Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 12-13, 2016

Optimal Performance Simulation of a Metal Fiber Filter for Capturing Radioactive Aerosols

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1. Introduction

Conventional HEPA filter that used in nuclear power plant has pleated media for low pressure drop. Consequently, the filters must provide high collection efficiency as well as low pressure drop. Fig. 1 shows schematic diagram of conventional HEPA Filter at nuclear power plant. Unfortunately, conventional HEPA filters are made of glass fiber and polyester, and pose disposal issues since they cannot be recycled. In fact, 31,055 HEPA filters used in nuclear facilities in the U.S are annually disposed [1]. In addition to tremendous cost needed to deal with the waste, HEPA filters also have low heat resistance and pressure resistance compared to metal fiber filters.

There is a strong need to study and develop metal fiber filters that can be reused and meet the performance standards of current glass fiber HEPA filters while withstanding the harsh conditions posed by nuclear facilities. In this study, the metal fiber filter used for removing radioactive aerosol is systematically dissected and studied in order to figure out the optimal design which can be applied to the actual operation conditions in nuclear heating, ventilation and air conditioning (HVAC) systems for particle collection.

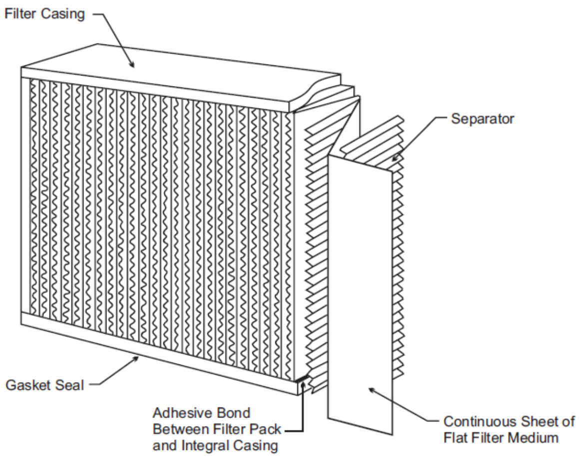


Fig. 1. General design of a Conventional Pleated HEPA Filter at Nuclear Power Plant Air Cleaning Unit

2. Methods and Results

2.1 Modeling Procedure

A modeling flow that predict metal fiber filter performance consisting of four primary parts which include inputting basic conditions, calculating important non-dimensional variables, computing different single fiber collection efficiencies and calculating the total collection efficiency.

The first step in modeling procedure is to decide on the input variables by carefully considering the particle conditions, filter conditions and flow conditions. Next, secondary factors are derived based on the assumptions made and using the input variables from the previous step. From these secondary factors, single fiber collection efficiency can be computed. Lastly, using the calculated single fiber collection efficiency and all the initial inputs, the total collection efficiency can finally be estimated. Although standard temperature and pressure are typically used to calculate the efficiency of particle collection filters, actual temperature and pressure normally observed in nuclear power plants are used to calculate physical properties such as viscosity and mean free path for simulation inputs.

Fig. 2 shows the aerosol collection mechanism of single fiber filter. An aerosol collection model that can predict collection efficiency of single fiber filter is constructed by considering a combination of particle deposition mechanisms. The five basic mechanisms are interception, inertial impaction, diffusion, gravitational settling, and electrostatic attraction.

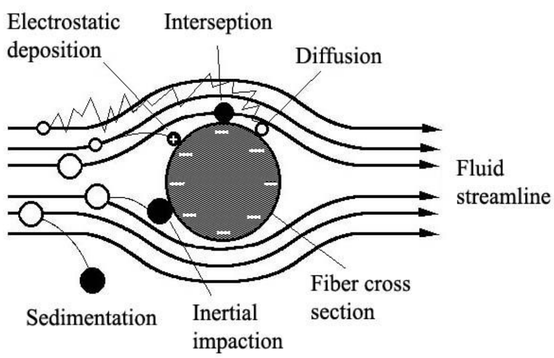


Fig. 2. Aerosol Collection Mechanism of a Single Fiber Filter

The general equation used for calculating the total collection efficiency (η_{total}) of a filter is given by Equation 1, where η_s is the collection efficiency of the single fiber, ε is porosity, L is filter thickness (mm), D_f is filter fiber diameter (μm), and β is a heterogeneous constant. The single fiber collection efficiency (η_s) equals the sum of single fiber interception efficiency

(η_{int}), single fiber impaction efficiency (η_{imp}), single fiber sedimentation efficiency (η_{sed}) and single fiber diffusion efficiency (η_{dif}) with assumption that each term acts independently and has a value of less than 1. η'_{dif} is an interaction term that accounts for enhanced collection due to interception of the diffusing particles [2].

$$\eta_{total} = 1 - \exp\left(-\frac{4 \cdot (1-\epsilon) \cdot L \cdot \eta_S}{\pi \cdot D_f \cdot \beta}\right) \quad \ldots\ldots (1)$$

$$\eta_s = \eta_{int} + \eta_{imp} + \eta_{sed} + \eta_{dif} + \eta'_{dif} \quad \ldots\ldots (2)$$

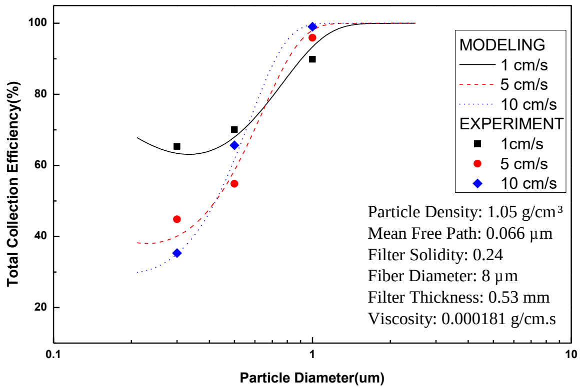
2.2 Experiment Procedure

A filter test system consists of five primary components that include an aerosol generation system; an aerosol concentration detector; an airflow rate measuring system; pressure gauges; and a test filter unit. The aerosol generation system consists of an atomizer, a diffusion dryer, and a particle charge neutralizer. The atomizer is used for generating polystyrene latex (PSL) aerosols and the generated aerosols pass through the diffusion dryer to remove moisture. The test aerosols then pass through a Kr-85 charge neutralizer to reduce the particle charge to the Boltzmann charge distribution. Test particles in the size range of 0.3 to 1.0 μm are used to evaluate the collection efficiency.

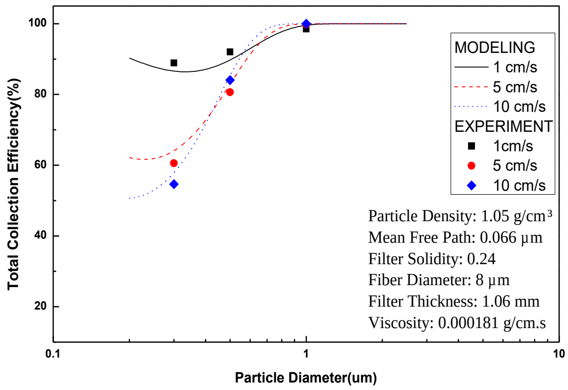
2.3 Results of Modeling and Experiment

Fig. 3 shows the further comparison between experimental and theoretical results investigating the effect of filter thickness and face velocity on the filter efficiency as a function of particle size. For the most part, the experimental result matched closely with the predicted values by simulation and the accuracy improved more as the filter thickness increases. The filtration efficiency of the metal fiber filter is found to be 98.6% for the 1.0 μm PSL test particles, and the pressure drop is 100.6 Pa for the face velocity of 10.0 cm/s with thickness 0.53 mm.

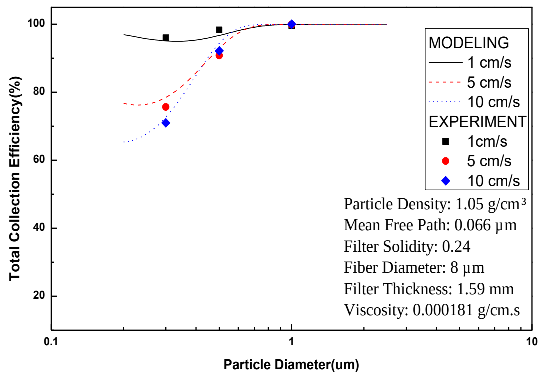
From the correlation analysis between the model and experiment, a good agreement with R^2 value of 0.999 is found at the face velocity of 5 cm/s indicating good reliability of the model. An R^2 is a statistic used in the theoretical models that main purpose is either the prediction of future outcomes or the testing of hypotheses. That is a statistical measure of how well regression line approximates the experiment data. An R^2 of determination ranges from 0 to 1. The coefficients of 1 mean that the regression graph absolutely fits the data.



(a) Filter Thickness: 0.53 mm



(b) Filter Thickness: 1.06 mm

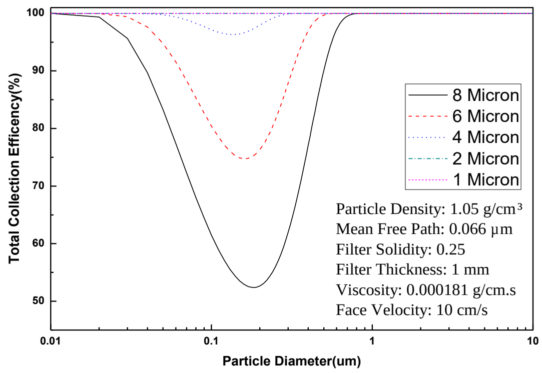


(c) Filter Thickness: 1.59 mm

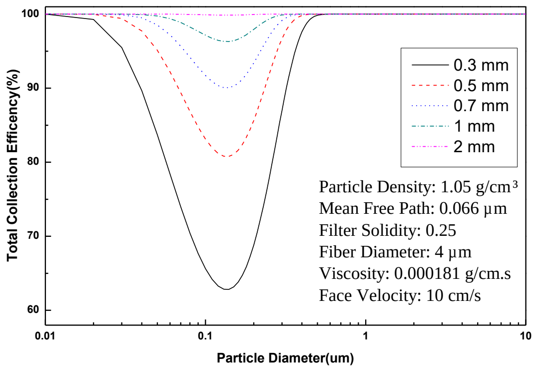
Fig. 3. Comparing Results of Efficiency between Theoretical and Experiment Values as Functions of Particle Diameter and Face Velocity

2.4 Results of Sensitivity Analysis

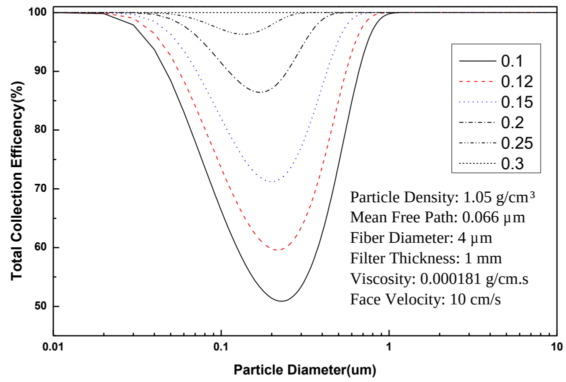
Fig. 4 shows the modeling results of particle collection efficiency for each design factor. Fig.4 (a) shows the modeling results on the effect of fiber diameter on total collection efficiency. As fiber diameter decreases, the total collection efficiency across all particle diameter increases. At the specified particle density, mean free path, solidity, thickness, viscosity and face velocity, the total collection efficiency was 53% at fiber diameter of 8 µm, 74% at 6um and 97% at 4 µm. At fiber diameter less than 2 µm, total collection efficiency is 100% over the entire particle diameter range. Modeling results with varying filter thickness is demonstrated on Fig.4 (b) which shows that thicker filter results in improved total collection efficiency with increasing thickness. For filter thickness above 2mm, total collection efficiency maintains near 100% across the specified particle diameter range. Fig.4 (c) shows that total collection efficiency improves with increasing solidity. In fact, at solidity higher than 0.3, total collection efficiency of 100% can be observed at all particle sizes. Lastly, Fig.4 (d) analyzes the effect of face velocity on collection efficiency and the analysis reveals that lower face velocity results in higher collection efficiency. At face velocity lower than 5 cm/s, collection efficiency stayed above 98% across all particle diameter range.



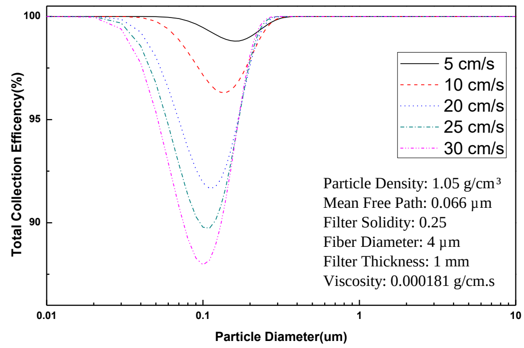
(a) Variable: Fiber Diameter (µm)



(b) Variable: Thickness (mm)



(c) Variable: Solidity



(d) Variable: Face velocity (cm/s)

Fig. 4. Modelling Results of Most Penetrating Particle Size as a Function of Face Velocity

2.5 Optimizing Result of Metal Fiber Filter

Fig. 5 shows the theoretical optimizing result of metal filter design. In order to meet the standards of HEPA filter qualifications, which require 99.97% collection efficiency at 0.3 µm particle size, the optimal conditions are given by metal fiber diameter less than 4 µm, filter thickness longer than 1 mm, solidity larger than 0.2, and face velocity lower than 5 cm/s, which is equal to those of the conventional HEPA filter.

Since metal fiber media with fiber diameter less than 2 µm is not commercially produced, and the face velocity used to test nuclear facility HEPA performance is at 5 cm/s in accordance with the standard established in ASME AG-1. Therefore, fiber diameter and face velocity were configured from practical condition.

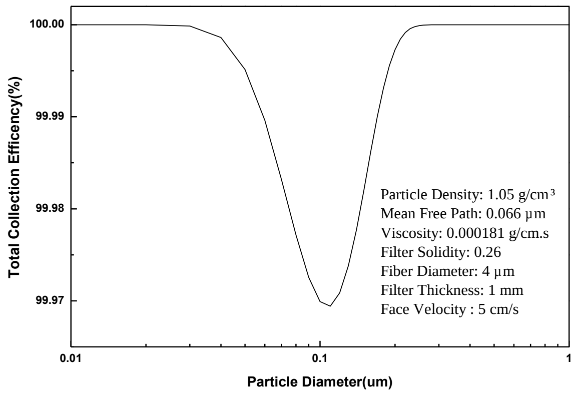


Fig. 5. Theoretical Results of Particle Collection Efficiency for Optimum Design Factor

3. Conclusions

A HEPA Filter that made glass fiber filter cannot be recycled and have low thermal and pressure resistances. Therefore, there is a strong need to develop HEPA filters using metal fiber. In this study, in order to derive the optimal design for metal fiber HEPA filter, a numerical model is developed and its results are compared to experimental data to test reliability. Moreover, sensitivity analysis is performed using important parameters to determine which parameters have large influence on the filter performance.

Using the model developed in this study, optimal design parameters for pleated metal fiber filters are derived which include fiber diameter less than 4 μm, solidity larger than 0.2, filter thickness larger than 1 mm, and face velocity lower than 5 cm/s. With these conditions, the metal filter qualified for the HEPA filter standard which specified 99.97% efficiency in the 0.3 μm particle size range.

REFERENCES

[1] Bergman W., Larsen G., Lopez R., Wilson K., Witherell C., and McGregor M. 1997. Further Development of the Cleanable Steel HEPA Filter, Cost/Benefit Analysis, and Comparison with Competing Technologies. DOE/NRC Nuclear Air Cleaning and Treatment Conference. 24st ed. 708-742.

[2] Rubow K.L. and Davis C.B. 1991. Particle penetration characteristics of porous metal filter media for high purity gas filtration. Proceeding of Institute of Environmental Science. pp. 834.