An Aerosol Transport Analysis in the Marviken Test by SIRIUS Code

Hyung Seok Kang*, Donggun Son, and Kwang Soon Ha
KAERI, 111, Daedeok-daero, 989 Beon-gil, Yuseong-Gu, Daejeon, 34057, Republic of Korea
**Corresponding author: hskang3@kaeri.re.kr*

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 severe accidents [1,2]. A thermal-hydraulic data needed in the SIRIUS calculation was separately provided by the CSPACE (COMPASS-SPACE) code [3]. A SIRIUS validation for an aerosol deposition during its transportation in the closed loop was performed using the Marviken test results [4,5]. In this calculation, the SIRIUS calculation was independently conducted using the thermal-hydraulic data generated at the time interval of 1 s by the CSPACE code. KAERI recently has developed the coupled calculation method between the SIRIUS and CSPACE codes. It is necessary to perform the SIRIUS validation for the aerosol transport against the Marviken test for seeing the difference between the separated calculation and coupled calculation.

2. Aerosol Removal Models in the SIRIUS Code

The gases and aerosols of fission products are transported through the RCS as loaded into the carrier gas or liquid. 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* [1,4]. 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}) [6].

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

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

The gravitational settling 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 [6].

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

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

Aerosol particles in the mixture of steam and hydrogen flow 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. (5) and (6) [6].

$$\Lambda_{IMP}^{SS} = 0.126 M_{IMP}^{0.26} \left(1 + 2.92 M_{IMP}^{1.28}\right)^{0137} \quad (5)$$

$$\Lambda_{IMP}^{D} = 0.337 M_{IMP}^{0.21} \left(1 + 1.74 M_{IMP}^{0.19}\right)^{0.14} \quad (6)$$

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. (7) where D_{12} is a diffusion coefficient of the vapor in the noncondensible gas [1]. The removal rate constant for the diffusiophoresis (Eq. (8)) can be obtained by dividing diffusiophoresis velocity (u_{dif}) by effective height (h_{eff}).

$$u_{dif} = \frac{F\, D_{12}}{\delta} \ln\left[\frac{P_\infty - P_{s,w}}{P_\infty - P_s}\right] \quad (7)$$

$$\lambda_{diff} = \frac{u_{diff}}{h_{eff}} \quad (8)$$

The thermophoresis accounts for the movement of the aerosol particles suspended in the mixture gas flow toward a cooler temperature region. We use the velocity due to the thermophoresis (Eq. (9)) proposed by Epstein [6]. The removal rate constant (Eq. (10)) 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.

$$u_{th} = \frac{\mu\kappa}{\chi\rho_g L}\left[\frac{T_\infty}{T_w} - 1\right]\left[\frac{1-(\kappa \Pr)^{1.25}\left(T_w/T_\infty\right)}{1-(\kappa \Pr)^{1.25}}\right] Nu \quad (9)$$

$$\lambda_{th} = \frac{u_{th}}{h_{eff}} \quad (10)$$

3. Numerical Analysis for the Aerosol Transport

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.

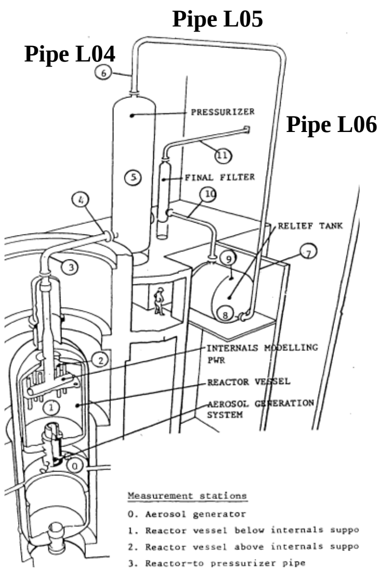


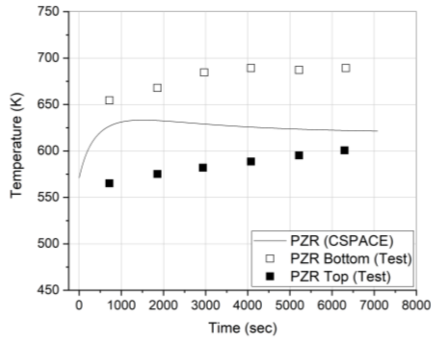
Fig. 1. Schematic diagram of the Marviken test facility [5]

Table 1: Test Condition [5]

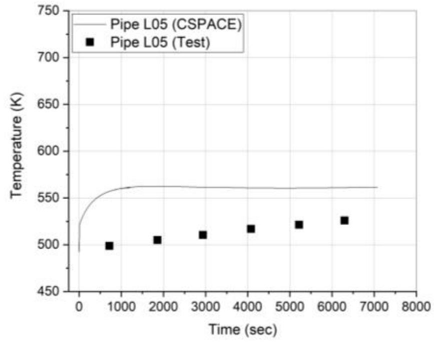
	Injection Time (s)	Flow Condition
Steam	0 - 7080	400 ℃, 40 g/s
CsOH	0 - 7080	70.1 g/s
CsI	60 - 7080	11.8 g/s
Te	240 - 7080	11.0 g/s

3.2 CSPACE Calculation

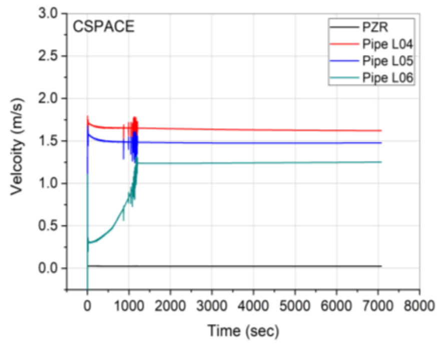
A heat transfer phenomenon between the steam and walls from the pressurizer to the pipe L06 in the Marviken test facility was simulated by the CSPACE as a transient case for 7080 s with a time step size of 0.01 to 0.1 s. A nodalization for the CPACE analysis was constructed with a total of 32 cells. In the nodalization, 1 cells are used for the pressurizer, 4 cells for the pipe L04, 10 cells for the pipe L05, and 15 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 between the top and bottom regions in the pressurizer, and the steam temperature at the pipe L05 with an error range of approximately 10%. The predicted steam velocities at the pressurizer and the pipes are approximately 0.026 m/s and approximately 1.2 – 1.7 m/s, respectively.



(a) Temperature at PZR



(b) Temperature at Pipe L05



(c) Steam Velocity at PZR and Pipes

Fig. 2. CSPACE Calculation Results

3.3 SIRIUS Calculation

The SIRIUS analysis was simultaneously performed to predict 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 at each time step by the CSPACE calculation. The aerosol removal models of the SIRIUS code applied on each component in the Marviken test facility are shown in Table 2. The SIRIUS results (Fig. 3 and Table 3) show that the calculated aerosol airborne mass accurately predicts the measured data with an error range of approximately 3%. In addition, the calculated aerosol deposition mass at the PZR and pipe L05 predict the test data with an error range of approximately 30%. This uncertainty is not large when considering the aerosol loss in the test.

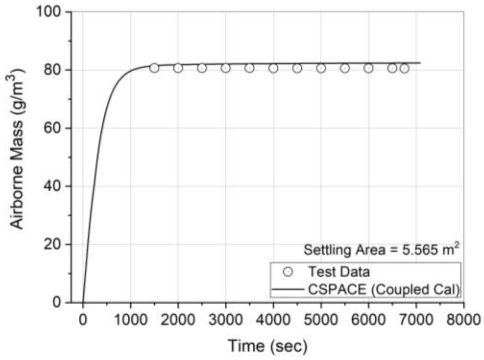


Fig. 3. Airborne Aerosol Mass in the PZR

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	O	O
Elbow1	X	O	O	O
Pipe L05	X	X	O	O
Elbow2	X	O	O	O
Pipe L06	X	X	O	O

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

		Test	SIRIUS	Difference [%]
Deposited Aerosol Mass on the PZR Wall [kg]	Cs	23.55	18.02	-23.4
	I	2.18	1.53	-29.8
	Te	4.32	2.94	-31.9
Deposited Aerosol Mass on the Pipe L05 Wall [kg]	Cs	2.64	2.62	-0.7
	I	0.23	0.22	-4.3
	Te	0.19	0.42	+12.1
Discharged Aerosol Mass to Relief Tank [kg]	Cs	30.45	39.73	+30.4
	I	2.42	3.40	+40.4
	Te	5.33	6.65	+24.7
Ratio of injected aerosol to recovered aerosol [%]	Cs	92.00	100	-
	I	86.85	100	-
	Te	93.76	100	-

4. Conclusions

A numerical analysis by the simultaneous calculation of the SIRIUS and CSPACE codes was performed against the aerosol transport test conducted at the Marviken test facility. The SIRIUS code accurately predicted the deposited aerosol mass on the walls with an error range of approximately 30%. As a further work, the validation of the SIRIUS and CSPACE codes will be performed for an aerosol behavior in the integral test facility.

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] M. Z. Podowski, R. M. Podowski, D. H. Kim, J. H. Bae, and D. G. Son, "COMPASS - New Modeling and Simulation Approach to PWR In-Vessel Accident Progression," *Nuclear Eng. and Tech.*, Vol. 51, pp.1916-1938 (2019).

[4] H. S. Kang, K. S. Ha, S. I. Kim, and D. H. Kang, "Numerical Analysis for an Aerosol Transport Phenomenon in the Marviken Test Facility Using SIRIUS Code," *Proc. of KNS Autumn Meeting*, Gyeongju, Oct. 26-27 (2017).

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

[6] 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).