R. D. Astleford, et al., MAAP5 User Manual Vol. 2, Fauske & Associates (2008).

[7] M. Epstein and P. G. Ellison, "Correlations of the rate of removal of coagulating and depositing aerosols for application to nuclear reactor safety problems," *NED*, 107, pp. 327-344 (1988).