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Removal of Aerosol Through Fibrous Filter as a Function of Particle Size and Velocity

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입자의 크기와 유속에 따른 섬유질 여과포에 의한 부유입자 제거 연구

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Abstract

Filtration efficiency tests were conducted on a fiberglass mat filter with DOP aerosol having a diameter from 0.1μm to 0.45μm in the face velocity range of 1cm/sec to 10cm/sec. Filtration of submicron particles by a fibrous filter is characterized by a face velocity. The size of DOP aerosol which has a minimum removal efficiency decreases with increasing the velocity. A numerical solution of the diffusion equation is obtained for a fiberglass mat filter by using "Kuwabara's cell model" for the flow field and Von Mises Transformation for the actual flow around a fiberglass. The present theoretical results agree quite well with the experimentals for fiberglass mat. This result could be contributed to predict the removal efficiency on an air filter and to optimize the operating condition of an air purification system with a filter.

요 약

유리섬유 여과포에 의한 0.1～0.45μm 크기의 DOP 부유입자의 제거효율시험을 1～10cm/sec의 유속범위에서 수행하였다. 섬유여과포에 의한 미세입자의 여과는 여과속도에 의하여 결정되는데, 최소제거 효율을 나타내는 DOP 입자의 크기는 여과속도가 증가함에 따라 감소한다. Kuwabara Cell Model과 Von Mises Transformation을 사용하여 유리섬유 여과포내에서 확산에 의한 입자 제거효율을 수치해석적으로 전개하여 구하였으며, 이 계산치는 실험치와 잘 일치하였다.

본 실험의 결과는 여과포의 입자제거효율을 예측하고 최적 운전조건을 추구하는데 기여할 수 있을 것이다.

1. Introduction

The medium of HEPA(High Efficiency Particulate Air) filter, which is of use to remove radioactive airborne particles at a nuclear industy, consists of glass fibers of submicron diameter.(1,2)

A filtration mechanism of particles by a fibrous filter has been subjected to numerous studies. Many investigators have predicted an aerosol size for minimum efficiency through fibrous filters. These predictions are generally based on theoetical single fiber filtration mechanism of diffusion, interception and inertial impaction, usually ignoring electrostatic charge and gravitational effects. The particle size of minimum filtration is generally known to occur in the vicinity of $0.3\mu m$ aerosol at relatively low filtration velocity.(1,3) A size for minimum efficiency is important since certain air cleaning systems are required to remove submicron particulates. Davies et al. suggested that the predominant filtration mechanism depends on the particle size, filtration velocity and filter fiber size.(3,4)

As all filter are composed of individual fibers, an understanding of the mechanisms,which the particles are collected on fibers, and the flow pattern around them is of fundamental importance.

This report presents the development of a numerical procedure to predict the diffusion efficiency of a single fiber at low velocities and the comparision of the theoretical values with the experimental.

2. Theoretical Considerations

Since real filter structure is more or less irregular and non uniform, it requires the use of a filter model which is amenable to mathematical analysis to obtain the solution of the flow field. The following assumptions could be required to get the solution in a filter model: (1) that a particle which collides with the fiber remain in contact and is not separated following its initial collection by the fibers; (2) that the presence of particles in the gas stream and on the fibers does not change the flow pattern around the fibers; (3) that neither the particles nor the fibers are electrically charged, and gravitational effect is so small that the mechanism of gravity and electrical attraction can be neglected.

2.1. Flow Field

The solution of a filtration problem first requires the selection of a flow field. Theoretical fiber glass filter consists of irregular and non-uniform cylinders (Fig. 1) and the flow in the filter is viscous flow.(5,12) The flow of Lamb's isolated cylinder is only determined by Reynolds number, but the flow of Kuwabara's cell model is characterized by the distance between the axes of the neighboring cylinder(3); the flow for very small Reynolds number ($Re<Df/2b$) is determined by not Reynolds number but the volume fraction of fiber in the filter. The flow field solution of Kuwabara's cell model is more approximation than that of Lamb's isolated cylinder for very small Reynolds number.(5,6) The volume fraction is

$$\alpha=1-\varepsilon=(rf/b) \tag{1}$$

The following expressions are obtained from Kuwabara's cell solution using the stream function and the radial and tangential velocity.(5)

$$\psi=\frac{\sin\theta}{2K}\left\{\left(1-\frac{\alpha}{2}\right)\frac{1}{r}-(1-\alpha)r+2r\ln r-\frac{\alpha}{2}r^3\right\}u_0 \tag{2}$$

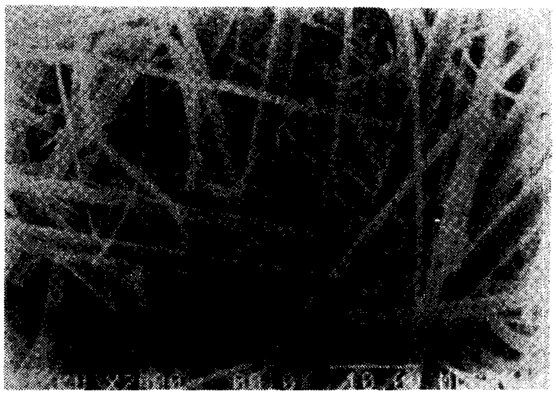


Fig. 1. Electron Micrograph of Glass Fiber

Where $K=-\frac{1}{2}\ln\alpha-\frac{3}{4}+\alpha-\frac{\alpha^2}{4}$

$$ur=\frac{1}{r}\frac{\partial\phi}{\partial\theta} \quad (3)$$

$$v\theta=-\frac{\partial\phi}{\partial r} \quad (4)$$

2.2. Single Fiber Efficiency

The single fiber efficiency represents that particles passing within $2Y$ of the distance of cell boundary are deposited on the single fiber as shown in Fig.2. (8) The single fiber efficiency and the overall efficiency of the filter mat are related to the following equation. (4,7,9)

$$E=1-P \quad (5)$$

where $P=\frac{\text{Down-stream aerosol concentration}}{\text{Up-stream aerosol concentration}}$

$$E=1-\exp\left[\frac{-4\eta L\alpha}{\pi Df(1-\alpha)}\right] \quad (6)$$

2.3. Single Fiber Efficiency by Diffusion.

Particles smaller than about 1μm in diameter are suspended in gases. The particle irregularly moves in the flow by the Brownian motion—the thermal motion of the molecules in the air effects on particles. The single fiber efficiency by diffusion means that the fiber deposits particles from the flow by the deviation and the possibility of the Brownian motion of the particles. An attractive forces on the surfaces are strong enough to capture the particles. (4,6)

Under a small volume of fluid in the vicinity of the cylindrical fiber, the material balance on the aerosol can be obtained as the following equation. (6,12)

$$\frac{\partial n}{\partial t}=-\mathrm{div}(-D\,\mathrm{grad}\,n)-\mathrm{div}\,v_0 n$$
$$-\mathrm{div}(u_0-v_0)n \quad (7)$$

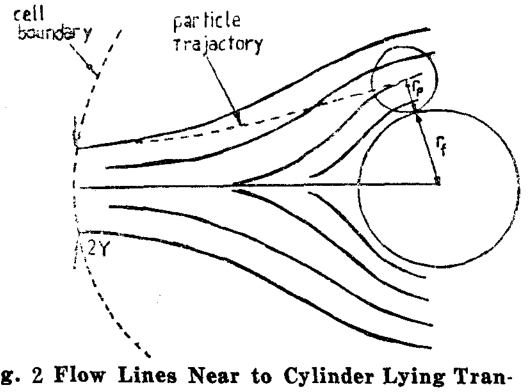


Fig. 2 Flow Lines Near to Cylinder Lying Transvers to Flow

From the Stokes-Einstein relations, the diffusion coefficient of particles can be estimated as the following equation. (13)

$$D=kT/f \quad (8)$$

From the Eq. (8), the coefficient of frictional resistance can be calculated as the following equation.

$$f=3\pi\mu Dp/C \quad (9)$$

where C is defined by the following equation.

$$C=1+\frac{\lambda}{rp}[1.257+0.4\exp(-1.10rp/\lambda)] \quad (10)$$

For air at 20°C and atmospheric pressure, the mean free path of the gas molecular is

$$\lambda=6.53\times10^{-6}\text{cm} \quad (11)$$

Also, Chandrasekhar suggests that the Brownian diffusion equation could be indicated as the following equations. (14)

$$\frac{dn}{dt}=D\nabla^2 n \quad (12)$$

Rewritting Eq. (12) in cylindrical coordinate, it can be expressed as the folowing.

$$\frac{\partial n}{\partial n}+v\theta\frac{1}{r}\frac{\partial n}{\partial\theta}+ur\frac{\partial n}{\partial r}$$
$$=D\left[\frac{\partial^2 n}{\partial r^2}+\frac{\partial n}{r\partial r}+\frac{1\partial^2 n}{r^2\partial r^2}\right] \quad (13)$$

Because a concentration of the boundary layer at the 2nd and the 3rd term on right hand side of Eq. (13) is very lower than that of the 1st term, they can be neglected.

If a new set of dimensionless quantities is defined by the following:

$UR=ur/u_0$,

$V\Theta=v\theta/u_0$,

$R=r/rf$,

$N=n/n_0$,

$\tau=u_0t/rf$ and

$Pe=u_0Df/D$,

the Eq. (13) becomes

$$\frac{\partial N}{\partial \tau}+\frac{V\theta}{R}\frac{\partial N}{\partial \Theta}$$
$$+UR\frac{\partial N}{\partial R}=\frac{2}{Pe}\left[\frac{\partial^2 N}{\partial R^2}\right] \qquad (14)$$

The convective diffusion Eq. (14) can be solved numerically if the following boundary conditions are used.(15)

$$N=1 \text{ at } R\geqq\infty,$$
$$N=0 \text{ at } R=1+RP \text{ and}$$
$$N=1 \text{ at } R=1+RP,\ \theta=0 \qquad (15)$$

A general solution has been obtained to Eq. (14) with the above boundary conditions.

In order to apply to streamline type passing around a single fiber, Eq. (14) is converted to (ψ,θ) coordinate using von Mises transformation.(16) Then the Eq. (14) becomes

$$\frac{\partial N}{\partial \tau}+\frac{V\theta}{R}\ \frac{\partial N}{\partial \theta}=\frac{V\theta^2 UO^2\left[\frac{2}{Pe}\frac{\partial N}{\partial \psi}\right]}{\partial \psi} \qquad (16)$$

The particles diffuse to the cylinder from a thin layer adjacent to its surface. That is, the thickness of the diffusion boundary must be small, compared to the distance between the axes of the neighboring cylinder (i.e. $r_f+\delta<b-r_f$). There is no change in the particle concentions out of the diffusion layer.

The particle deposition rate per unit length of cylinder is

$$J=2D(rp+rf)\int_0^{\pi}\left(\frac{\partial n}{\partial r}\right)_{r=rf+rf}d\theta \qquad (17)$$

The single fiber efficiency by diffusion is

$$\eta_D=\frac{J}{n_0u_0Df} \qquad (18)$$

Eq. (18) can be converted to a dimensionless diffusion equation as the following:

$$\eta_D=\frac{2(1+\mathrm{RP})}{Pe}\int_0^{\pi}\left(\frac{\partial N}{\partial R}\right)_{R=1+RP}d\theta \qquad (19)$$

After N is determined, Eq. (19) can be solved. Eq. (19) has been solved by a finite difference method on a CDC-74 computer using a network grid with the coordinate ψ divided into 30 equal parts and the interval $(0,\pi)$ for the θ coordinate divided into 30 equal parts. The computational procedure is shown in Fig. 3. The computed η_D with the velocity and the particle size is shown in table 1.

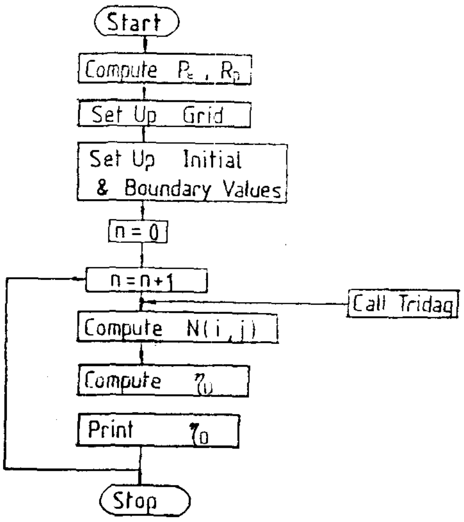


Fig. 3 Flowchart for Calculation of Diffusion Efficiency on Glass Fiber

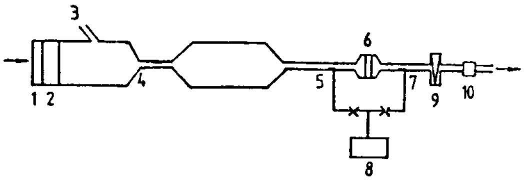
Table 1. Single Fiber Efficiency by Diffusion

dp \ u_0	1.0	4.0	10.0
0.1	0.19	0.075	0.040
0.2	0.11	0.035	0.019
0.25	0.09	0.030	0.016
0.3	0.072	0.025	0.014
0.4	0.053	0.023	0.012
0.45	0.05	0.020	0.010

3. Experimentals

A schematic digram of the experimental system is shown in Fig. 4. The experiments were carried out with filter volume fraction of $\alpha=0.05$, filter thickness of $L=0.11$cm, fiber diameter of $Df=2.2\mu$m (number average value). A fiber size was measured with a electroscope (Fig. 1).

The flow rate ranged from 1 to 10cm/sec. DOP (dioctyl phthalate) aerosal from 0.1 to 0.45μm was generated by the Thermal Generator (F-1000-DG,) as shown in Fig. 4. The



1. Pre-Filter
2. HEPA-Filter
3. Aerosol-Generator
4. Mixing Baffle
5. Upstream Sample
6. Filter Holder
7. Downstream Sample
8. Particle Counter
9. Rotameter
10. Vacuum Pump

Fig. 4 Experimental Apparatus for Filter Efficiency Test

aerosol concentrations at the upstream and downstream of the test filter were mesured by using the Active Scattering Aerosol Spectrometer (ASAS-X). The overall efficiency and the penetration rate through the test filter were calculated by Eq. (5) from the measured concentrations.

4. Comparison of the theoretical values with Experimental Data

A single fiber efficiency contains diffusion, interception and inertial impaction. Because the particle size is samll and the velocity is slow in the experiments, single fiber efficiency by inertial impaction could be neglected. Therefore, a single fiber efficiency is indicated as the following:

$$\eta=\eta_R+\eta_D \qquad (20)$$

The efficiency of a sigle fiber by an interception is independant of velocity as long as the flow pattern is unchanged. It is characterized by an interception parameter.(9,10) Also, Lee has suggested η_R as the following equation.(4,11)

$$\eta_R=\left(\frac{1-\alpha}{K}\right)\frac{RP^2}{1+RP^2} \qquad (21)$$

The equations derived above will be compared here with the experimental filter efficiency. The experimental single fiber efficiency by the Eq. (20) and the results are shown in Fig. 5 with Chen's.(12) Fig. 5 shows that a single fiber efficiency, η, RP, Pe and Re are presented in order to consider fiber radius, filtration velocity and particle size, not to consider volume fraction. The deviations of the experimental values from the theoretical are less than 15%(Fig. 5). A single fiber efficiency on the flow rates and the particle sizes is shown in Fig. 6. The minimum filter effictency is to occur in the vicinty

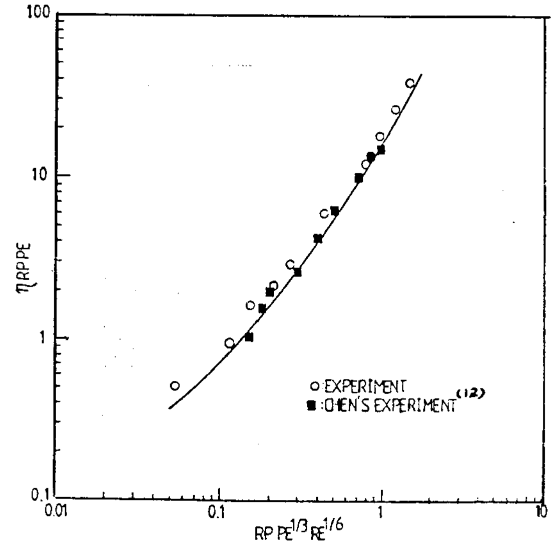


Fig. 5 Experimental and Theoritical Single Fiber Efficiency as a Function of ηR_pP_e and $R_p P_e^{1/3}R_e^{1/6}$

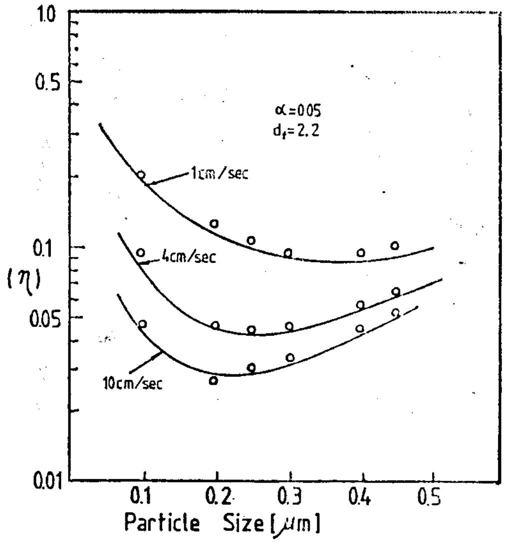


Fig. 6 Single Fiber Efficiency as a Function of Particle Size and Velocity.

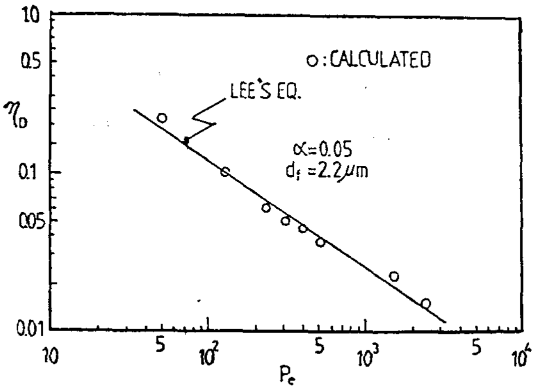


Fig. 7 Effect of Peclet Number on Diffusion Efficiency

of 0.35μm at 1cm/sec velocity, 0.25μm at 4 cm/sec and 0.2μm at 10cm/sec. Therefore, the particle size at which the minimum filtration efficiency occurs will vary depending on the volume fraction of a filter and the flow velocity. The experimental results are more or less greater than the theoretical, due to forming chain-like particles on a fiber.

Fig. 7 shows that the theoretical, efficiency on a single fiber by diffusion, η_D, agrees quite well with results obtained from the empirical formula derived by Lee, et al.[(4)] Therefore, this efficiency is charcterized by the filtration velocity and the fiber diameter.

5. Conclusion

A numerical method has been developed for predicting the efficiency of a given fibrous filter in the region of diffusion, and the theoretical value agrees quite well with the experimental.

The minimum efficiency is dependant on diffusion effect that is characterized by a slow velocity and a small particle size.

This rusult could contribute in the optimization of the operating conditions of air-purification system with a filter.

Nomenclature

b	outer cell radius in cell model, cm
C	Cunningham slip correction, dimensionless
D	diffusion coefficient of particle
Df	fiber diameter, cm
Dp	particle diameter, cm
E	collection efficiency of a filter, dimensionless
f	cofficient of frictional resistance
J	particle deposition rate per unit length of cylinder
K	Kuwabera's hydrodynamic factor, dimensionless
k	Boltzmann Constant
L	filter thickness, cm
N	n/n_0, dimensionless
n	particle concentration, number/cm
n_0	undisturbed particle concentration, number/cm
P	penetration
Pe	peclet number$=u_0Df/D$, dimensionless
R	r/rf, dimensionless
r, θ	cylindrical coordinate, cm and rad.
rf	fiber radius, cm
rp	particle radius, cm
Re	Reynolds number$=\rho u_0Df/\mu$, dimensionless
RP	interception parameter$=rp/rf$, dimensionles
T	absolute tempterature, °K
t	time, sec
u_0	undisterbed flow velocity, cm/sec
UR	ur/u_0, dimensionless
ur	flow velocity in radial directions
v_0	particle velocity, cm/sec
$V\theta$	$v\theta/uo$, dimensionless
$v\theta$	flow velocity in tangential directions
y	ordinate where the streamline cuts the cylinder, b
α	fiber volume fraction of the filter.
ε	porosity of the filter
μ	fluid viscocity, poise

η	single fiber efficiency
η_D	single fiber efficiency by diffusion
η_R	single fiber efficiency by interception
λ	mean free path of the gas molecular, cm
δ	diffusion layer, cm
ϕ	dimensionless stream function
∇^2	Laplace oprator

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