A SIRIUS Validation for an Aerosol Deposition by a Turbulent Flow in the LACE-3A Test

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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]. A thermal-hydraulic data needed in the SIRIUS calculation was provided through a coupled calculation between the SIRIUS code and the CSPACE (COMPASS-SPACE) code [3]. A SIRIUS validation for an aerosol deposition owing to an inertia force and a turbulent flow during its transportation in the closed loop was performed using the LACE-3A test results [4,5].

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* [1,3]. 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].

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

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

$$\lambda_t = \lambda_{sed} + \lambda_{imp} + \lambda_{diff} + \lambda_{th} + \lambda_{tub} \quad (3)$$

Aerosol particles in the mixture of steam and hydrogen flow in the RCS loop during the severe accident can be removed when the aerosol collide with the bent wall due to their inertia force. In addition, aerosol particles in the RCS loop may also be deposited owing to a turbulent flow effect (Fig. 1) along the wall of the interface system pipe when the mixture gas flows with a high velocity into the interface system during an interface system loss of coolant accident (ISLOCA). For modelling the aerosol removal by the turbulent flow, we also use the dimensionless aerosol removal rate constants (Eqs. (4) to (8)) as function of dimensionless suspended mass concentration following Epstein and Ellison [6]. In Eq. (8), S is the particle stop distance shown in Fig. 1 and f represents the friction factor for the turbulent flow [5].

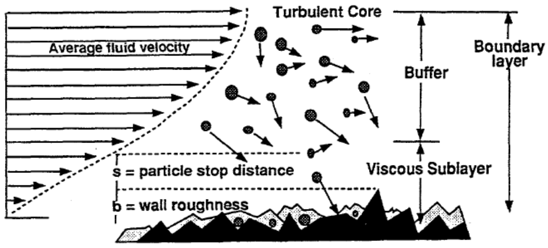

Fig. 1. Schematic diagram of the turbulent deposition [5]

$$\Lambda_{tub}^{SS} = 3.04\times10^{-3} M_{tub}^{0.606}\left(1+4.16\times10^{-3} M_{tub}^{1.36}\right)^{0.25} \quad (4)$$

$$\Lambda_{tub}^{D} = 4.06\times10^{-3} M_{tub}^{0.512}\left(1+3.07\times10^{-3} M_{tub}^{1.106}\right)^{0.397} \quad (5)$$

$$M_{tub} = \left(\frac{\gamma K_o h_{eff}\mu^4\chi}{\alpha^{2/3} f^{5/2}\rho^3\rho_g^2 u_g^5}\right)\left(\frac{\gamma g\rho\varepsilon_o}{\alpha^{1/3}\mu K_o}\right)^{7/4}\cdot m_p \quad (6)$$

$$\Lambda_{tub} = \left(\frac{\chi^2\gamma g h_{eff}\mu^3\varepsilon_o}{\alpha f^{5/2} K_o u_g^5\rho^3\rho_g^2}\right)\cdot\lambda_{tub} \quad (7)$$

$$S = \frac{f u_g^2\rho_g\alpha^{1/3}\rho\nu^{2/3}}{\chi\mu^2} \quad (8)$$

3. Numerical Analysis for the Turbulent Deposition

3.1 LACE-3A Test Condition and Results [4,5]

The test was conducted by injecting the aerosol sources of MnO and CsOH into the LACE-3A test facility (Fig. 2). The injected aerosols were transported with the N_2-steam flow from the injection pipe to the discharge pipe. The mass of the aerosol deposited on the wall of the pipe with the diameter of 6.3 cm were measured in the test. The test conditions are summarized in Table 1. The test results showed that approximately 70% of the injected aerosol mass is deposited on the pipe wall of 6.3 cm diameter.

Table 1: Test Condition at the Injection Pipe [4]

	Injection Time (s)	Flow Condition
N_2-Steam	0 - 3600	298 ℃, 75 m/s
Aerosol Injection (MnO, CsOH)	0 - 3600	0.6 g/s
CsOH/MnO	0 - 3600	Mass Fraction 0.18

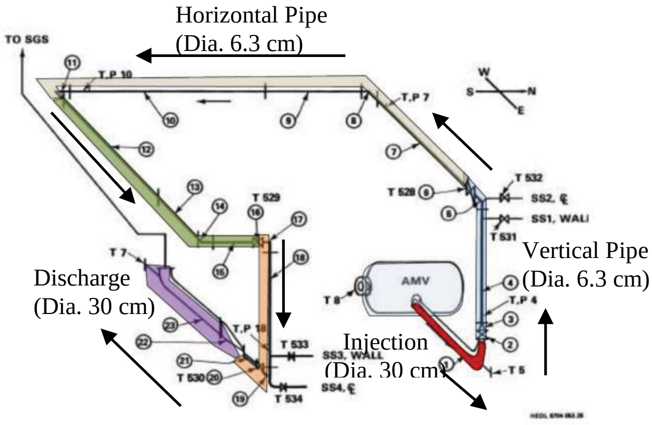

Fig. 2. Schematic diagram of the LACE-3A test facility [4]

3.2 CSPACE Calculation Results

A flow and heat transfer phenomenon of the N_2-steam mixture from the vertical pipe to the discharge pipe in the LACE-3A test facility was simulated by the CSPACE as a transient case for 3600 s with a time step size of 0.0001 s to 0.01 s. A nodalization for the CSPACE calculation was constructed with a total of 38 cells. In the nodalization, the elbows located in the bend regions of the piping system were simulated with 1 cell, respectively. The velocity and temperatures shown in the injection condition of the N_2-steam flow (Table 1) were given as the inlet boundary condition for the CSPACE calculation. The initial pressures for the pipes in the CSPACE calculation were given on the basis of the MELCOR results (Fig. 3) because the measured pressures were not shown in the test report [4,5].

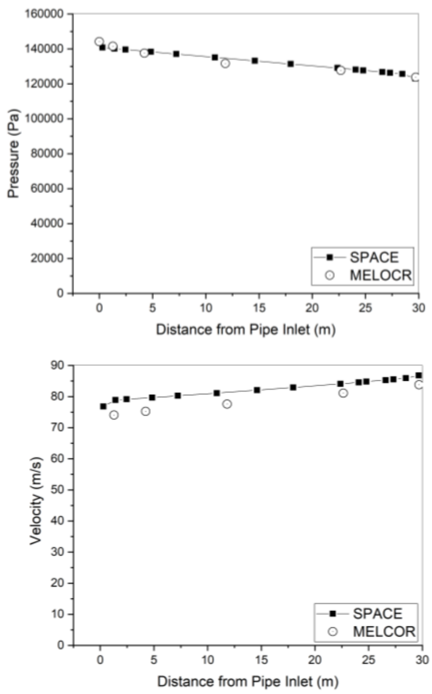

Fig. 3. CSPACE Calculation Results

The calculated pressure and velocity by the CSPACE are shown in Fig. 3. The CSPACE accurately predicted the pressures and velocities predicted by MELOCR with an error range of approximately 10%. The predicted pressure and velocity of the N_2-steam at the discharge pipe are approximately 1.3 MPa and 85 m/s, respectively.

3.3 SIRIUS Calculation Results

The SIRIUS analysis was simultaneously performed to predict the deposited aerosol mass on the walls during the aerosol transportation from the injection pipe to the discharge pipe in the LACE-3A test facility using the thermal-hydraulic results at each time step by the CSPACE calculation. The aerosol removal models of the SIRIUS code applied in this calculation were the inertia impaction and the turbulent flow. In the calculation, the hygroscopic model for the aerosol CsOH was not considered.

The SIRIUS results (Fig. 4 and Table 2) show that the calculated aerosol deposited mass along the pipe of diameter 6.3 cm accurately predicts the measured data with an error range of approximately 10%. In particular, the predicted aerosol mass retention fraction on the pipe wall of 6.3 cm diameter shows good agreement with the measured data.

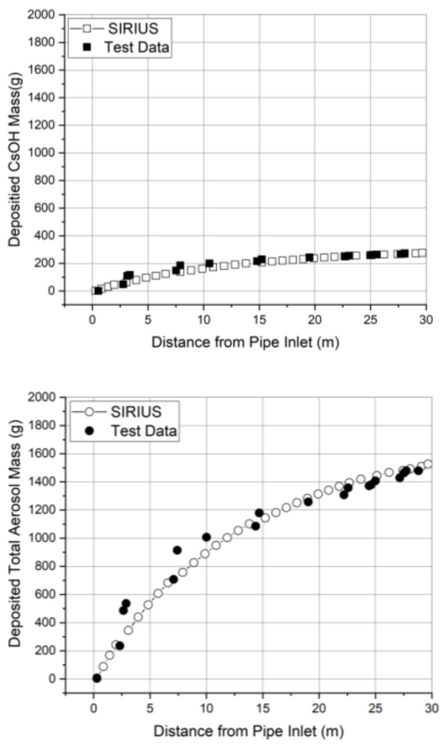

Fig. 4. Comparison of the Deposited Aerosol Mass on the Pipe Wall between the SIRIUS Results and Test Data

Table 2: SIRIUS Results for the LACE-3A Test

	Aerosol	Test	SIRIUS
Mass retention fraction on the pip wall (dia. 6.3 cm)	CsOH	> 0.7	0.706
	MnO	> 0.7	0.706

4. Conclusions and Further Work

A numerical analysis by the simultaneous calculation of the SIRIUS and CSPACE codes was performed against the aerosol transport test, for measuring the turbulent deposition, conducted at the LACE-3A test facility. The SIRIUS code accurately predicted the deposited aerosol mass on the walls with an error range of approximately 10%. As a further work, the SIRIUS calculation for the LACE-3A test will include the hygroscopic model to account the size variation of the aerosol CsOH.

ACKNOWLEDGMENTS

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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," *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] U.S.NRC, State-of-the-Art Reactor Consequence Analyses Project, Vol 2: Surry Integrated Analysis, Technical Report, NUREG/CR-7110, Vol. (2012).

[5] B. J. Merrill and D. L. Hagrman, MELCOR Aerosol Transport Module Modification for NSSR-1, Technical Report, INEL-96/0081, INEL (1996).

[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).