Validation of the SIRIUS Code for Aerosol Deposition Using the STORM SR-11 Experiment

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1. Introduction

During a nuclear severe accident, volatile fission products released from degraded fuel are transported through the reactor coolant system (RCS) in both gaseous and aerosol phases. A significant fraction of these radioactive aerosols deposits on RCS piping surfaces through thermophoresis and turbulent eddy impaction, contributing to radionuclide retention within the primary circuit [1, 2]. However, previously deposited aerosols may be resuspended under high-velocity gas flows in the late phase of an accident, potentially altering the radiological source term [3, 4]. Accurate prediction of aerosol deposition and resuspension is therefore essential for reliable source term evaluation.

As part of the integrated severe accident code development effort in Korea, the CINEMA (Code for INtegrated severe accidEnt Management Analysis) code has been developed since 2011 by a consortium of KHNP, KAERI, KEPCO E&C, and FNC Technology [5]. The CINEMA code consists of three coupled modules: CSPACE for in-vessel thermal-hydraulics and core degradation; SACAP for ex-vessel severe accident phenomena; and SIRIUS (SImulation of Radioactive nuclide Interaction Under Severe accident) for fission product release, transport, and aerosol behavior within the RCS [5, 6]. The SIRIUS module has been previously validated against the LACE-3A turbulent deposition test and the Marviken aerosol transport experiment [7, 8]. However, a systematic validation of SIRIUS against a benchmark that includes both thermophoretic deposition and aerosol resuspension has not yet been fully reported.

The STORM SR-11 experiment, conducted at the Joint Research Centre (JRC) in Ispra, Italy, in April 1997, provides well-characterized separate-effect data for aerosol deposition and resuspension in a straight pipe under conditions representative of PWR relief lines during a station blackout sequence [9]. The test was adopted as International Standard Problem No. 40 (ISP-40) by the OECD/NEA CSNI, and has served as a reference validation benchmark for major severe accident codes including MELCOR and ASTEC/SOPHAEROS [9, 10, 11].

In this study, the CINEMA code is applied to simulate the aerosol deposition phase (Phase 1) of the STORM SR-11 experiment. The objective is to validate the aerosol transport modeling capability of CINEMA and to contribute to its systematic verification and validation (V&V) database for severe accident source term analysis.

2. Methods and Results

2.1 Experimental Modeling

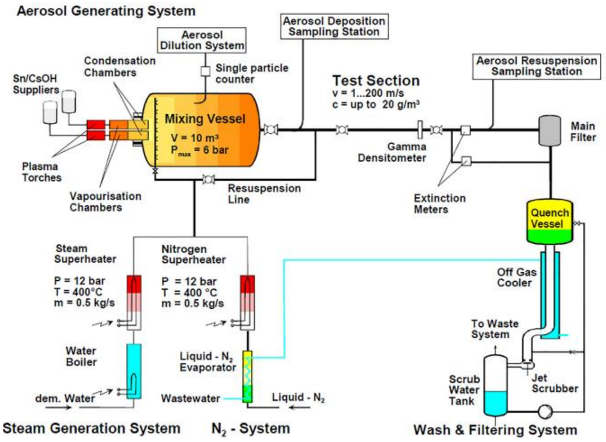

Fig. 1. Schematic flow diagram of the STORM SR-11 experimental facility at JRC Ispra

Figure 1 illustrates the STORM SR-11 experimental apparatus. The system is a horizontal pipe-type aerosol test facility based on the STORM facility at JRC Ispra. The test section consists of a stainless steel pipe with an inner diameter of 63 mm and a total length of 5.0055 m.

Upstream of the test section, a mixing vessel is installed to homogenize the aerosol and carrier gas. Downstream, a collection and measurement unit is positioned, integrating an impactor, a filter, and an optical extinction device. The pipe exterior is equipped with electric ovens, allowing for the intentional creation or elimination of temperature gradients between the pipe wall and the gas phase. Following the completion of the test, the test section is segmented to recover the residual mass in each interval.

Tin dioxide (SnO_2) is utilized as the representative aerosol. The particle size distribution is characterized by a geometric mean diameter (GMD) of approximately 0.43 µm and a geometric standard deviation (GSD) of approximately 1.7. The overall operating conditions and system configuration strictly adhere to the OECD NEA ISP-40 standard conditions.

The experiment is divided into two primary phases: the deposition phase and the resuspension phase. In the deposition phase, SnO_2 aerosols are injected into the test section using a carrier gas mixture of steam and N_2. During this 9,000-second period, external ovens are activated to heat the pipe walls, thereby inducing thermophoresis. In the subsequent resuspension phase, the carrier gas is switched to pure N_2, and the ovens are turned off to achieve near-isothermal conditions between the gas and the walls. The mass flow rate is then increased in six discrete steps, ranging from 0.102 to 0.224 kg/s, while monitoring the outlet concentration and the mass collected by the impactors and filters. Table 1 illustrates the evolution of gas species and mass flow rates employed throughout the experiment.

Table 1. Injected gas species and their corresponding mass flow rate.

Gas	Mass flow rate [kg/s]
Steam	1.1060×10^{-2}
Nitrogen	0.5467×10^{-2}
Air	0.5728×10^{-2}
Argon	0.7194×10^{-2}
Helium	0.0119×10^{-2}
Total	3.5975×10^{-2}

To simulate the STORM SR-11 test using the CINEMA code, a nodalization scheme was developed, as shown in Figure 2. The test section is modeled using 10 computational cells, each integrated with a corresponding heat structure to represent thermal behavior. A Time-Dependent Boundary Condition (TFBC) is applied at the inlet for the injection of carrier gas and aerosols, while the outlet is defined by a pressure boundary condition.

Although the original experiment aims to evaluate both deposition and resuspension, the current study focuses exclusively on the validation of the deposition phase because the resuspension model is not yet implemented in the CINEMA code. Since thermophoresis is the dominant deposition mechanism and its accuracy depends heavily on the temperature gradient between the bulk gas and the wall surface, the heat transfer coefficients of the heat structures were meticulously calibrated. This adjustment ensures that the thermal-hydraulic conditions of the simulation precisely match the experimental data, providing a robust basis for aerosol behavior analysis.

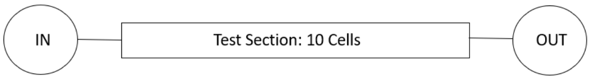

Fig. 2. Nodalization scheme of the STORM SR-11 test section for CINEMA code simulation.

2.2 Thermal-Hydraulic Analysis and Validation

Figure 3 illustrates the axial distributions of the wall temperature and the bulk gas temperature measured in the STORM SR-11 experiment. Throughout the test, the thermal-hydraulic conditions remained in a near steady-state. Since thermophoresis is the dominant deposition mechanism in this study, the accurate reproduction of these two temperature profiles is a crucial factor for the simulation.

The wall temperature decreases from approximately 250 °C at the inlet to 208 °C at the outlet, representing a total drop of 42 °C with a gradient of about 8.4 °C/m. This wall temperature profile was incorporated into the code as a boundary condition to ensure exact agreement with the experimental data. In contrast, the internal gas temperature is calculated through the wall heat transfer model of the code where the CINEMA code utilizes the Dittus-Boelter correlation. To match the observed gas temperature profile, the wall heat transfer coefficients were appropriately adjusted. Consequently, the calculated gas temperature decreased nearly linearly from approximately 375 °C at the inlet to 330 °C at the outlet, showing an almost identical distribution to the experimental results. These results demonstrate that the thermal-hydraulic conditions required for the evaluation of thermophoresis have been adequately implemented.

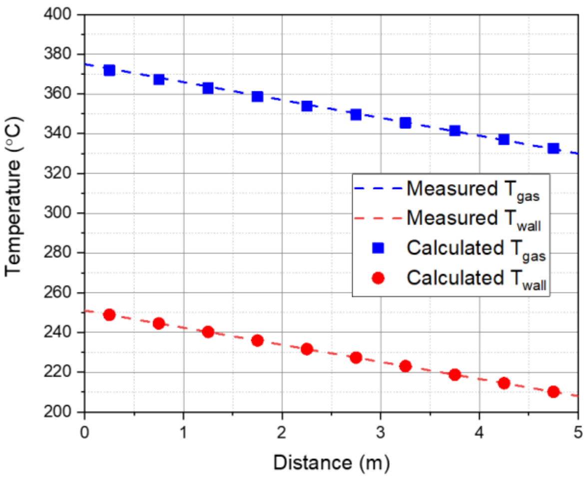

Fig. 3. Comparison of axial temperature profiles for gas and wall surfaces in the STORM SR-11 test section.

2.3 Aerosol deposition Analysis and Validation

Figure 4A illustrates the axial distribution of the deposited aerosol mass per unit area. The calculated mass begins at approximately 0.263 kg/m^2 at the inlet and reaches a maximum of 0.264 kg/m^2 near 0.75 m before gradually decreasing to 0.255 kg/m^2 at the outlet. The relatively lower deposition predicted in the first cell compared to the second cell is attributed to the Fauske & Associates, Inc. correlation employed in the CINEMA code. This correlation distinguishes between a steady state where aerosol generation and removal coexist and a decay state involving only removal. Consequently, the gravitational settling in the first cell is estimated to be relatively small. The subsequent decrease after the second cell is interpreted as a result of the narrowing temperature gradient between the bulk gas and the wall along the pipe which reduces the deposition rate induced by thermophoresis.

Figure 4B presents the fractional contribution of each deposition mechanism along the axial direction. In the inlet region, the contribution of gravitational settling is negligible and thermophoresis accounts for approximately 99 % of the total removal. Throughout the remaining sections, thermophoresis remains the dominant mechanism maintaining a contribution level of approximately 97 % while the remainder is attributed to gravitational settling. Notably, no deposition occurred via turbulent diffusion. This is because the Epstein and Ellison (1988) correlation used in CINEMA is only valid when the particle stopping distance (S) exceeds 4.7. In the present simulation, the value of S remained below this threshold causing the turbulent model to remain inactive.

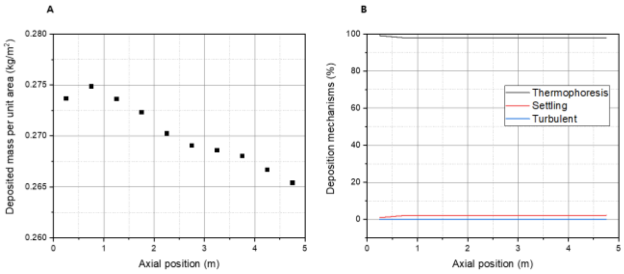

Fig. 4. Axial distribution of deposited aerosol mass (A) and fractional contributions of deposition mechanisms (B) in the STORM SR-11 test section.

Figure 5 compares the total deposited mass reported in the ISP-40 meetings while Table 2 summarizes the thermophoresis models adopted by each code. The total deposition mass presented in the experiment was 162 g whereas the CINEMA code predicted a higher value of 257 g. Most codes utilize the Talbot equation as their thermophoresis model and CINEMA employs the same approach. Results from many codes applying this model exhibited a general trend of overestimation compared to the experimental data. In contrast, MELCOR which uses the Brock equation showed a relative tendency toward underestimation. Notably, the second attempts by Tractebel and the University of Bochum incorporated specific constants suggested by Talbot rather than the default values resulting in deposition masses that were closer to the experimental values.

An analysis of the removal mechanisms calculated by each code confirms that thermophoresis is consistently the dominant mechanism. Discrepancies between codes may arise not only from the choice of thermophoresis correlations but also from differences in implementation and input parameters. For instance, some MELCOR users designated air as the carrier gas and those using MELCOR 1.8.2 substituted SnO_2 with similar materials as it was not available in the library. Furthermore, aerosol coefficients such as the dynamic shape factor and slip factor were not always specified allowing user defined settings to influence the results. Considering these factors, although the absolute prediction of CINEMA is higher than the experimental value, it is evaluated to simulate the experiment at a reasonable level when compared with other international benchmark results.

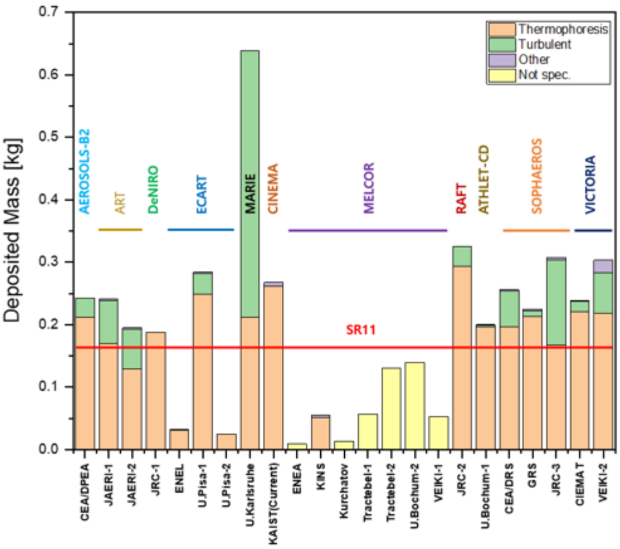

Fig. 5. Comparison of total deposited aerosol mass among ISP-40 participating codes for the STORM ST-11 experiment.

Table 2. Summary of numerical codes and thermophoresis models adopted by ISP-40 participating organizations

Code	Thermophoresis model
Aerosol-B2	Talbot's equation
Art	Brock's equation (Knudsen <0.2) Waldman's equation (Knudsen > 0.2)
Athlet-CD	Talbot's equation
DeNiro	Talbot's equation
Ecart	Talbot's equation
Marie	Talbot's equation
MELCOR	Brock's equation
Raft	Springer's model
Sophaeros	Talbot's equation
Victoria	Talbot's equation

3. Conclusions

In this study, a numerical validation of the STORM SR-11 test was performed using the CINEMA code developed to predict aerosol behavior during nuclear power plant severe accidents. The STORM SR-11 experiment is a representative test simulating aerosol deposition induced by thermophoresis and resuspension driven by high-velocity gas flows. Since the current version of the CINEMA code does not yet include a resuspension model, this study focused on evaluating the predictive performance of the code specifically for the deposition phase.

The thermal-hydraulic analysis results showed that the CINEMA code reproduced the internal temperature profiles of the test section with high accuracy providing reliable boundary conditions for the thermophoresis calculations. In the aerosol deposition analysis, CINEMA predicted a total deposited mass of 257 g which is higher than the experimental value of 162 g. This outcome is consistent with the general overestimation trend observed in many ISP-40 participating codes that utilize the Talbot correlation. Although there is a discrepancy in the absolute mass values, the CINEMA code demonstrated a reasonable simulation capability in terms of the axial deposition distribution trends and the physical interpretation of dominant removal mechanisms.

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