Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

Performance Evaluation of Aerosol Filtration for HEPA Level Metal Fiber Filter

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***Keywords :** aerosol filtration, metal fiber filter, severe accident mitigation

1. Introduction

Air filtration plays a vital role in various industrial environments, particularly in facilities that have the potential to handle or generate aerosols containing hazardous particles, such as radioactive materials from fission products in nuclear power plants(NPPs). High Efficiency Particulate Air (HEPA) filters, traditionally constructed from glass fiber media, are extensively used as the primary barrier against the release of these hazardous aerosols[1]. While HEPA filters are highly effective, capable of achieving over 99.97% removal efficiency for 0.3 µm particles, they present significant operational challenges, particularly under severe accident conditions[1,2].

During the severe accident in NPPs, fission products as form of aerosol can be released into the environment, mixed with steam and/or various non-condensable gases[3].

While HEPA filters can be employed to remove these aerosols, they face operational limitations such as rapid clogging, limited lifespan, and performance degradation under extreme conditions like high temperatures, high airflow velocities, fire, and exposure to corrosive chemicals. The susceptibility of glass fiber HEPA filters to fire damage and their inherent difficulties in recycling once contaminated further underscore the need for advanced filtration solutions[1].

To overcome these challenges, metal fiber filters have emerged as a promising alternative and complementary technology[4,5]. These filters are typically fabricated from metal filaments and sintered metal powder, often made of stainless steel or other highly corrosion-resistant alloys like Inconel and titanium, structured into a three-dimensional matrix. Metal fiber filters offer superior thermal and mechanical properties, distinguishing them from conventional filters. Their notable advantages include high porosity (often exceeding 85%) and permeability, which contribute to a lower pressure drop. Furthermore, they exhibit excellent resistance to high temperatures (up to 550℃, and even 1000–1600℃ for ceramic fiber variants) and are resistant to various chemical challenges, including hydrofluoric acid[5].

To utilize the advantages of metal fiber filters in increasing safety margin of NPPs as a part of a mitigation system for severe accidents, a facility called the Radioactive Material Reduction System is proposed. This system consists of three filter elements made from metal fibers such as a demister, pre-filter, and main-filter, each designed to target different particle sizes for each section. The demister captures droplets and particles of larger sizes, the pre-filter targets micron-sized particles, and the main-filter captures sub-micron particles. Because a rage of particle sizes is expected during the system operation period, the three-stage RMRS is anticipated to enhance the system's capacity and efficiency.

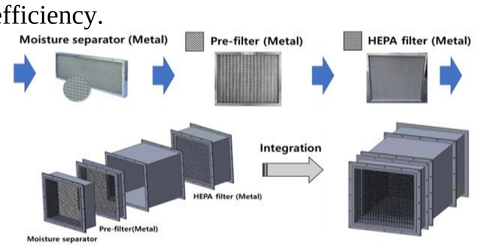

Fig. 1. Conceptual images of RMRS(Radioactive Material Reduction System)

2. Methods and Results

2.1 Experimental facility and Test matrix

To evaluate performance of the proposed system, the RMRW performance test facility was proposed presented in Fig. 2.

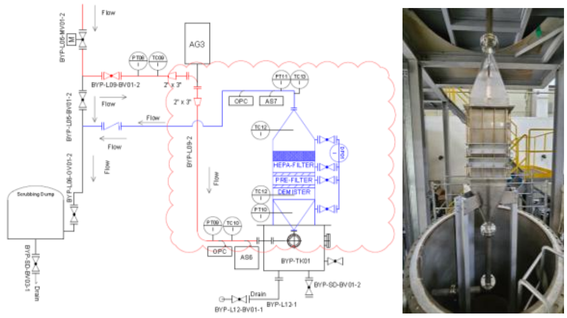

Fig. 2. Image of RMRS(Radioactive Material Reduction System) performance test facility

The experiment facility consists of three main parts: system (Air compressor, flow control valves and heater), aerosol generation and sampling and the test section including several thermal hydraulic instruments. The variables for the performance test were defined as temperature of the system. The area of the filtration in the Main-filter was about 1.737m^2. Using this experiment setup, several performance tests was conducted as outlined in Table I. The "Test No." indicates the specific conditions of each experiment. For example, NA-09-06-30 means that "NA" represents of main carrier gas, such as air with nitrogen; "09" indicates the number of filter element in the main-filter; and "06" specifies the flow velocity through the main-filter; and "30" denotes the target system temperature.

The temperature range of the test matrix was selected based on the expected operation conditions of the system, while the face velocity was determined by the maximum flow rate of the RMRS fan during normal operation.

In addition, the aerosol particles used for the test was solid, spherical particles with a physical diameter of 0.3μm. These particles were fully mixed with ethanol and injected into the test section via a two fluid nozzle, which included ethanol evaporation process.

Table I: Test Matrix for RMRS Performance Test

Test No.	Face Velocity	System Temp.
NA-09-06-30_0	0.06m/s	30℃
NA-09-06-30-A	0.06m/s	30℃
NA-09-06-50-A1	0.06m/s	50℃
NA-09-06-70-A	0.06m/s	70℃
NA-09-06-90-A	0.06m/s	90℃

2.2 Test Results

The test results of the performance evaluation of the system are presented in Table II. In this table, two tests conducted under identical conditions were performed to verify the appropriateness of the test procedure and the consistency of the results.

Table II: Test Results for RMRS Performance Test

Test No.	Inlet Temp. [℃]	Face Velocity [m/s]	Efficiency [%]
NA-09-6-30_0	33.11	0.047	99.962
NA-09-6-30-A	30.78	0.044	99.954
NA-09-6-50-A1	53.60	0.045	99.820
NA-09-6-70-A	73.98	0.051	99.235
NA-09-6-90-A	90.45	0.055	99.977

As shown in Table II, the face velocity across all cases were measured at around 0.05m/s. According to the test matrix, the face velocity of the filter was set at 0.06 m/s. However, the face velocity measured during the experiment averaged 0.05m/s which represents the average of the real-time measurements of face velocity taken during the whole experiment period. The differences in the face velocity over time is due to the increase in pressure drop caused by aerosols filtering through the filter. The system temperature, represented by the inlet of the test section, varied from 30℃ to 90℃. These results show the influence of system temperature on filtration efficiency.

The results show that the variation in filtration efficiency was approximately 0.7% over the temperature range of 30.78℃ to 90.45℃. This indicates that the system can maintain a filtration efficiency of at least 99% despite temperature fluctuations.

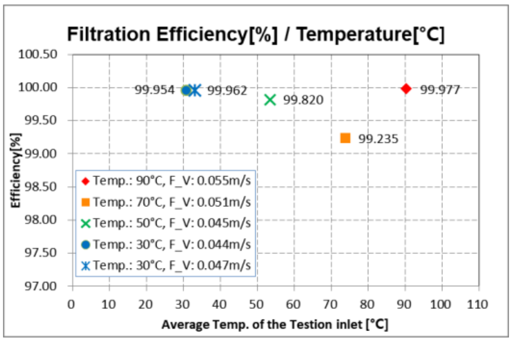

Fig. 3. Test results for RMRS(Radioactive Material Reduction System) performance in terms of system temperature variation

Several filtration mechanisms are influenced by temperature changes, including thermophoresis, steam condensation, and diffusional deposition (Brownian diffusion). Therefore, it is expected that an increase in system temperature can enhance particle movement, potentially leading to higher filtration efficiency.[6-8]

Overall, the experimental results showed that higher filtration efficiencies were observed under high-temperature conditions compared to low-temperature conditions when comparing the 30℃ and 90℃ environments. However, based on the overall data, consistent trends that clearly support this observation were not obtained. This may be due to the multi-stage filtration process of the system, which makes it difficult to isolate and verify the effects of a single filtration mechanism. Additionally, the observed variations are likely related to the effects of reusing the system through cleaning procedures performed between multiple experiments.

3. Conclusions

In this study, the aerosol filtration efficiency of a Radioactive Material Reduction System (RMRS) utilizing metal fiber filters was evaluated. The results confirmed that the RMRS maintains a filtration efficiency of over 99% across a system temperature range of 30.78℃ to 90.45℃. However, a clear correlation between temperature and filtration efficiency was not consistently observed, likely due to the system's multi-stage filtration process and the effects of system reuse. In the near future, RMRS performance tests will focus on evaluating its spatial impact and assessing system differential pressure during operation and clogging, to enhance the system's reliability and practical applicability.

ACKNOWLOGEMENT

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government(MOTIE) (No.RS-2023-00257695

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