An Experimental Study on Collection Efficiency by Model Filter

By

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The mechanism of the removal of aerosol particles was experimetally studied with a model filter. The model filter was composed of four filter elements which were manufactured by sticking glass fibers on a brass plate. The diameters of the fiber were 40 μ and 80 μ and the porosity of the filter was 0.75–0.88. The aerosols whose diameters were 0.7 μ and 1.0 μ were prepared with Sinclair-La-Mer type generator and stearic acid was used as aerosol particles. The experiment was carried out with the conditions that $Re=d_f u_s \rho / \mu_g$ were ranged between 0.1 and 1.0. In some cases there seemed to appear minimum collection efficiency. The results were analyzed by Fucks' model filter theory.

1. Introduction

The problem of the removal of aerosol particles from gas streams has become of increasing importance from the point of air pollution control.

To remove the large-size particles, several devices such as scrubbers and cyclones are used, while for the removal of the particles of the size of 1 micron or smaller fibrous filters or electrostatic precipitator are often used.

The collection mechanism and efficiency of aerosol particles by fibrous filters have been studied by several workers. Suspended particles may be removed from the gas stream by direct interception, by Brownian diffusion, or by the forces of inertia, gravity or electrical attraction. Most works analyzed the separation mechanism based on the assumption that the particles are collected on isolated cylinders. These results have been applied to estimate the efficiency of the practical fibrous filter which are composed of individual fibers. Practical fibrous filters have the complex arrangement and high porosity, and the interfiber distances are large compared with the size of the particles. These facts are the reasons why the experimental results related to the efficiency of filter depend extremely on the characters

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of the fibrous filters. As the first step to obtain the deep understanding on the separation mechanism, the authors conducted an experimental study with the model filter which was composed of the regularly arranged fibers.

2. Experimental Equipment and Procedure

2.1 Experimental Equipment

Fig. 1 shows the schematic diagram of the experimental equipment. The test aerosols were prepared by Sinclair-La-Mer type generator ⑥ which consisted of an evaporator, a reheater, and a condensor. Sodium chloride was used as the aerosol nuclei by evaporation in the electric furnace ②. The temperature of the electric furnace was kept at 500±5°C by manual control of transformer ③. Stearic acid was vaporized in the evaporator and was superheated in the reheater, and was condensed by passing through the condenser. Temperatures in the evaporating and reheating sections regulated by bimetal thermoregeulator within ±1°C. Relatively uniform sized aerosol particles generated by the aerosol generator were drawn into the main filtration equipment ⑧ as shown in Fig. 2.

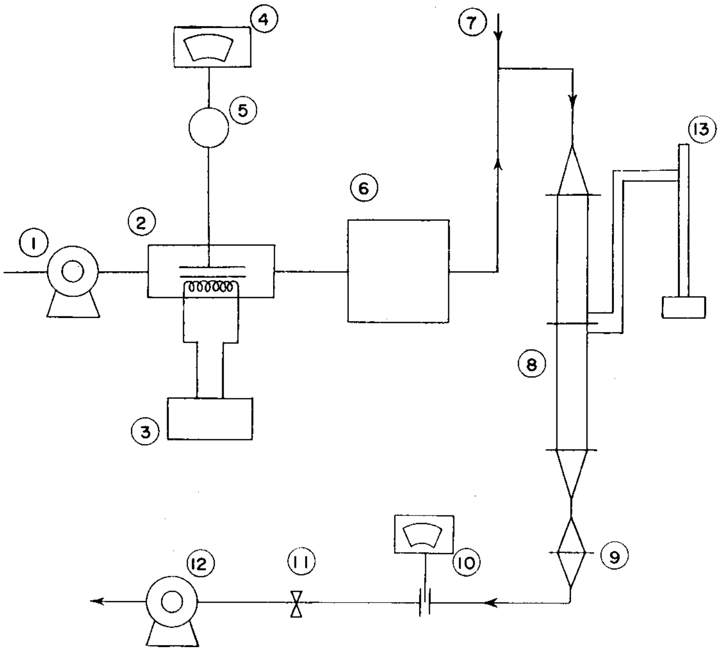

Fig. 1. Schematic diagram of experimental apparatus.
① Compressor ② Nuclei generator ③ Transformer ④ Galvanometer ⑤ Thermocouple ⑥ Sinclair-La-Mer type aerosol generator ⑦ By-pass for air supply ⑧ Main filtration equipment ⑨ Absolute filter holder ⑩ Anemometer ⑪ Control valve for air ⑫ Blower ⑬ Göttingen type micromanometer

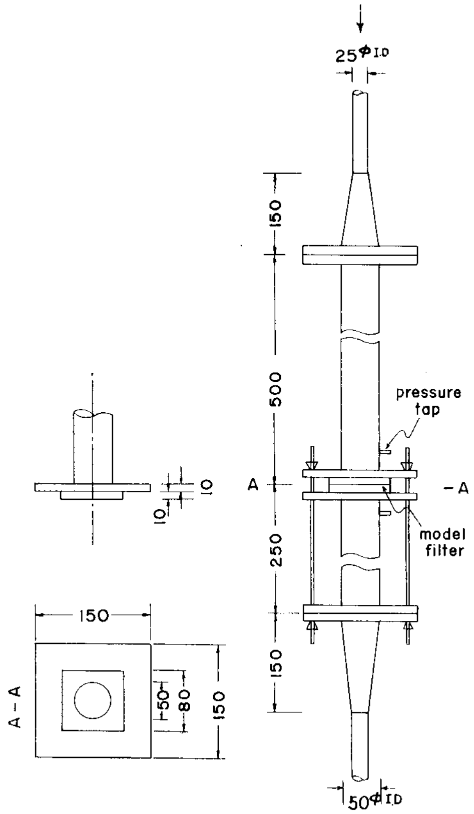

Fig. 2. Main filtration equipment.

The main filtration equimpment was made of transparent acrylic acid resin, the diameter of which was 50 mmφ and the length of which was 750 mm long. A model filter was set in the upstream side at 500 mm apart from the entrance of the equiment.

After aerosols were passed through the model filter, the uncaptured aerosols in the air were collected by absolute filter ⑨ (American air filter) which is guaranteed 99.97% collection efficiency for particles of 0.3 μ diameters.

Flow rate of gas was measured with the hot-wire anemometer ⑩.

To obtain the stable conditions, the aerosol generator was operated for at least 5 hours prior to the experiment and was maintained at a constant temperature within ± 1°C.

2.2 Model Filter

Glass fibers were stuck with paste on a brass plate as shown in Fig. 3. An element thus manufactured was called a filter element. These four elements were

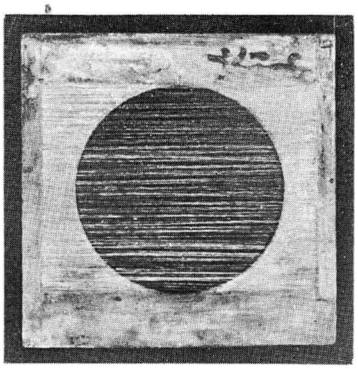

Fig. 3. Filter element.

held between the flanges to construct a model filter.

Table 1 shows the specification of model filter. It was noted that the porosity ε was calculated with Eq. 1 by assuming that the model filter is effective in the area of $4(l+d_f)$ in Fig. 4.

$$\varepsilon = 1-\pi/4\left(1+\frac{l}{d_f}\right)\left(1+\frac{h}{d_f}\right). \qquad (1)$$

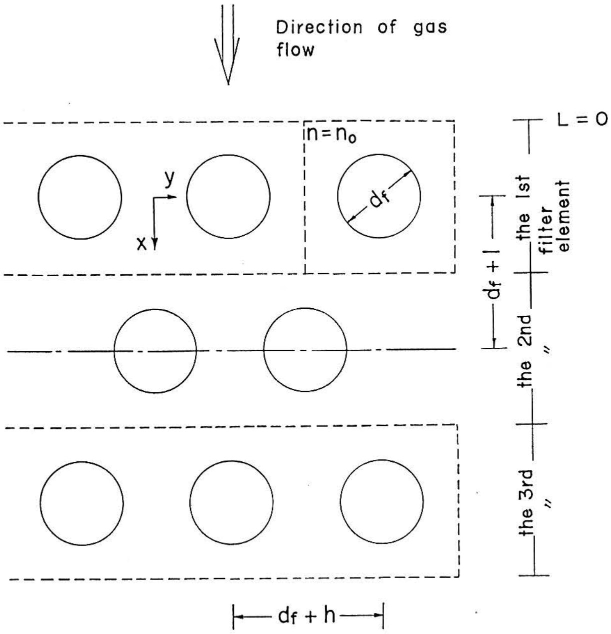

Fig. 4. Ideal arrange of fibers.

Table 1. Specification of model filter.
material of fiber: glass
density of fiber : 2.56 (g/cm^3)

d_f (μ)	h/d_f (−)	l/d_f (−)	ε (−)
40	0.5	2.50	0.851
40	0.5	1.75	0.810
80	0.5	2.75	0.860
80	0.5	1.25	0.767
80	0.5	0.875	0.726

2.3 Measurement of the Diameter of Particles

The size of aerosol particles was optically determined by measuring the refractive angle β_1 by use of Owl's equipment. Calibration was conducted with the relation between refractive angle β_1 and particle diameter d_p obtained by Mori[1] and Kitani[2]. The relation between the particle diameter and the temperatures in generator was obtained as shown in Fig. 5. Fig. 5 indicates that the diameter of partilces was nearly proportional to the temperature in the evaporator.

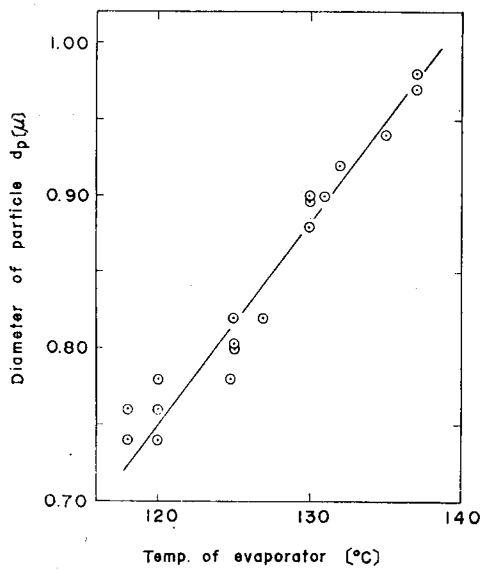

Fig. 5. Relation between diameter of particle (d_p) and temperature in aerosol generator.
(Temp. of nuclei generator: 500°C
" " reheater : 140°C)

2.4 Determination of Collection Efficiency of the Model Filter

The over-all collection efficiency was determined by the following equation:

$$E = 1 - n/n_0 \qquad (2)$$

where n and n_0 were the number concentrations of aerosols at the outlet and the inlet, respectively. In this work, n and n_0 were determined as the weights of particles collected on the model filter and absolute filter. The weights of particles were measured by chemical balance after the filtration operation of about 20 minutes. The pressure drop at the begining and the end of the operation was checked by Göttingen micromanometer.

Setting up the material balance over a system of thickness ΔL, and solving with the boundary conditions: $n=n_0$ and $n=n$ at $L=0$ and $L=L$, respectively, the ratio of n to n_0 can be calculated as follows.

$$n/n_0 = \exp\{-4\eta_e L(1-\varepsilon)/\pi\varepsilon d_f\} \tag{3}$$

where η_e is the collection efficiency for one fiber which is equivalent to a cylinder.

The number of the filter elements ν is $L/(d_f+l)$, and the over-all collection efficiency E can be obtained from Eq. 3 as follows.

$$\begin{aligned} E &= 1-n/n_0 \\ &= 1-\exp\{-4\eta_e\nu(1+l/d_f)(1-\varepsilon)/\varepsilon\pi\} \end{aligned} \tag{4}$$

2.5 Experimental Conditions

Table 2 shows the experimental conditions carried out here.

Table 2. Experimental conditions.
Kind of fibrous filter: Glass fiber filter
Kind of aerosol: Stearic acid
Density of particle: 0.837 (*g/cm*³)
Particle diameter (d_p): 0.7 and 1.0μ
Superficial velocity in model filter: 1.8–37 *cm/sec*

Table 3. Experimental Results (1).
d_f: 80 (μ) h/d_f: 0.5 l/d_f: 2.75 ε: 0.860

	d_p: 1.0 (μ)			d_p:0.7 (μ)		
	Re_0: 0.086 R_e: 0.1 u_0: 1.6 (cm/sec)					
ν	$-\log(n/n_0)$	η_ν (−)	n_0 (mg/m³)	$-\log(n/n_0)$	η_ν	n_0 (mg/m³)
1	0.00524	1.558×10^{-2}	419.7	0.00833	2.476×10^{-2}	196.6
2	0.0106	1.568		0.0209	3.107	
3	0.0155	1.533		0.0334	3.300	
4	0.0209	1.568		0.0462	3.436	
1	0.00524	1.553	59.20	0.00922	2.739	250.4
2	0.0123	1.828		0.0205	3.040	
3	0.0177	1.751		0.0311	3.077	
4	0.0218	1.616		0.0391	2.902	
	Re_0: 0.430 R_e: 0.5 u_0: 8.0 (cm/sec)					
1	0.00436	1.279×10^{-2}	134.4	0.00904	1.167×10^{-2}	106.0
2	0.00877	1.304		0.0243	1.568	
3	0.0128	1.266		0.0377	1.622	
4	0.0164	1.217		0.0502	1.621	
1	0.00261	0.7770	227.8	0.0121	1.557	137.5
2	0.00524	0.7791		0.0233	1.502	
3	0.00789	0.7910		0.0398	1.712	
4	0.0123	0.9168		0.0492	1.588	

3. Experimental Results and Consideration

3.1 Effect of Filter Elements on Collection Efficiency

Experimental results were shown in Table 3 and 4.

Table 4 Experimental Results (2).

d_f: 40μ								
	l/d_f: 2.50 h/d_f: 0.5 ε: 0.851				l/d_f: 1.75 h/d_f: 0.5 ε: 0.810			
d_p (μ)			0.7	1.0			0.7	1.0
R_e (−)	u_0 (s/cmec)	R_{e0} (−)	η_e (−)	η_e (−)	u_0 (cm/sec)	R_{e0} (−)	η_e (−)	η_e (−)
0.1	3.16	0.085	4.31×10^{-2}	4.11×10^{-2}	3.01	0.081	5.69×10^{-2}	3.52×10^{-2}
〃	o	o	5.33	3.86	o	〃	4.01	3.15
0.3	9.49	0.255	2.56	2.17	9.04	0.243	2.85	1.72
o	o	〃	2.87	3.18	〃	〃	2.12	2.15
0.5	15.8	0.426	2.03	1.91	15.1	0.405	2.62	2.22
o	〃	o	1.71	2.04	o	〃	2.16	1.85
0.7	22.2	0.596	2.21	2.46	21.1	0.567	2.09	2.62
o	〃	o	1.88	1.74	o	〃	2.38	3.17
d_f: 80μ								
	l/d_p: 1.25 h/d_f: 0.5 ε: 0.767				l/d_f: 0.875 h/d_f: 0.5 ε: 0.721			
d_f (μ)			0.7	1.0			0.7	1.0
R_e (−)	u_0 (cm/sec)	R_{e0}	η_e (−)	η_e (−)	u_0 (cm/sec)	R_{e0} (−)	η_e (−)	η_e (−)
0.1	1.43	0.077	4.38×10^{-2}	3.39×10^{-2}	1.34	0.072	2.77×10^{-2}	3.26×10^{-2}
〃	〃	〃	3.53	3.89	〃	〃	3.00	3.65
0.3	4.28	0.230	3.17	1.79	4.02	0.216	2.88	2.61
〃	〃	〃	2.62	1.72	〃	〃	1.99	2.49
0.5	7.13	0.384	1.41	2.10	6.70	0.361	1.32	2.65
〃	〃	〃	2.24	1.51	〃	〃	1.70	1.97
0.7	9.98	0.537	1.56	1.67	9.39	0.505	1.52	2.23
〃	〃	〃	1.48	1.45	〃	〃	2.19	2.64
1.0	14.3	0.767	1.33	2.37	13.4	0.721	1.56	2.11

After Fucks[3], the logarithm of the concentration ratio, i.e., the concentration after passing through layers n_ν to the concentration in inlet gas n_0 is directly proportional to the numbers of layers, namely

$$\ln(n_\nu/n_0) = -\nu\gamma \qquad (5)$$

for the particles of radius smaller than 0.1μ and for the monodisperse aerosol particles.

Fig. 6 shows that this relation is held in this experiment for the particle radius

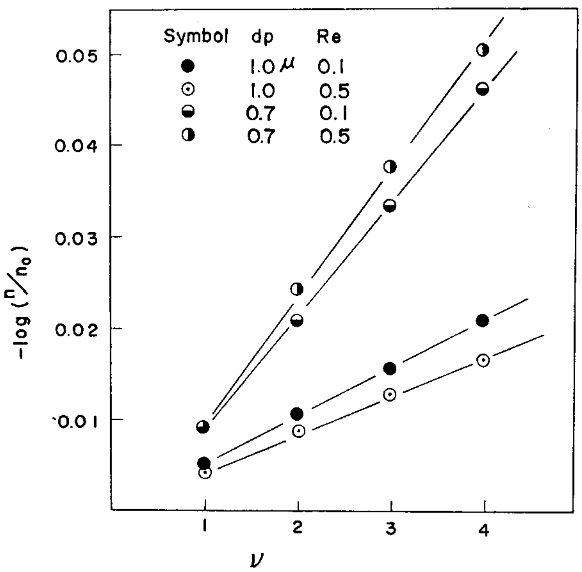

Fig. 6. Relation between log (n/n_0) and the νth element. (For model filter of d_f=80 and ε=0.860)

of 0.35 μ and 0.5 μ. In other words, all the parts within the model filter contributed to the collection of particles with almost equivalent action.

3.2 Effect of *Re* on Collection Efficiency

The collection efficiencies η_e calculated from Eq. 3 for the model filter consisting of four elements were plotted against Reynolds number $Re=d_f u_s \rho/\mu_g$ as in Fig. 7. Under certain experimental conditions, there could be recongnized the minimum collection efficiency at Reynolds number between 0.3 and 0.5.

The orders of inertia parameter ψ and interception parameter R in this experiment was 10^{-3}. Therefore, the collection efficiency due to inertia and interception for a single isolated cylinder was calculated as at most $O(10^{-3})$[4].

The orders of collection efficiency for a cylinder by diffusion and settling mechanisms are calculated as $O(10^{-3})-O(10^{-4})$[5].

The order of collection efficiencies in this work was $O(10^{-2})$. It is, therefore, supposed that the other factors such as interference effect between fibers, coagulation of particles and so on will affect the collection of particles, and that the collection mechanism by a filter is very complex.

Fucks[3] proposed the theory of collection mechanism of a filter taken account of the idealized arrange of fibers. The authors analyzed the experimental results in this work on the modified theory derived by him.

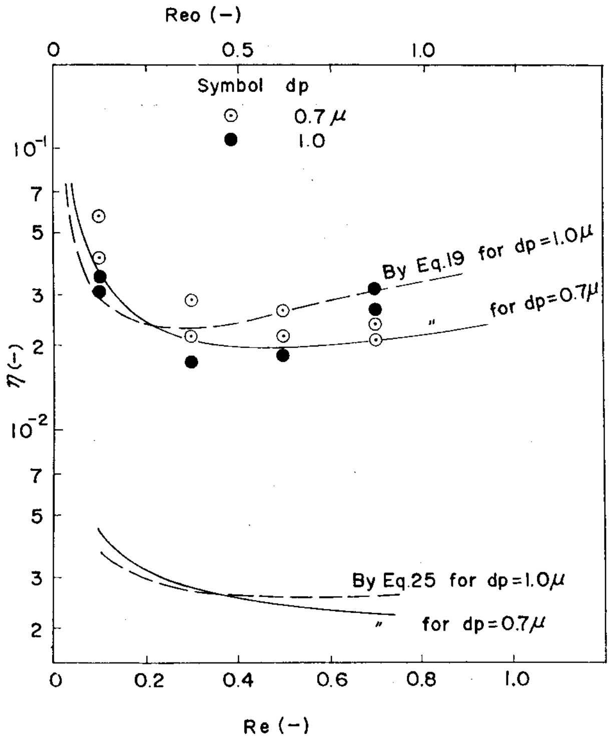

Fig. 7. Experimental and calculation results of η against Reynolds number (d_f: 40, l/d_f: 1.75, h/d_f: 0.50, ε: 0.810).

3.3 Theoretical Analysis of Collection of Particles by Model Filter

Suspended aerosol particles may be removed from gas stream by inertia, interception, sedimentation, and diffusion in fibrous filters. It is assumed that the effect due to electrical force is negligible.

a. Collection by inertial and interception effects

When gas enters at the midpoint (O) of two fibers (A and B) in Fig. 8, it is assumed that the flow is separated into two parts which proceed to the points p_1 and p_2 at the next row of fibers and that the velocity of gas is equal to $u_s = u_0/\varepsilon$. Particles at the points on a-a will move circularly due to the existency of the fibers of that row and they undergo centrifugal forces towards r. The force balance leads to the velocity of particles towards r as follows, assuming that the resistance to the particles by fluid follows to the drag force by Stokes' law:

$$u_r = (1/18)(d_p^2 \rho_p u_s^2 / \mu_g r) \qquad (6)$$

where r is the radius of curvature of the streamline. When the gas stream deviates

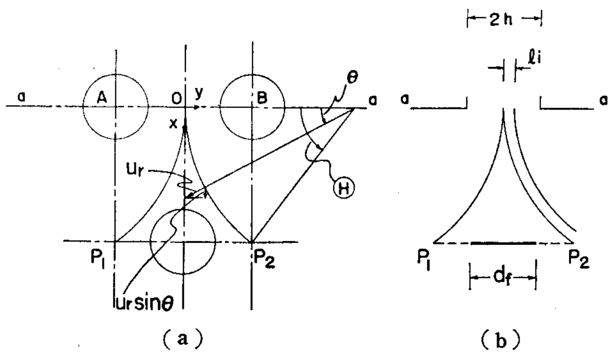

Fig. 8. Pattern of air flow within filter and collection of particle due to inertia.

by the angle $d\theta$, the displacement of the particle on this streamline towrads x-direction dl_i is given by $dl_i = u_r(\sin\theta) r d\theta / u_s$. When gas moves from the first layer ($\theta=0$) to the next ($\theta=\Theta$), the displacement of particle to x-direction is derived as follows, integrating dl_i.

$$l_i = u_s(1-\cos\Theta)(1/18) d_p^2 \rho_p / \mu_g \tag{7}$$

It can be seen from Fig. 8 that the angle Θ is equal to $2\tan^{-1}\left(1+\frac{h}{d_f}\right) \Big/ \left(1+\frac{l}{d_f}\right)$ i.e.,

$$\Theta = 2\tan^{-1}\left(1+\frac{h}{d_f}\right) \Big/ \left(1+\frac{l}{d_f}\right). \tag{8}$$

The authors assumed that the collection mechanism of particles due to inertia on the filter was the analogous one on a fiat plate of the width d_f as shown in Fig. 8-b, based on the theory of the collection by impingement after Fucks. If the particles within the width l_i at the plane a-a are removed when gas curved at an angle Θ, the collection efficiency by this plate is expressed as $(l_i/h)\{d_f/(d_f+h)\}$. Therefore, the collection efficiency of fiber is given from Eq. 7 as

$$\begin{aligned} \eta_I &= (l_i/h)\{d_f/(d_f+h)\} \\ &= (1/18)(d_p^2 \rho_p u_0/\mu_g h)(1/\varepsilon)\left\{1 \Big/ \left(1+\frac{h}{d_f}\right)\right\}(1-\cos\Theta) \\ &= \psi\{1/(h/d_f)\}(1/\varepsilon)\left\{1 \Big/ 1+\frac{h}{d_f}\right)\Big\}(1-\cos\Theta) \end{aligned} \tag{9}$$

where

$$\begin{aligned} \psi &= (1/18)(d_p^2 \rho_p u_0/\mu_g d_f) = (1/18)\, Re_0\, (d_p/d_f)^2 (\rho_p/\rho) \\ &= \text{inertial parameter.} \end{aligned} \tag{10}$$

When the center of the particle reaches the line $p_1 - p_2$ and its surface comes in contact with the edge of the plate, the paticle will be caught by this plate. If this mechanism is called the collection due to interception effect, the collection efficiency due to this mechanism reduces to

$$\eta_C = (l_i/h)d_p/(d+h_f)$$
$$= \psi(d_p/h)(1/\varepsilon)\left\{1\Big/\left(1+\frac{h}{d_f}\right)\right\}(1-\cos\Theta) \quad (11)$$

b. Collection of particles due to Brownian effect

The average gas velocity u_δ within infinite small layer δ near the plate is assumed to be analogous to the one in a parallel capillary channel of width 2h, namely, $u_\delta \simeq u_s(3\delta/2h)$. The thickness of the layer δ within which the particles collected by diffusion is given by

$$\delta = (4L_\delta h\mathfrak{D}/3\pi u_s)^{1/3} \quad (12)$$

assuming that the velocity of gas is the same as that of particle.

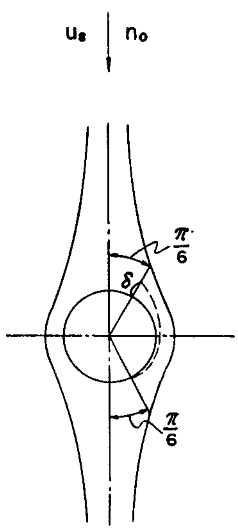

Fig. 9. Schematic diagram of collection of particle due to diffusion.

To derive collection efficiency due to diffusion, the concept by Langmuir[6] was introduced. As shown in Fig. 9 the particles which existed within the layer at $\varphi=\pi/6$ from the upstream were supposed to be caught when they pass along the surface of the fiber to the downstream by an angle $\varphi=(2/3)\pi$. So the distance along which the particles pass will be written as $L_\delta=(1/3)\pi d_f$. The collection efficiency due to diffusion, η_D, is therfore expressed as follows:

$$\eta_D = \left(2\int_0^\delta n_0 u_\delta ds\right)\Big/ h u_s n_0$$
$$= (2^7/3)^{1/3}(\mathfrak{D}/hu_0)^{2/3}\{\varepsilon/(h/d_f)\}^{2/3}$$
$$= (2^7/3)^{1/3}(1/S_c Re_0)^{2/3}\{\varepsilon/(h/d_f)^2\}^{2/3} \quad (13)$$

where $D = 1/S_c Re_0$ = diffusion parameter. (14)

c. Collection by settling

Collection efficiency due to settling is easily obtained from Fig. 8–a as follows:

$$\eta_S = n_0 v_s d_f / n_0 u_0 (d_f + h)$$
$$= G\Big/\left(1+\frac{h}{d_f}\right) \quad (15)$$

where $G = (1/18)d_p^2\rho_p g/u_0\mu_g$ (16)

and $v_s = (1/18)d_p^2\rho_p g/\mu_g$ = terminal velocity. (17)

If the collection efficiency of fibers of model filter is the sum of the above four collection efficiencies, it is given by

$$\eta_{\text{all}} = \eta_I + \eta_D + \eta_S + \eta_C \,. \tag{18}$$

The collection efficiency thus obtained is drawn in Fig. 10 to compare the experimental results.

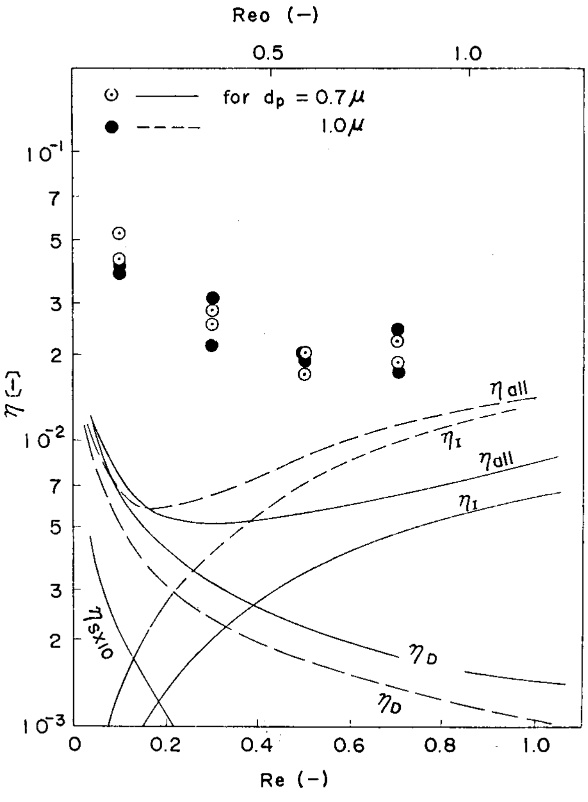

Fig. 10. Comparison between η_e and η due to individual effect for the filter of d_f=40, ε=0.851, and l/d_f= 2.50.

Assuming that the collection is due to inertia and diffusion only, and multiplying 1.5 and 5.5 on η_I and η_D, respectively, i.e.,

$$\eta_0 = 1.5\eta_I + 5.5\eta_D \tag{19}$$

then the collection efficiencies by Eq. 19 fit the experimental results as shown in Fig. 7, from which, however, the effect of l/d_f on η_e can not be clearly recongnized though the collection efficiency would relate to the disposition of fibers in filter.

To compare other workers' data with Eq. 19, it was assumed that l/d_f is approximately equal to h/d_f. By use of Eq. 1,

$$\varepsilon = 1 - \pi/4\left(1 + \frac{h}{d_f}\right)^2.$$

the collection efficiencies Eqs. 9, 11, 13, and 15 will be rewritten as follows:

$$\eta_I = \psi/\varepsilon\{\pi/4(1-\varepsilon)\}^{1/2}[\{\pi/4/1-\varepsilon)\}^{1/2}-1] \quad (20)$$

$$\eta_C = \psi R/\varepsilon\{\pi/4(1-\varepsilon)\}^{1/2}\{(\pi/4(1-\varepsilon))^{1/2}-1\} \quad (21)$$

$$\eta_D = (2^7/3)^{1/3}D^{2/3}[\varepsilon/\{(\pi/4(1-\varepsilon)\}^{1/2}-1\}^2]^{2/3} \quad (22)$$

$$\eta_S = G/\{\pi/4(1-\varepsilon)\}^{1/2} \quad (23)$$

where $R = d_p/d_f$ = interception parameter. (24)

Accordingly, if the collections by settling and interception are negligible, η_0 can be calculated using Eqs. 19, 20, and 22.

This is shown in Fig. 11. From this figure it is observed that Eq. 19. overesti-

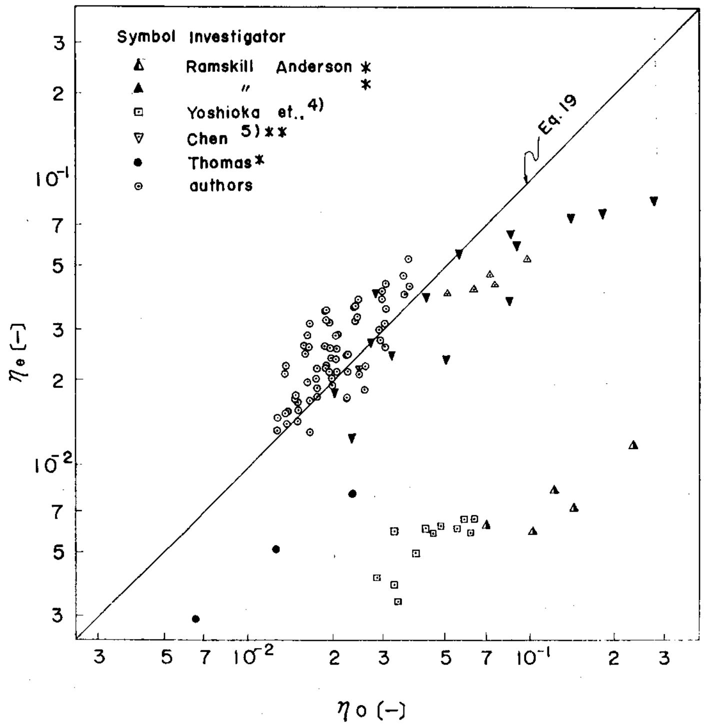

Fig. 11. Relation between η_e and η_0 by Eq. 19.
(* cited from Chen[5)], ** to be regarded ε as average value of 0.95 in calculating Eq. 19.)

mates other investigators data. The discrepancies from others' data would depend on the experimental conditions, especially, on usage of high concentration of particles and of dense filters.

Friedlander[7] proposed the following experimental equatioh fitting his data and the others' taking account of the combined collection mechanisms:

$$\eta_{ICD} = 6S_c^{-2/3}Re_0^{-1/2} + 3R^2Re_0^{1/2} . \tag{25}$$

Our results were about 10 times higher than the values by this equation as shown in Fig. 7. The reason of this difference may be considered that the order of R was 10^{-2} in our experiment and therefore, the second term on right side of Eq. 25 which indicates the effect of inertial deposition became too small.

2.4 Effect of ε on η_e.

The effect of ε i.e. $(1-\alpha)$ on η_e is shown in Fig. 12. The data were meager and scattered, so the effect of α on η_e could not be clarified in this work, but it seems that η_e increased as α increased, as described by Chen[5].

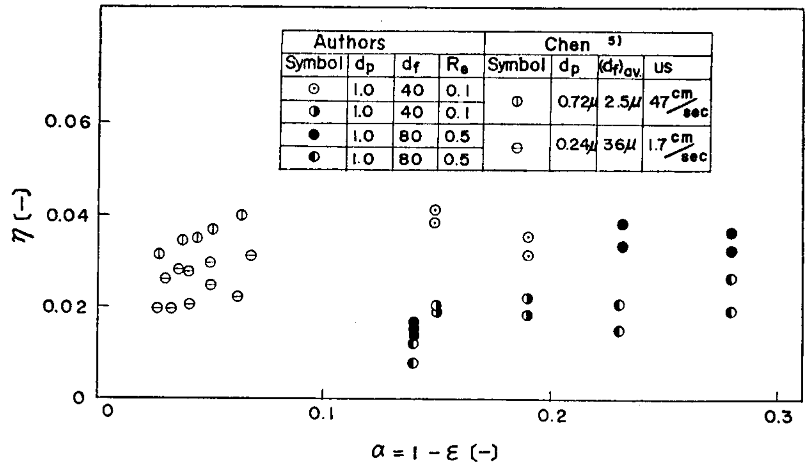

Fig. 12. Effect of neighboring fiber interference on collection efficiency η_e.

Conclusion

The experimental work was carried out with model filter composed of four elements.

(1) The collection efficiency for each element had almost the same values.

(2) In some runs, there seems to appear the minimum collection efficiency at Reynolds number (Re) between 0.3 and 0.5.

(3) The experimental results were analyzed by the model based on Fucks, and

the following equation to fit our data was obtained

$$\eta_0 = 1.5\psi/\varepsilon\{\pi/4(1-\varepsilon)\}^{1/2}[\{\pi/4(1-\varepsilon)\}^{1/2}-1]$$
$$+5.5(2^7/3)^{1/3}D^{2/3}[\varepsilon/\{\pi/4(1-\varepsilon)^{1/2}-1\}^2]^{2/3}$$

assuming that the collection mechanism due to interception and settling are negligible.

This equation overestimates other investigators' results.

(4) The collection efficiency seems to increase as the fraction of fibrous fibers increased.

Nomenclature

d_f	:	diameter of fiber d_p: diameter of particle	[cm]
D	:	diffusion parameter $1/S_cRe_0$	[—]
$\mathfrak{D}$	:	diffusion coeffidient of particle	[cm²/s]
E	:	over-all collection efficiency	[—]
g	:	gravitational force	[cm/s²]
G	:	settling parameter	[—]
h	:	length between neighbouring fibers perpendicular to gas flow	[cm]
l	:	length between neighbouring fibers parallel to gas flow	[cm]
l_i	:	stop distance of particle	[cm]
L	:	thickness of model filter $\nu(d_f+l)$	[cm]
L_δ	:	distance along which particles move	[cm]
n	:	number concentrations of particles at arbitrary	[No./cm³]
n_0	:	number concentrations of particles at inlet	[〃]
r	:	distance from center or radius of curvature	[cm]
R	:	interception parameter d_p/d_f	[—]
Re	:	Renyolds number based on u_s, $d_fu_s\rho/\mu_g$	[—]
Re_0	:	Renyolds number based on u_0, $d_fu_0\rho/\mu_g$	[—]
S_c	:	Schmidt number$=\mu_g/\rho\mathfrak{D}$	[—]
u_0	:	velocity of gas far from filter	[cm/s]
u_r	:	〃 of particle towards r in Fig. 8	[〃]
u_s	:	velocity of gas within filter u_0/ε	[〃]
u_δ	:	〃 near the surface of filter	[〃]
v_s	:	terminal velocity of particle	[〃]
x	:	rectangular coordinate	[cm]
y	:	rectangular coordinate	[cm]

Greek

α	:	volume fraction of fibers in filter	[—]
β_1	:	refractive angle of particle	[degree]
γ	:	coefficient defined in Eq. 5	[—]
δ	:	thickness of layer near the surface of filter	[cm]
θ	:	angle in Fig. 8	[degree]
Θ	:	〃	[〃]
ε	:	porosity of a filter or an element $1-\alpha$	[—]
η	:	collection efficiency	[—]
η_{all}	:	〃 〃 denfined in Eq. 18	[〃]
η_D	:	〃 〃 due to diffusion	[〃]
η_e	:	〃 〃 for a fiber defined in Eq. 3	[〃]
η_I	:	〃 〃 due to inertia	[〃]
η_{ICD}	:	〃 〃 defined in Eq. 25	[〃]
η_0	:	〃 〃 defined in Eq. 19	[〃]
η_S	:	〃 〃 due to seetling	[〃]
μ_g	:	coefficient of viscosity of gas	[g/cm s]
ρ	:	density for gas ρ_P: density for particle	[g/cm^3]
ν	:	the order of the element in model filter	[—]
		or numbers of model filter elements	[No.]
ψ	:	inertial parameter$=(1/18)d_p^2 u_0 \rho / d_f \mu_g$	[—]

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