Numerical Analysis for an Aerosol Transport Phenomenon in the Marviken Test Facility Using SIRIUS Code

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1. Introduction

KAERI (Korea Atomic Energy Research Institute) has developed a computational code SIRIUS (Simulation of Radioactive nuclides Interaction Under Severe accidents) for predicting a radioactive material behavior in the RCS (Reactor Coolant System) in a nuclear power plant during severe accidents [1]. The SIRIUS consists of an estimation of the initial inventories, species release from the core, aerosol generation, gas transport, and aerosol transport. A thermal-hydraulic data needed in the SIRIUS calculation is provided by the CSPACE (COMPASS-SPACE) code. The CSPACE is being developed by KAERI for simulating the severe accident phenomena of the pressurized water reactor through combining the COMPASS (COre Meltdown Progression Accident Simulation Software) and the SPACE (Safety and Performance Analysis CodE for nuclear power plants) codes [2]. Aerosol removal models in the SIRIUS code was validated using test results performed in a single component such as ABCOVE-5, 6, and 7 [3]. As the next step, it is necessary to validate the fission product transport models when they are moving through the closed loop like in the RCS.

2. Aerosol Removal Models in the SIRIUS Code

The gases and aerosols of fission products are transported through the reactor coolant systems and containments as loaded into the carrier gas or liquid such as steam or water. If the RCS and containment are simulated as nodes and linked by a general thermal-hydraulic code, the fission product transport equations for the gas and aerosol phases of the *i*-group can be designated by Eqs (1) and (2) at the given thermal-hydraulic node *n* [1]. In the Eq. (2), an aerosol removal rate ($\lambda_{t,i}^{n}$) consists of gravitational settling (λ_{sed}), inertia deposition (λ_{imp}), diffusiophoresis (λ_{diff}), and thermophoresis (λ_{th}).

$$\frac{dm_{v,i}^{n}}{dt} = \dot{m}_{v,i,in}^{n} - \dot{m}_{v,i,out}^{n} + \dot{G}_{v,i}^{n} \qquad (1)$$

$$\frac{dm_{a,i}^{n}}{dt} = \dot{m}_{a,i,in}^{n} - \dot{m}_{a,i,out}^{n} - \lambda_{t,i}^{n} m_{a,i}^{n} + \dot{G}_{a,i}^{n} \qquad (2)$$

2.1 Gravitational Settling Model

The gravitational settling, sedimentation, simulates the aerosol falling down to the bottom wall due to gravity according to its mass increase through a coalescence process in the relatively high aerosol concentration region. We use the dimensionless aerosol removal rate constant (Eqs. (3) and (4)) for the gravitational settling as a function of dimensionless suspended mass concentration on the basis of test data and numerical analysis results [4]. The removal rate constant for the sedimentation (λ_{sed}) can be obtained by substituting M_{sed} (Eq. (5)) and Λ_{sed} (Eq. (6)) into Eqs. (3) and (4). The steady state condition (SS) means that the loss rate of aerosol mass by the sedimentation is balanced by the supply rate of aerosol source. The decay (D) means the absence of aerosol source.

$$\Lambda_{sed}^{D} = 0.528 M_{sed}^{0.235} \left(1 + 0.473 M_{sed}^{0.754}\right)^{0.786} \qquad (3)$$

$$\Lambda_{sed}^{SS} = 0.266 M_{sed}^{0.282} \left(1 + 0.189 M_{sed}^{0.8}\right)^{0.695} \qquad (4)$$

$$M_{sed} = \left(\frac{\gamma^{9} g h_{eff}^{4} \varepsilon_{o}^{5}}{\alpha^{3} K_{o} \mu \rho^{3}}\right)^{1/4} \cdot m_{p} \qquad (5)$$

$$\Lambda_{sed} = \left(\frac{\gamma \varepsilon_{o} \chi^{2} \mu h_{eff}^{2}}{\alpha K_{o} g \rho}\right)^{1/2} \cdot \lambda_{sed} \qquad (6)$$

2.2 Inertia Impaction Model

Aerosol particles in the steam and hydrogen stream in the RCS loop can be removed when the aerosol collide with the bent wall due to their inertia. For modelling the inertia removal phenomenon, we also use the dimensionless aerosol removal rate constant as function of dimensionless suspended mass concentration following Epstein and Ellison such as Eqs. (7) and (8) [4]. The removal rate constant for the inertia impaction (λ_{imp}) can be obtained by substituting M_{IMP} (Eq. (9)) and Λ_{IMP} (Eq. (10)) into Eqs. (7) and (8).

$$\Lambda_{IMP}^{SS} = 0.126 M_{IMP}^{0.26} \left(1 + 2.92 M_{IMP}^{1.28}\right)^{0137} \qquad (7)$$

$$\Lambda_{IMP}^{D} = 0.337 M_{IMP}^{0.21} \left(1 + 1.74 M_{IMP}^{0.19}\right)^{0.14} \qquad (8)$$

$$M_{IMP} = \left(\frac{\gamma K_{o} h_{eff}}{\chi K_{o} u_{g}}\right)\left(\frac{\chi \mu D}{\alpha^{1/3} \rho u_{g}}\right)^{2/3} \left(\frac{\gamma g \rho \varepsilon_{o}}{\alpha^{1/3} \mu K_{o}}\right)^{13/12} \cdot m_{p} \qquad (9)$$

$$\Lambda_{IMP} = \frac{h_{eff}}{u_g}\left(\frac{\chi\mu D}{\rho u_g}\right)^{2/3}\left(\frac{\gamma g \rho \varepsilon_o}{\alpha\mu K_o}\right)^{1/3} \cdot \lambda_{imp} \qquad (10).$$

2.3 Diffusiophoresis Model

The diffusiophoresis simulates the aerosol diffusion due to the aerosol concentration gradients in a nonuniform gas mixture. This concentration gradient usually occurs around the wall surface because the (u_{diff}) due to the diffusiophoresis may be expressed as Eq. (11) where D_{12} (Eq. (12)) is a diffusion coefficient of the vapor in the noncondensible gas [1]. The removal rate constant for the diffusiophoresis (Eq. (13)) can be obtained by dividing diffusiophoresis velocity (u_{dif}) by effective height (h_{eff}).

$$u_{dif} = \frac{F\,D_{12}}{\delta}\ln\left[\frac{P_\infty - P_{s,w}}{P_\infty - P_s}\right] \qquad (11)$$

$$D_{12} = \frac{1.858\cdot 10^{-3}T^{3/2}\sqrt{1/M_1 + 1/M_2}}{P_\infty\,\Omega\,(\sigma_1+\sigma_2)/2} \qquad (12)$$

$$\lambda_{diff} = \frac{u_{diff}}{h_{eff}} \qquad (13)$$

2.4 Thermophoresis Model

The thermophoresis accounts for the movement of the aerosol particles suspended in the gas flow toward a cooler temperature region resulted from local differences in internal energy of the gas. We use the velocity due to the thermophoresis (Eq. (14)) proposed by Epstein [4]. The removal rate constant (Eq. (15)) for the thermophoresis can be obtained by dividing thermophoresis velocity (u_{th}) by effective height (h_{eff}). The effective height is defined as the ratio of volume to surface area of the control volume.

$$u_{th} = \frac{\mu\kappa}{\chi\rho_g L}\left[\frac{T_\infty}{T_w} - 1\right]\left[\frac{1-(\kappa\,\mathrm{Pr})^{1.25}\left(T_w/T_\infty\right)}{1-(\kappa\,\mathrm{Pr})^{1.25}}\right]\mathrm{Nu} \qquad (14)$$

$$\lambda_{th} = \frac{u_{th}}{h_{eff}} \qquad (15)$$

3. Numerical Analysis for Aerosol Transport Phenomenon in the Marviken Test Facility

The aerosol removal models in the SIRIUS code was analyzed against the Marviken test (Test-2b) performed at Marviken Power Station. The Marviken test facility consists of a reactor vessel, a pressurizer, vertical and horizontal pipes, a condenser, and a relief tank.

3.1 Marviken Test Condition and Results [5]

The Marviken test (Test-2b) was conducted by injecting the aerosol sources of CsI, CsOH, and Te into the pressurizer. The injected aerosols were transported with the steam from the pressurizer to the relief tank. The mass of the aerosol deposited on the walls of the pressurizer and pipes were measured in the test. The test conditions are summarized in Table 1. The test results showed that approximately 40% of the injected aerosol mass is deposited on the pressurizer bottom region. The discharged mass to the relief tank is approximately 50% of the injected aerosol mass.

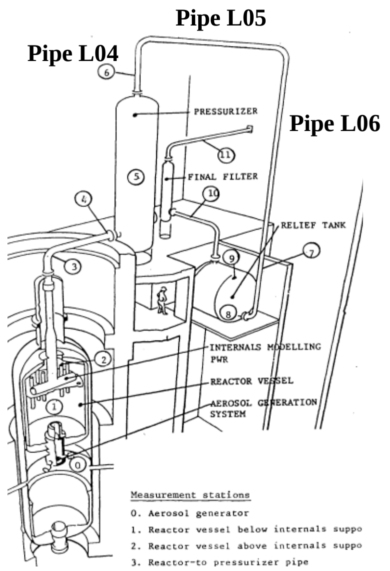

Fig. 1. Schematic diagram of the Marviken test facility

Table 1: Test Condition

	Injection Time (s)	Flow Condition
Steam	0 - 7080	400 ℃, 40 g/s
CsOH	0 - 7080	70.1 g/s
CsI	60 - 7080	11.8 g/s
Te	240 - 7080	11.0 g/s

3.2 CSPACE Calculation

A heat transfer phenomenon between the steam and walls from the pressurizer to the pipe L06 in the Marviken test facility was simulated by the CSPACE as a transient case. A nodalization for the CPACE analysis was constructed with a total of 30 cells. In the nodalization, 5 cells are used for the pressurizer, 4 cells for the pipe L04, 10 cells for the pipe L05, and 9 cells for the pipe L06. The elbow with 1 cell was located between the horizontal pipe and the vertical pipes. The measured wall temperatures were given as boundary conditions for the CPACE calculation. The predicted temperature, pressure, and velocity by the CSPACE are shown in Fig. 2. The CSPACE accurately predicted the measured steam temperature at the top region in the pressurizer and at the pipes with an error range of approximately 10%. The predicted steam velocities at the pressurizer and the pipes are 0.026 m/s and 1.2 m/s – 1.7 m/s, respectively.

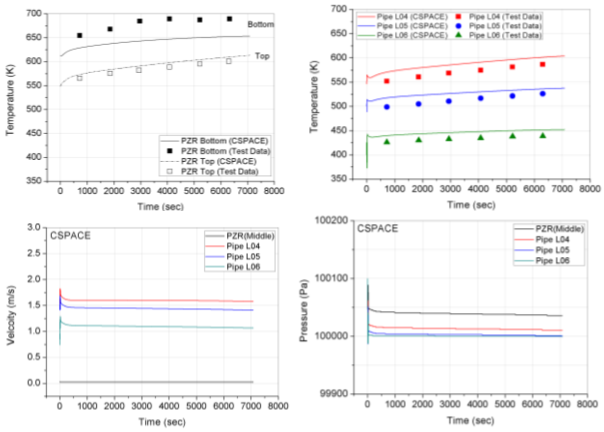

Fig. 2. CSPACE Calculation Results

3.3 SIRIUS Calculation

The SIRIUS analysis was performed to calculate the deposited aerosol mass on the walls during the aerosol transportation from the pressurizer to the pipe L06 in the Marviken test facility using the thermal-hydraulic results predicted by the CSPACE and the SIRIUS input. The CSPACE results were printed out as a text file with the time step of 1 s for the SIRIUS calculation. The SIRIUS input included the application conditions on each component (Table 2), the model constants, and the deposition areas for the aerosol removal calculation. The SIRIUS results show that the calculated aerosol mass accurately predicts the measured data with an error range of 40% except the Te deposited mass on the Pipe L05.

Table 2: Application Conditions of Aerosol Removal Models in the SIRIUS Calculation

	Sedimen-tation	Inertia Impaction	Thermo-phoresis	Diffusio-phoresis
Pressurizer	O	X	O	O
Pipe L04	X	X	X	X
Elbow1	X	O	X	X
Pipe L05	O	X	O	O
Elbow2	X	O	X	X
Pipe L06	X	X	X	X

Table 3: SIRIUS Results for the Marviken Test-2b

		Test	SIRIUS	Difference [%]
Deposited Aerosol Mass on the PZR Wall [kg]	Cs	23.55	36.13	33.9
	I	2.18	3.07	40.8
	Te	4.32	5.88	36.1
Deposited Aerosol Mass on the Pipe L05 Wall [kg]	Cs	2.64	3.33	26.1
	I	0.23	0.28	21.7
	Te	0.19	0.54	184.2
Discharged Aerosol Mass to Relief Tank [kg]	Cs	30.45	30.61	0.52
	I	2.42	2.59	7.02
	Te	5.33	4.94	7.31
Ratio of injected aerosol to recovered aerosol [%]	Cs	92.00	100	-
	I	86.85	100	-
	Te	93.76	100	-

4. Conclusions

A numerical analysis using the SIRIUS code was conducted against the aerosol transport test performed at the Marviken test facility. The SIRIUS code accurately predicted the deposited aerosol mass on the walls with an error range of approximately 40%. However, the SIRIUS code needs to be validated against other integrated test results to accurately evaluate its uncertainty.

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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,” The Korea Nuclear Society Spring Meeting, Jeju, Korea, May 18-19 (2017).

[2] D. H. Kim, etc., Annual Report of Development of Severe Accident Code and Methodology, KAERI (2016).

[3] 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 (2016).

[4] 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).

[5] Marviken Power Station, The Marvikent Experiment – Test 2b Results, Technical Report, MXE-202b (1985).