Preliminary Analytical Reviews on the Performance of Fibrous Filter

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1. Introduction

Following the Fukushima accident, the Containment Filtered Vent System (CFVS) has emerged as a severe accident alternative for ensuring the integrity of containment. Though various types of CFVS exist at Nuclear Power Plants (NPPs), such as sand-bed type, dry filter type, wet type, and so forth, the type we are focusing on now is the wet type CFVS. The wet type CFVS is composed of a tank including nozzles in a liquid pool, moisture separators, and a few dry filters such as a metal fiber filter and a molecular sieve. After injecting gases from the containment into the CFVS under severe accident conditions, the CFVS will release decontaminated radioactive materials to the environment. To protect against the release of uncontrolled fission products to the environment, we need to confirm the performance of the CFVS in terms of not only the integral capability but also the capabilities of the individual components. Therefore, preliminary analytical evaluation of the metal fiber filter, one of the main components of the CFVS, was performed in this study.

2. Methodology and Results

Generally, the performance of a filter is expressed according to the pressure drop and the collection efficiency. So, methods of analytically predicting the pressure drop and collection efficiency for a filter were reviewed. Based on these reviews, cases were calculated.

2.1 Pressure drop of filters [1]

There are many ways to perform the calculation of the pressure drop across clean fibrous filters. Most expressions are based on Darcy's law, as follows

$$\Delta P = \mu V_0 L_f F \qquad (1)$$

where μ : Gas dynamic viscosity, [Pa.s]
V_0: Filtration velocity, [m/s]
F : Drag coefficient, dimensionless
L_f: Length of all fibers per unit filter area, [m^{-1}]

The total length of the fiber is expressed by

$$L_f = \frac{4CZ}{\pi d_f^2} \qquad (2)$$

where C : packing density, dimensionless
Z : Filter thickness, [m]
d_f : Mean equivalent fiber diameter, [m].

The pressure drop of a single fiber filter is obtained from Equations (1) and (2) as

$$\Delta P = F\frac{4\mu C V_0 Z}{\pi d_f^2} \qquad (3)$$

where F is a drag coefficient

$$F = 16\pi C^{1/2}(1 + 56C^3)\ ,\ 0.006<C<0.3$$

2.2 Particle collection efficiency

Predominant removal mechanisms for aerosols in metal fiber filters are assumed to be Brownian diffusion, interception, and inertial impaction. The collection efficiencies due to diffusion, interception, and impaction are described as follows [2, 3]:

The collection efficiency due to Brownian diffusion (E_D),

$$E_D = 2.6\left(\frac{1-C}{Ku}\right)^{1/3} Pe^{-2/3} \qquad (4)$$

where Pe : Peclet number ($\frac{d_f U}{D_{diff}}$)
U : Filtration velocity, [m/s]
D_{diff} : Diffusion coefficient of aerosol particles ($\frac{k_B T C_c}{3\pi\eta d_p}$)
k_B : Boltzmann constant
T : Temperature [K]
η : Viscosity [Pa.s]
C_c : Cunningham correction factor
$\left(1 + 2.493\frac{\lambda}{d_p} + 0.84\frac{\lambda}{d_p}\exp(-0.435\frac{d_p}{\lambda})\right)$
λ : Mean free path [m]
Ku : Kuwabara hydrodynamic factor
$(-0.5\ln C - 0.75 + C - 0.25C^2)$
d_p : Particle diameter [m]

The collection efficiency due to interception (E_R),

$$E_R = \frac{(1-C)R^2}{Ku(1+R)} \qquad (5)$$

where R : Interception parameter (d_p/d_f)

The collection efficiency due to inertial impaction (E_{Imp}),

$$E_{Imp} = \frac{(Stk)J}{2Ku^2} \qquad (6)$$

where Stk : Stokes number ($\frac{\rho_p d_p^2 C_c U}{18\eta d_f}$)
ρ_p : Particle density [kg/m^3]
$J = (29.6 - 28C^{0.62})R^2 - 27.5R^{2.8}$

2.3 Results for the performance of a single filter

Based on Equations (1) through (6), analytical calculations were performed for both the pressure drop and the collection efficiency.

2.3.1 Calculations of pressure drop for a single filter

Fig.1 shows the pressure drop versus the fibrous filter diameter with changes of the packing density, temperature, and pressure. Pressure drop is found to decrease with increasing filter diameters and decreasing packing densities, as expected. According to Equation (3), the difference of the pressure drops for both the standard condition (293 K, 101 kPa) and the severe condition (473 K, 1000 kPa) is due only to differences of the viscosity for each condition.

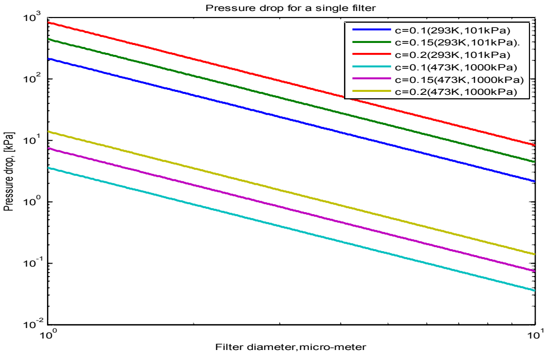

Fig. 1. Filter pressure drop versus filter diameter for packing densities of 0.1, 0.15, 0.2 (d_f : 1~10 µm)

2.3.2 Comparison of single collection efficiency due to diffusion, interception, and impaction

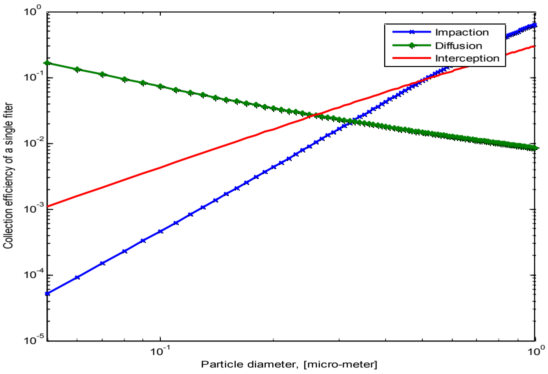

Fig. 2. Comparison of collection efficiencies for diffusion, interception and diffusion (d_p : 0.05~1.0 µm)

The collection efficiencies due to inertial impaction and interception become dominant with increasing particle size, while the collection efficiency due to Brownian diffusion is dominant over the region of small size of particles (less than 0.1~0.2 µm), as can be seen in Fig. 2, as expected. However, all equations applied in this study were valid for the standard condition (293 K, 101 kPa), 0.005< C <0.2 and for the Stokes region.

3. Conclusions

To estimate the performance of a metal fiber filter in the wet type CFVS, preliminary evaluation was carried out for a fibrous filter. If the molecular sieves are not included, the metal fiber filter is the final filtering barrier for aerosols in the CFVS. Therefore, it is crucial to confirm the performance of the metal fiber filter in both analytical and experimental ways.

Pressure drop across a filter and collection efficiency are ways to explain the performance of a fibrous filter. Based on data from the literature survey, pressure drop and collection efficiency for a single filter were calculated. The trends of pressure drop and collection efficiencies due to various deposition mechanisms of particles onto the fiber of the filters were roughly confirmed. But, all previous studies are valid only for standard conditions, while fine aerosol particles (less than 1~2 µm) go into the metal fiber filter in the CFVS under severe conditions. Therefore, to obtain better quantitative predictions of the performance of the metal fiber filter, a new model able to evaluate the performance of fibrous filters under severe conditions should be developed.

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REFERENCES

[1] D. Thomas, P.Contal, V.Renaudin, P.Penicot, D.Leclerc and J. Vendel, Modelling Pressure Drop in HEPA Filters During Dynamic Filtration, J. Aerosol Sci. Vol.30, pp235-246, 1998

[2] C.B. Song, H.S. Park, Analytic solutions for filtration of polydisperse aerosol in fibrous filter, Power Technol., 170, pp.64-70, 2006

[3] Hinds, Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, John Wiley & Sons, Inc., 1999