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Evaluation of Aerosol Sampling Efficiency for ART Facility using Particle Loss Calculator

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1. Introduction

During a severe accident, some radioactive materials are released from heated fuel rods and molten corium as gases and condensed as aerosols. The containment spray system prevents significant radioactive releases even under containment failure conditions by scrubbing the airborne radioactive aerosols. It is very important to estimate the behaviors of radioactive materials under the severe accident conditions[1]. Experiments have been conducted to measure aerosol concentration behavior in the containment and to assess the influence of spray system. ART (Aerosol Retention Test) experiments have been performed in KAERI to evaluate the aerosol retention in containment by spray[2]. In ART test facility, some aerosols generated in the mixing chamber are transported to a vessel through the main piping and sampled via a sampling system. During this process, aerosol particle losses occur due to mechanisms such as diffusion, sedimentation, and inertial deposition. This study evaluates the sampling efficiencies and transport efficiencies of the sampling system and main piping system in the ART test facility. The calculations were performed using the "Particle Loss Calculator (PLC)" software developed by the Max Planck Institute for Chemistry. The theoretical models employed by the PLC tool have been previously validated in the literature. Specifically, for simple and non-extreme configurations such as a horizontal straight pipe, the calculated sampling losses exhibit a highly satisfactory agreement with experimental measurements[3]. The assessment covers both the transport efficiency in the main piping and the inlet efficiency of the sampling system.

2. Methods

2.1 Calculation Tool

The PLC tool calculates aerosol losses based on empirical and theoretical formulas established in the literature[3]. It accounts for various loss mechanisms, including diffusion, sedimentation, turbulent deposition, and inertial deposition in bends and contractions. The tool allows users to input sampling parameters (orientation, aspiration angle, flow rate) and tubing parameters (length, diameter, curvature). The tool calculates aerosol losses at both the sampling nozzle and within the transport pipes. Losses at the sampling nozzle primarily arise from the aspiration angle and non-isokinetic sampling conditions. Furthermore, particle losses in the piping are evaluated based on mechanical mechanisms, including diffusion, sedimentation, turbulent deposition, and inertial deposition in bends and contractions. It should be noted that the PLC accounts for the mechanical losses of aerosols; other phenomena, such as thermophoresis or condensation, are not considered in the calculation[3].

2.2 System Configuration

Figure 1 shows a schematic of ART test facility. As shown in Fig.1, the vessel resembles the containment building, and aerosol is injected into the vessel. When the vessel is filled with aerosol, it is isolated by shutting the inlet and outlet. There are two sampling nozzles for ELPIs (electrical low pressure impactor, DEKATI) installed at the top and bottom of the vessel. Initially, SiO_2 aerosol was generated and injected into the vessel, and then the vessel was kept isolated. Then, water sprayed from the vessel top to remove the aerosol[2].

The analysis was divided into two parts: the main piping and the sampling system.

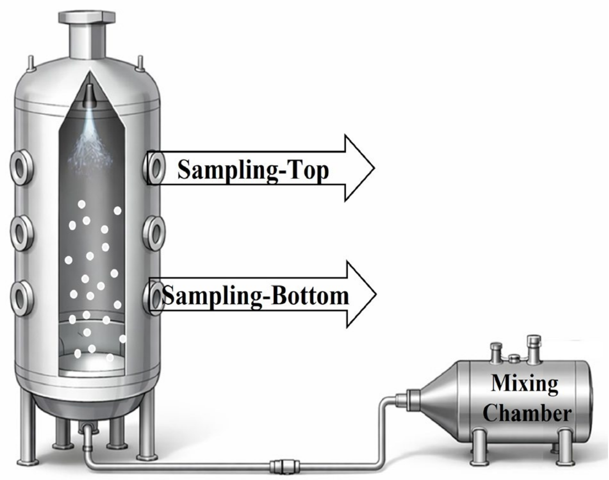

Fig. 1. Schematic of ART test facility.

2.2.1. Main Piping system

The main aerosol transport line from the mixing chamber to the ART test facility was divided into 9 distinct sections with varying length and diameters, including bends as shown in Fig.2.

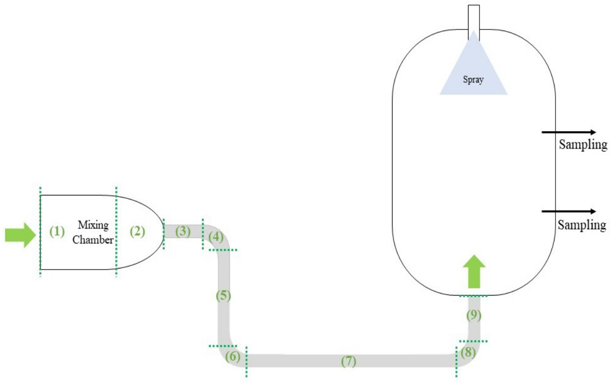

Fig. 2. Geometric segmentation of main piping line

2.2.2. Sampling system

Aerosol sampling was conducted at two locations within the experimental vessel using two ELPIs. Within the ELPI system, the sampled gas was diluted using a diluter with a dilution ratio of 8:1 to accommodate instances where the aerosol mass concentration exceeded the measurement limit of the ELPI. The sampling probe is oriented horizontally and an inner diameter of 1.78 mm. The sampling system consists of 14 sections with varying length and diameters, including bends as shown in Fig.3.

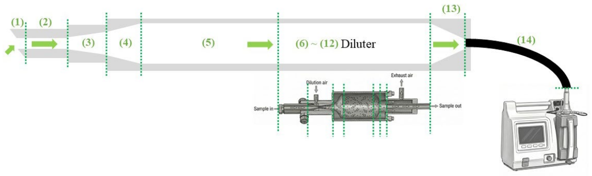

Fig. 3. Geometric segmentation of sampling system.

2.3 Aerosol Parameters

The aerosol particles used in the experiment were SiO_2 particles with an Aerodynamic Mass Median Diameter (AMMD) of 1 µm. For the calculation, the particle density is 2200 kg/m³ with a shape factor ranging from 1.0 to 2.0.

3. Results and Discussion

3.1 Transport Efficiency in Main Piping

The transport efficiency in the main piping was evaluated at varying main flow rates from 50 to 300 l/min, as illustrated in Fig. 4. The results indicate that transport efficiency increases as the flow rate increases. Specifically, for a particle diameter of 1 µm and a main flow rate of 200 l/min, the transport efficiency was calculated to be approximately 98%. Figure 4 demonstrates that across the entire tested flow range (50-300 l/min), the transport efficiency remained more than 90% for the referenced particle size.

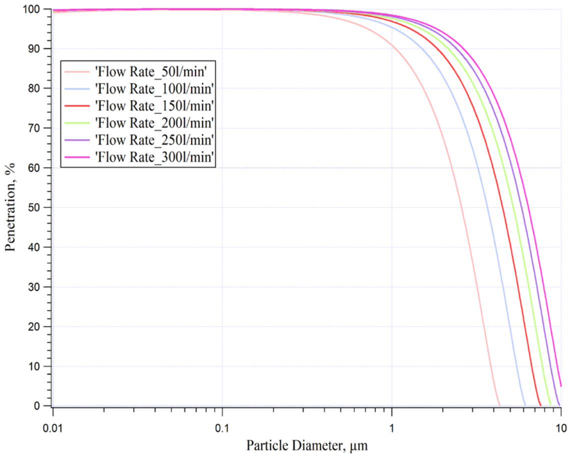

Fig. 4. Transport Efficiency of the main piping system at varying main flow rates from 50 to 300 l/min (Particle Shape Factor: 1.0).

3.2 Sampling System Efficiency

Figure 5 presents the inlet efficiency (total efficiency) of the sampling system under the assumption of a spherical shape (Shape Factor: 1.0). The total efficiency is determined by the product of the sampling efficiency and the transport efficiency within the sampling tubing.

Under the condition of a sampling flow rate of 2.5 l/min, the sampling efficiency for 1 µm particles was found to be approximately 63%. This calculation considered both operating conditions (low wind velocity) and static conditions (zero wind velocity), yielding similar results.

The transport efficiency through the sampling tubing was calculated to be approximately 85% for 1 µm particles. Sedimentation and inertial deposition in bends are the dominant loss mechanisms during aerosol transport to the ELPI. Without accounting for these two factors, the calculated transport efficiency for 1 µm particles is nearly 100%.

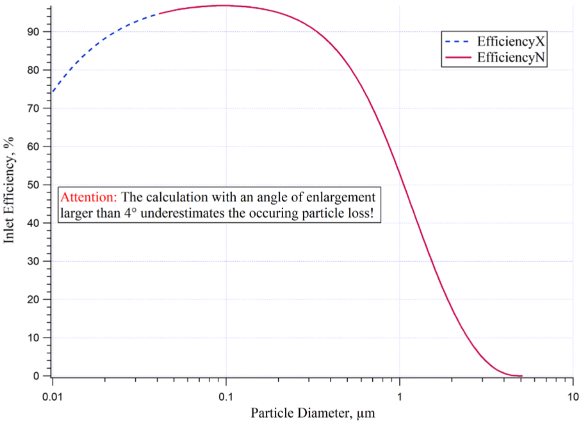

Fig. 5. The inlet efficiency (total efficiency) of the sampling system (Particle Shape Factor: 1.0).

3.3 Parametric Analysis

An analysis was conducted to understand the effect of sampling flow rate and probe geometry.

As shown in Fig. 6, increasing the sampling probe inner diameter (from 1.78 mm to 10 mm) resulted in increased sampling efficiency.

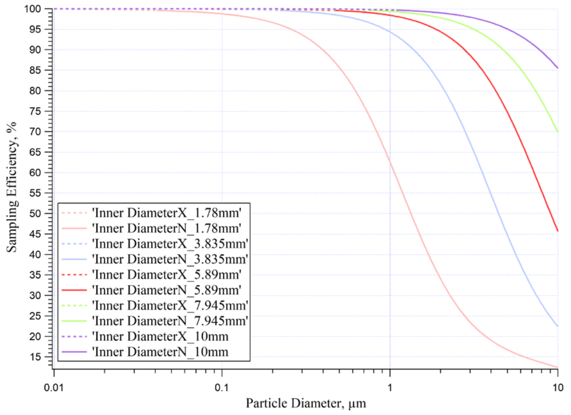

Fig. 6. Sampling efficiency of the sampling system according to sampling probe inner diameter (Particle Shape Factor: 1.0).

Furthermore, Fig.7 illustrates the effect of the sampling flow rate; as the sampling flow rate increased from 0.1 to 10 l/min, the sampling efficiency decreased. Lower flow rates allowed for higher efficiency.

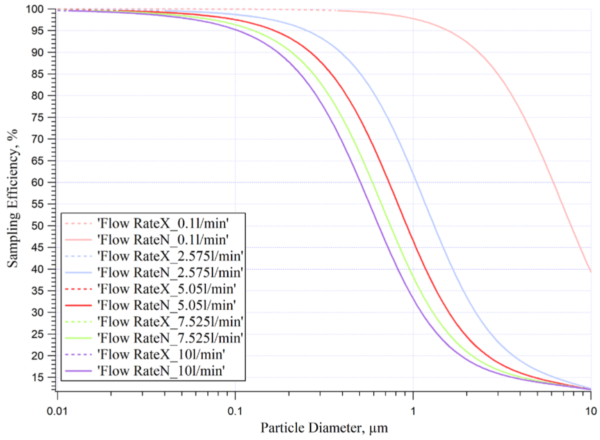

Fig. 7. Sampling efficiency of the sampling system according to sampling flow rate (Particle Shape Factor: 1.0).

Fig. 8 depicts the effect of the dynamic shape factor on the sampling inlet efficiency. A parametric analysis revealed that increasing the dynamic shape factor from 1.0 (ideal sphere) to 2.0 results in an overall enhancement of the sampling inlet efficiency. This improvement occurs because a higher shape factor reduces the particle's settling velocity, thereby decreasing sedimentation losses. Aerosol particles generated in the mixing chamber undergo frequent collisions, leading to significant agglomeration. Through this agglomeration process, the particles form irregular structures rather than remaining as perfect spheres. This change increases their shape factor from 1.0 to higher values.

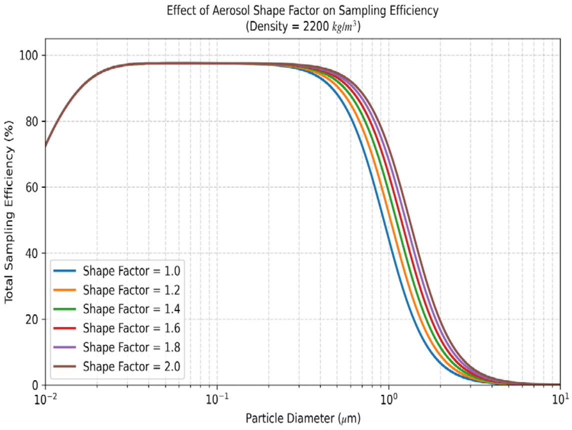

Fig. 8. Effect of shape factor on the sampling inlet efficiency of the sampling system.

3.4 Data Correction in Experiments

Figure 9 displays the aerosol concentration measured over time at the top of the test vessel with the ELPI. The aerosol concentration measured by the ELPI represents the particle concentration after transport through the sampling system, meaning it inherently includes particle losses. To determine the actual aerosol concentration within the experimental vessel, a data correction process was applied using the inlet efficiency calculated by the PLC. For each particle size channel, the measured number concentration was divided by its corresponding total sampling efficiency. The results of this data correction are presented in Fig. 10. This correction mathematically accounts for size-dependent loss mechanisms, such as sedimentation and inertial deposition, thereby providing a highly accurate estimation of the true aerosol behavior, particularly for particles (> 1 µm) where transport losses are most significant.

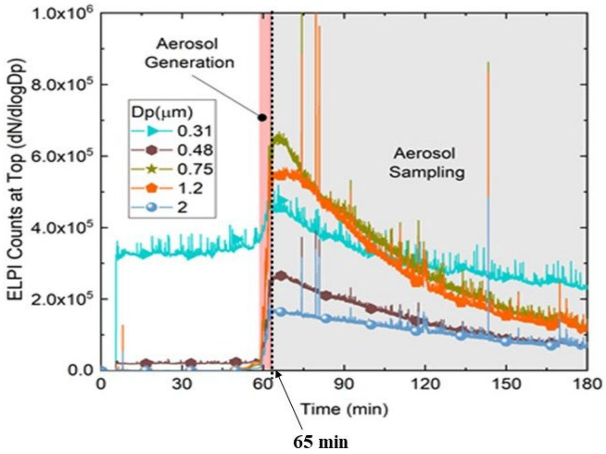

Fig. 9. Aerosol concentration measured at the top of the experimental vessel with ELPI.

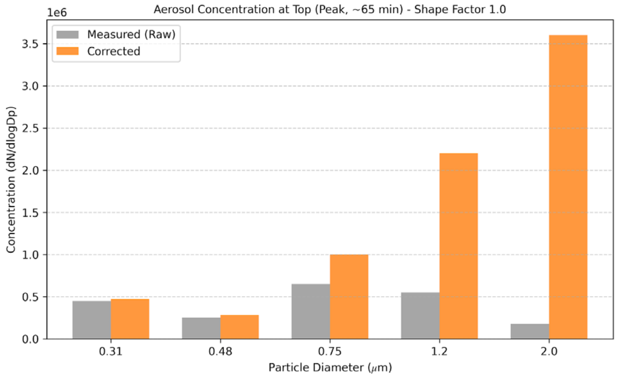

Fig. 10. Corrected aerosol concentration at the 65 min after aerosol generation.

4. Conclusion

This study evaluated the aerosol transport and sampling efficiencies of the ART test facility using the PLC. While the main piping showed more than 90% transport efficiency, the sampling system exhibited significant losses for particles larger than 1 μm due to sedimentation and inertial deposition.

Consequently, the agglomerated aerosols exhibit a lower settling velocity, which significantly mitigates sedimentation losses. Therefore, due to the agglomeration effect, the actual irregular aerosols are transported through the sampling system with a higher overall efficiency than a spherical model would predict.

By applying a data correction method based on PLC efficiencies, the actual aerosol concentration inside the vessel was reconstructed.

ACKNOWLEDGMENTS

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