Experimental Evaluation of Clean Air Delivery Rate for Radioactive Material Reduction System

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1. Introduction

Since the Fukushima Daiichi nuclear disaster in 2011, international safety standards for nuclear power have been significantly reinforced, accompanied by growing public demand for enhanced nuclear safety. In particular, the release of radioactive materials during severe accidents poses a serious threat to public health and the environment, making the development of effective mitigation systems a key focus in nuclear safety research.

Currently, commercial nuclear power plants in Korea employ the Containment Filtered Venting System (CFVS) as a severe accident management measure, which filters fission products prior to controlled discharge to the environment. However, with the recent strengthening of domestic regulations related to severe accidents management, the external release of radioactive materials—even after filtration—has come to be regarded as undesirable [1]. Consequently, increasing attention has been directed toward additional mitigation systems capable of proactively reducing the source term from the early stages of an accident.

In a previous study, a three-stage metal-fiber-based Radioactive Material Reduction System (RMRS), consisting of a demister, pre-filter, and main filter, was proposed, and its removal efficiency for aerosolized radioactive materials was experimentally evaluated [2].

In this paper, following the assessment of removal efficiency, we present the results of Clean Air Delivery Rate (CADR) tests, which represent the RMRS's aerosol cleaning capacity—that is, its ability to purify the contaminated air within an enclosed space. Unlike the design concept of the CFVS, the proposed system is designed to recirculate radioactive materials within the reactor containment or other confined internal spaces where radioactive aerosols remain suspended, rather than releasing them into the external environment during a severe accident. Therefore, in addition to filtration efficiency, the time-dependent CADR of the RMRS serves as a key performance indicator for reducing airborne radioactive materials within nuclear power plant structures under severe accident conditions.

2. Methods and Results

2.1 CADR (Clean Air Delivery Rate)

The theoretical Clean Air Delivery Rate (CADR) is defined as the product of the volumetric flow rate (Q) and the removal efficiency (η), as expressed in Eq. (1) [3, 4].

$$\mathrm{CADR}_T = \mathrm{Q} \times \eta \tag{1}$$

However, the actual CADR may vary depending on several factors, including the inlet and outlet locations of the RMRS, air mixing characteristics, and the volume of the space [3, 4].

To address these limitations, the Korea Air Cleaning Association (KACA) has established a standard test method, SPS-C KACA002-0132:2025, which specifies an appropriate test chamber volume and experimental procedure based on the theoretical CADR of an air cleaning device [5]. In this study, the CADR of the RMRS was evaluated in accordance with this standard test method. The equation used to determine the CADR is given in Eq. (2) as follows.

$$\mathrm{CADR} = \frac{V}{Nt}\left(\ln\frac{C_{i2}}{C_{t2}} - \ln\frac{C_{i1}}{C_{t1}}\right) \tag{2}$$

In this equation, CADR represents the aerosol cleaning capacity (m³/min), V is the volume of the test chamber (m³), and t is the operating time of RMRS, C_{i1} is the initial particle number concentration (#/cm³) at t = 0 under the natural removal condition, and C_{t1} is the particle number concentration (#/cm³) measured at time t (min) under the natural removal condition, C_{i2} is the initial particle number concentration (#/cm³) at t = 0 under the RMRS operating condition, and C_{t2} is the particle number concentration (#/cm³) measured at time t (min) under the RMRS operating condition.

2.2 Experimental facility & Material

The RMRS actively draws airborne aerosols using a fan and delivers them to a three-stage multi-layer filtration unit. The main filter applied in the CADR test consists of nine metal sintered filter elements. Each individual filter unit has an effective filtration area of 0.193 m², resulting in a total filtration area of 1.737 m².

The fan used in the present experiment was rated at 250 CFM (7.08 m³/min), corresponding to a face velocity of 0.068 m/s across the filter surface. All experiments were conducted using this configuration.

In a previous study conducted with the same RMRS, the aerosol removal efficiency was determined to be greater than approximately 99%, yielding a theoretical CADR of about 7 m³/min. Based on SPS-C KACA002-0132:2025, a suitable test chamber volume was selected in accordance with the specified criteria for this level of CADR. Accordingly, a test chamber with dimensions of 3.5 m (L) × 3.5 m (D) × 2.5 m (H), corresponding to a total volume of approximately 30.625 m³, was constructed [6]. Fig. 1 presents the schematic diagram of the test chamber established for evaluating the CADR of the RMRS, along with a photograph showing the RMRS installed inside the chamber.

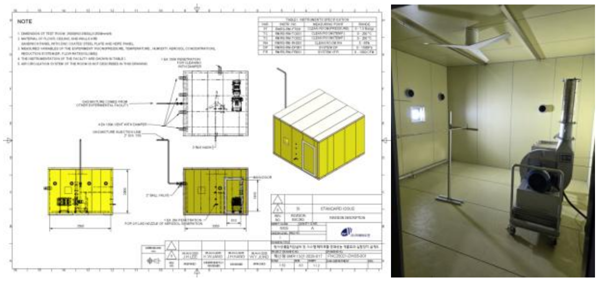

Fig. 1. Schematic diagram of the test chamber for evaluating the CADR of the RMRS and photograph of the RMRS installation inside the chamber.

The test aerosol was generated using a KCl solution, which was atomized into droplets through a two-fluid nozzle. The KCl solution was prepared by dissolving solid KCl (SAMCHUN, 99.0% purity) in ultra-pure water to a concentration of approximately 21.9% by weight.

To measure the real-time particle size-resolved number concentration of the aerosol, an ELPI®+ (Electrical Low Pressure Impactor) manufactured by Dekati was employed.

2.2 Test Results

Table I summarizes the experimental conditions investigated in this study. To evaluate the CADR of the RMRS under severe accident environmental conditions, tests were conducted at different temperatures under ambient atmospheric conditions. In addition, to simulate high-temperature and high-humidity conditions representative of severe accident, supplementary experiments were performed using steam as the carrier gas. For each test condition, the particle number concentration was measured for 20 minutes under both the natural removal condition and the RMRS operating condition in an identical environment.

Table I: Experimental conditions for evaluating the CADR of the RMRS

Test No.	Condition	Room Temp. [°C]	Face Velocity [m/s]
1	Air	30	0.068
2	Air	60	0.068
3	Steam	100	0.068

At 30℃, the RMRS exhibited the highest CADR of 3.31 m³/min. Under this condition, approximately 48.94% of the aerosols remained suspended after the natural decay test, whereas only 5.63% remained after the RMRS operation.

At 60℃, the CADR was evaluated as 1.74 m³/min. Following the natural removal test, 29.68% of the aerosols remained, while 9.52% remained after operation of the RMRS.

Under high-temperature (100℃) and high-humidity (RH 100%) conditions, the lowest CADR of 1.16 m³/min was observed. In this case, approximately 56.12% of aerosols remained after the natural decay test, and 26.23% remained after RMRS operation.

The results of the CADR are summarized in Table II. Graphs showing the time-dependent decrease in particle number concentration under natural removal and RMRS operation for each temperature condition are presented in Fig. 3, Fig. 4, and Fig. 5.

Table I: Experimental results of the CADR for the RMRS

Test No.	C_{i1} [#/cm^3]	C_{t1} [#/cm^3]	C_{i2} [#/cm^3]	C_{t2} [#/cm^3]	CADR [m^3/min]
1	4.25x10^4	2.08x10^4	7.69x10^4	4.33x10^3	3.31
2	1.24x10^5	3.68x10^4	8.71x10^4	8.29x10^3	1.74
3	5.88x10^7	3.30x10^7	7.13x10^7	1.87x10^7	1.16

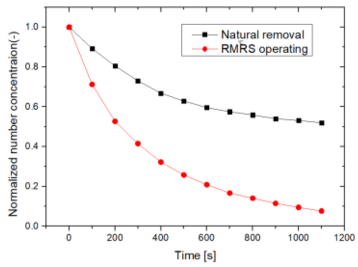

Fig. 2. Time-dependent particle number concentration graph under air at 30℃

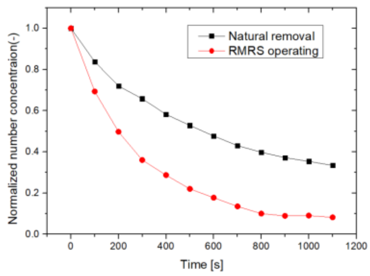

Fig. 3. Time-dependent particle number concentration graph under air at 60℃

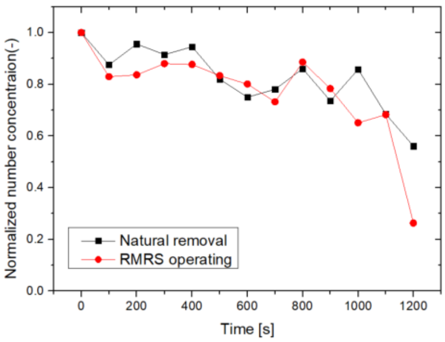

Fig. 4. Time-dependent particle number concentration graph under steam at 100℃

Variations in the initial particle concentrations occurred across the experimental cases. The reason for these variations is that precisely controlling the output rate of the aerosol generator is extremely difficult. However, we do not expect these differences in initial concentration to significantly impact the CADR. This is because the CADR is determined by the relative ratio of the change between the initial and final concentrations. Furthermore, all measured concentrations at the end of the tests remained within a measurable range, exceeding the lower detection limit of the measurement instrumentation (10^3 particles/cm^3).

3. Conclusions

The objective of this study was to evaluate the Clean Air Delivery Rates (CADR), aerosol cleaning capacity, of the Radioactive Material Reduction System (RMRS). The assessment was conducted in accordance with the standard test method SPS-KACA002-0132.

The CADR tests were carried out 30℃, 60℃ conditions, as well as under high-temperature, high-humidity conditions (100℃, steam) to simulate severe accident environments in nuclear power plants. Under a flow condition of 250 CFM (7.08 ㎥/min), the measured CADR were 3.31 ㎥/min at 30℃, 1.74 ㎥/min at 60℃, and 1.16 ㎥/min at 100℃. The results clearly indicate that CADR decreases significantly with increasing temperature.

This reduction may be related to the lower air density at higher temperatures. Although the volumetric flow rate remained constant at 250 CFM, the corresponding mass flow rate might have decreased, potentially leading to a lower evaluated CADR.

Moreover, under the high fraction of steam present in the test room atmosphere, condensation may have occurred during aerosol sampling, which could have hindered the accurate measurement of a significant portion of aerosols. Consequently, the measured RMRS operating performance might have appeared closer to the natural removal rate than it actually was.

These observations indicate that additional and continued experiments will be conducted to clarify these uncertainties and more accurately assess RMRS performance under high-temperature, high-humidity conditions. Also, the potential influence of initial aerosol concentration on natural removal mechanisms, such as coagulation and sedimentation, might be investigated in future experiments to refine the evaluation of the system effectiveness under severe accident environments.

ACKNOWLOGEMENT

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