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Performance of Various Filtering Technologies for Effluent Treatment under Severe Accident

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1. Introduction

Prevention of nuclear power plant's severe accident is one of the most important systematic role during its operation, because severe accident assumes the relatively higher possibility of radioactive material release than any other accident cases such as anticipated operational occurrences, design basis accidents, design extension condition accidents [1]. To mitigate the impact of severe accident, Containment Filtered Venting System (CFVS) was suggested to prevent containment building failure. Traditional design of CFVS is combination of pool scrubber and HEPA filter, however, it assumed volumetric flowrate is steady and low. Still there are different types of severe accidents such as Interfacing System Loss Of Coolant Accident (ISLOCA) or Steam Generator Tube Rupture (SGTR). ISLOCA and SGTR are representative bypass severe accidents of nuclear power reactor, they have relatively small possibility to be occurred, but contain much negative impacts. Fluid flowrate, particle type, particle diameter range are different according to the accident scenario, so proper type of filtration system should be suggested. Especially immediate high volumetric flowrate accident case, HEPA filter and pool scrubber can't be allowed because of their stability problem. To suggest proper filtration system according to the type of accident conditions, assessment methodology of filtration performance is required. This paper assessed theoretical performances of three different types of particle filters to mitigate radioactive material release to environment under severe accident; Cyclone separator, High Efficiency Particulate Air (HEPA) filter, and pool scrubber are considered because operation of these three filters is available without any external electrical supports. However, there is limitation of amount of flowrate through the filters because of their stability problem. This paper assumed flowrate of fluid that penetrates the filters is controlled by passive flowrate controller located between release section and filtration system. There are series of explanations of performances and characteristics of filters and overall Decontamination Factors (DFs) of each filter. DFs are calculated with reasonable temperature conditions, particle types, particle ranges, and fluid flow rates.

2. Filters

To mitigate nuclear power reactor's severe accident, this paper suggests three types of filters. In order to operate filtration system without any external electrical support, pool scrubber, HEPA filter, and cyclone separator could be considered as options for the mitigation syste. Herranz, L. E., et al assessed theoretical performance of pool scrubber under several severe accident scenarios by comparing two pool scrubbing codes [2]; BUSCA and SPARC. This paper assesses pool scrubber's performance with BUSCA code since BUSCA shows more conservative results than SPARC. HEPA filter is a specialized filter for capturing micro-scale particles, but it has a stability problem caused by pressure drop. Broadly, industrial facilities use cyclone separator to capture micro-scale particles made by their operations. Cyclone separator is cheap, and it has very simple design. This chapter will discuss about theoretical models of these three filtration systems.

2.1. Pool Scrubber

Five different aerosol deposition principles are assumed, and DF is calculated like (1-1) and (1-2).

$$DF = e^{\kappa_T t} \tag{1-1}$$

$$\kappa_T = \frac{1}{V}\sum_i \int v_i dA \tag{1-2}$$

t is bubble's exposure time in the pool, V is a volume of bubble, and v_i is deposition velocity. There are five deposition velocities in BUSCA; diffusiophoretic velocity, centrifugal impaction velocity, thermophoretic velocity, sedimentation velocity, Brownian diffusion velocity. Each deposition velocity terms are in terms of inlet velocity, gas temperature, pool temperature, ratio of gas components in bubble, depth of the pool. DF according to particle size is plotted at Fig. 1, boundary conditions are based on general severe accident case [1]. At small particle size region (< 0.1 ㎛), Brownian diffusion governs the filtering process. On the other hand, sedimentation and centrifugal impaction governs the filtering process at large particle size region (> 1 ㎛). However, there is no governing filtering principle between 0.1 ㎛ and 1 ㎛. Pool scrubber is not proper to be used under very high volumetric flowrate accident condition since scrubber can be damaged by fast turbulent flow. Boundary conditions used for calculation are at Table. I, and same conditions are applied at Filtration Performance Assessment part.

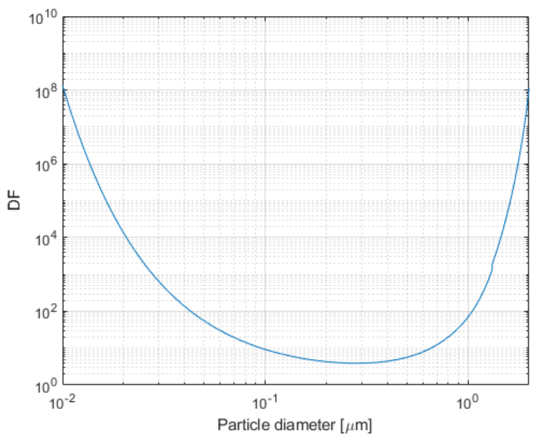

Fig. 1. DF according to particle diameter

Table. I: Conditions of DF calculation

Steam fraction	0.95
Gas flow rate	10 g/s
Pool depth	5 m
Gas temperature	500 K
Pool temperature	300 K

2.2. HEPA Filter

HEPA filter has very high efficiency with wide range, but fabrics in HEPA filter may disturb the flow of fluid streamlines if too much particles are stacked inside the filter. The solution of this problem is replacing old HEPA filter by a new one periodically. If particles are stacked between the fabrics too much, then pressure drop drastically made. High mass flowrate also can make large pressure drop as well. Then pressure drop can damage HEPA filter and loss its filtration ability because of physical failure of HEPA filter. HEPA filter's theoretical models are based on the model of Payet, S., et al and Da Roza, R. A. [5, 6].

$$E = 1 - exp\left[\frac{-4\eta\alpha L}{\pi D_f(1-\alpha)}\right] \quad (3)$$

where
E = the overall efficiency of filter
η = single fiber efficiency
α = solidity
L = thickness of filter
D_f = fiber diameter

HEPA filter's filtration efficiency should satisfy the standards of United State (US). Following Table. II shows the properties of general HEPA filter to satisfy the US standards. Fig. 2 is a graph of HEPA filter's efficiency according to particle diameter. Results of HEPA filter's filtration efficiency show that filtration efficiency is very high at overall particle diameter range. Fluid conditions are same with pool scrubber part.

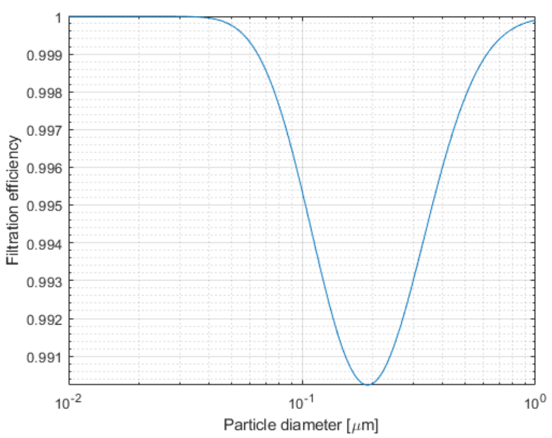

Fig. 2. HEPA filter's efficiency according to particle diameter

HEPA filter is very useful if mass flowrate and amount of radioactive particles are small. Else it needs external flowrate controller or extra filters that can capture lot of particles.

Table. II: HEPA filter properties

Filter size	610 mm × 610 mm
Filter thickness	0.3 mm
Fiber diameter	1.5 μm
Solidity	0.03

Filtration Performance Assessment part applied same conditions listed in Table. II.

3.3 Cyclone Separator

Cyclone separator's theoretical model of overall efficiency depends on its dimension and inlet velocity (4). Fig.4 is typical cyclone separator used in industrial facilities. Several dimension conditions of cyclone separator influence its overall efficiency [7].

$$\eta_t = 1/(1 + (D_{pc}/D_{pm})) \quad (4)$$

where

η_t = Overall efficiency
D_{pc} = $[9\mu b_1/2\pi N_e V_c(\rho_p - \rho)]^{0.5}$
D_{pm} = Weight mean diameter
b_1 = Cyclone inlet width
N_e = Effective number of spirals
V_c = Inlet velocity
ρ_p = Particle density
ρ = Gas density

Separation efficiency according to particle diameter is calculated based on equation (4) with $b_1 = 90mm$. Fig. 3 shows the separation efficiency according to particle diameter. The biggest advantage of cyclone separator is that there is no limitation of amount of capturing aerosols if the volume of hopper outlet is enough. Including HEPA filter and pool scrubber, many of other filters show weak filtration efficiency when volumetric flow rate is high. However, only cyclone separator shows good filtration performance at high volumetric flow region. Because the principle of cyclone separator is particle's centrifugal force, it means particles following streamlines of fluid can have higher possibility to meet the cyclone separator's surface easily as they have higher velocity.

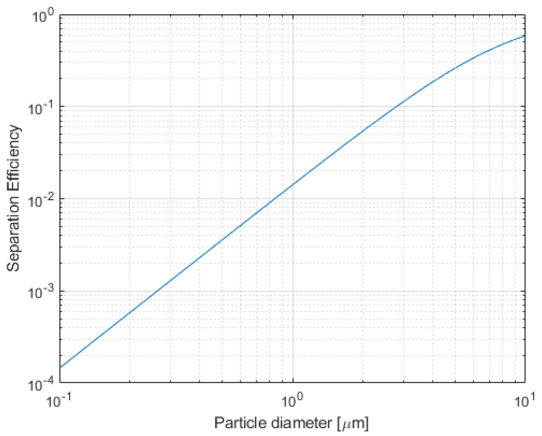

Fig. 3. Cyclone separator's separation efficiency according to particle diameter

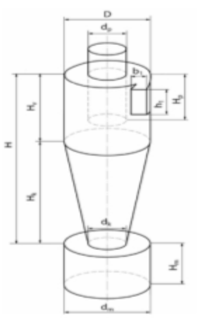

Fig. 4. Cyclone separator model [8]

Based on the filtration principle of cyclone separator, the mass of particle can be critical to the cyclone efficiency. Because resistance from fluid viscosity respectively more disturbs the movements of particles toward cyclone surface when the mass of particle becomes smaller. Consequently, cyclone separator should aim relatively large particles in order to get higher separation efficiency. Filtration Performance Assessment part applied same conditions described in this part.

4. Filtration Performance Assessment

In State-of-the-Art Reactor Consequence Analyses (SOARCA) report, there are deposition velocity results in terms of particles in certain diameter range. SOARCA evaluated source term for each of possible accident scenarios with MELCOR plot file. Table. III contains the median diameter of possible particle diameter ranges listed in SOARCA report. In addition, Table. III displays the DF according to particle types and filter types with each filter's proper mass flow rate.

Table. III -1: DF of cyclone separator when mass flowrate equals to 100 g/s

Median Diameter (μm)	**CsI**	**CsOH**	**MoO_2**
0.15	1.0004	1.0003	1.0006
0.29	1.0027	1.0022	1.0039
0.99	1.0324	1.0265	1.0465
1.8	1.1104	1.0903	1.1576
3.4	1.3810	1.3124	1.5411
6.4	2.2919	2.0608	2.8337
11.9	5.3457	4.5602	7.1970
22.1	15.780	13.079	22.155
41.2	53.796	44.105	76.681

Table. III-2: DF of HEPA filter when mass flowrate equals to 10 g/s

Median Diameter (μm)	Decontamination Factor
0.15	3.9501e+03
0.29	7.8652e+02
0.99	1.6690e+04
1.8	6.6875e+05
3.4	1.9635e+08
6.4	> 1e+15
11.9	> 1e+15
22.1	> 1e+15
41.2	> 1e+15

Table. III-3: DF of pool scrubber when mass flowrate equals to 25 g/s

Median Diameter (μm)	**CsI**	**CsOH**	**MoO_2**
0.15	5.9784e+01	5.5864e+01	7.0038e+01
0.29	1.6727e+01	1.4015e+01	2.6357e+01
0.99	5.8751e+04	2.2138e+04	5.3439e+05
1.8	1.0705e+05	4.0052e+04	9.8340e+05
3.4	1.9880e+05	7.5071e+04	1.8371e+06
6.4	> 1e+15	> 1e+15	> 1e+15
11.9	> 1e+50	> 1e+50	> 1e+50
22.1	> 1e+100	> 1e+100	> 1e+100
41.2	> 1e+100	> 1e+100	> 1e+100

Fig. 5 shows the filtration performances according to their flowrates according to particle's median diameter. Fig. 5 shows conservatively approached filtration efficiency data of CsOH since CsOH has the lowest DF value among CsI, CsOH, and
MoO_2 because of its material characteristics.

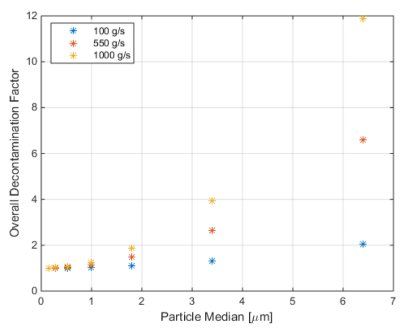

Figure. 5-1. DF of cyclone separator for different flowrates

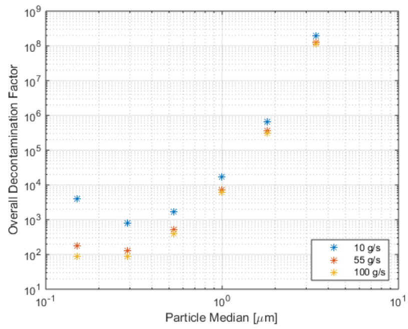

Figure. 5-2. DF of HEPA filter for different flowrates

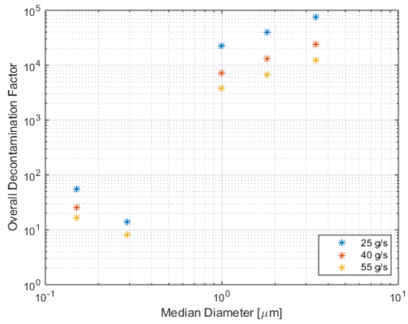

Figure. 5-3. DF of Pool scrubber for different flowrates

5. Application under SGTR

Steam Generator Tube Rupture (SGTR) accident case, it has small fluid flowrate when radioactive particle starts to be released through Main Safety Valve (~ 200 g/s). According to the aerosol study of SGTR by Auvinen. A., et al, possible released particle diameter range is from 0.49 to 0.84μm after particles pass through the steam generator tubes. Particle distribution can be assumed to follow lognormal distribution, so DF can be calculated. Table. IV shows Decontamination Factors of SGTR according to filter types when fluid mass flow rate equals to 200 g/s.

Table. IV: DF of SGTR according to different types of filters

Filter type	Decontamination Factor
Cyclone separator	1.0065
HEPA filter	1.9031×10^3
Pool scrubber	9.9398

6. Conclusion

Pool scrubber, HEPA filter, and cyclone separator are considered for the options of mitigation system for severe accident scenario, since they can be operated without any electrical support. Cyclone separator has good DF value when mass flowrate and particle diameter value are large enough. Although cyclone separator doesn't have limitation of amount of capturing aerosols, it can't be used by itself due to its poor filtration efficiency at low particle diameter range. That is the reason why cyclone separator is excluded to be considered as a filter to mitigate severe accident. However, in case of valve failure accident or valve stuck open scenario, large flowrate will be predicted, and Fig. 5-1 shows that cyclone separator may be very useful in high mass flowrate conditions. Another case, HEPA filter generally has the large DF for wide particle diameter range, but it can't be used for entire accident period by only itself because pressure drop can be built up if aerosols are stacked on HEPA filter's surface too much. Pool scrubber also theoretically doesn't have limitation of amount of capturing aerosols, but it has relatively small DF at the certain particle diameter range (0.3 ~ 0.6 μm). Pool scrubber also should keep its mass flowrate being low enough to avoid failure of system, because fluid flow can be turned to very fast turbulent flow after passing through orifice because of the small diameter of orifice (~ 2 cm). If mass flowrate through the pool scrubber is not controlled properly, then exposure time of bubble in the pool can be very short, and it can induce small DF. Consequently, instead of single type filter, two series connected type filter can be considered. The role of filter which series connected is capturing large amount of aerosols and second filter's role is capturing comparative small amount of aerosol with very high filtration efficiency. Based on the DF results, two series connected type filters can be proposed; Cyclone separator – HPEA filter and pool scrubber – HEPA filter. If mass flowrate which contains radioactive particles is high enough and particle diameter range is large (> 10 μm), then former series connected type can be used. Another case, if mass flowrate is low (~ 100 g/s) then later series connected type filter can be used.

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