Transient Behavior of Granular Filtration of Aerosols—Effect of Aerosol Deposition on Filter Performance

T. Takahashi, S. A. Walata and Chi Tien
Department of Chemical Engineering and Materials Science
Syracuse University
Syracuse, NY 13210

The twin features of the dynamic behavior of granular filtration are the histories of the effluent quality and the pressure drop necessary to maintain a given flow rate. The macroscopic conservation and rate equations that describe the dynamic behavior of granular filtration can be written as (Tien and Payatakes, 1979; Tien, 1982)

$$u\left(\frac{\partial c}{\partial \theta}\right) + \frac{\partial \sigma}{\partial \theta} = 0 \tag{1}$$

$$\frac{\partial \sigma}{\partial \theta} = (u) \cdot (\lambda)\, c \tag{2}$$

$$\Delta p = \int \left(\frac{\partial p}{\partial z}\right) \cdot dz \tag{3}$$

with the following initial and boundary conditions:

$$c = c_{in}, \quad z = 0, \quad \theta \geq 0 \tag{4a}$$

$$c = 0, \quad \sigma = 0, \quad z > 0, \quad \theta < 0 \tag{4b}$$

where λ denotes the filter coefficient and the meanings of the other symbols are as given in the Notation.

If a filter bed is viewed as an assembly of unit collectors, the efficiency of the unit collectors, η, can be related to the filter coefficient, λ, by the following expression:

$$\lambda = \frac{1}{\ell} \ln \frac{1}{1 - \eta} \tag{4c}$$

where the axial distance of a unit collector, ℓ, is given as (Payatakes et al., 1973)

$$\ell = \left[\frac{\pi}{6(1 - \epsilon)}\right]^{1/3} dg \tag{5}$$

Accordingly, if one has the information on the unit collector efficiency, η (and hence the filter coefficient, λ), and the pressure gradient or, more specifically, if one knows how these quantities vary with the extent of deposition (or σ, the specific deposit), then one can predict the dynamic behavior of granular filtration. The purpose of this work is to obtain the required information experimentally.

Experimental

Apparatus

A schematic diagram of the apparatus used in the experimental work is shown in Figure 1. The apparatus was designed and constructed to accomplish several purposes:

- To generate monodispersed aerosols of reasonably high concentrations.
- To measure the effluent concentration of experimental filters of various heights over prolonged periods of operation.
- To measure the pressure drop increase across the filter bed as a function of time.

All the experimental data reported here were collected using aerosol suspensions generated by a collision atomizer (BGI Model CN-1, Waltham, Massachusetts) from suspensions of polyvinyltoluene latex spheres (2.02 μm dia., Dow Chemical Company, Indianapolis, IN). Nitrogen gas from cylinders was passed through the three nozzles of the atomizer to provide a spray of droplets, which was directed against a baffle to remove large droplets. The spray passed through an electric heater in order to vaporize the water sticking to the solid spheres.

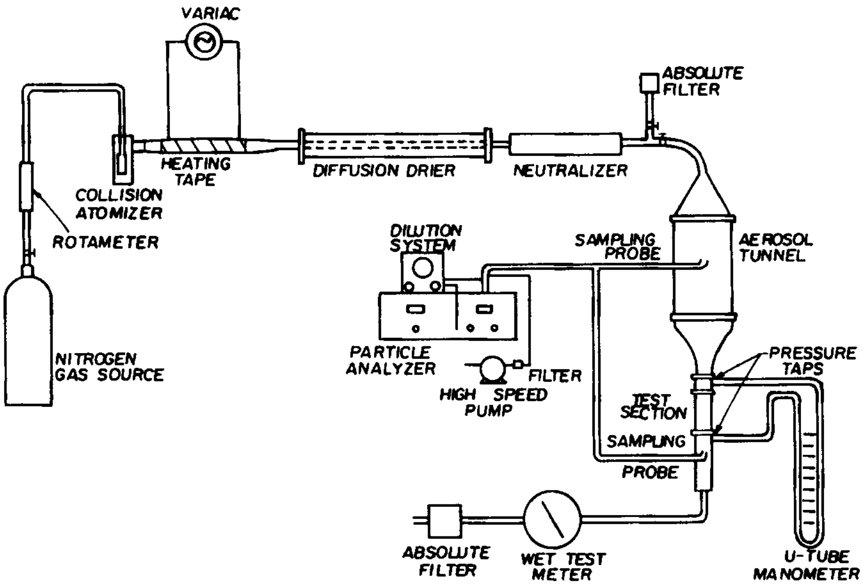

Figure 1. Diagram of experimental apparatus.

The aerosol then passed through a neutralizer (Thermo Systems, Inc., Model 3012, St. Paul, MN), which reduced the electrostatic charges of the aerosol particles. After leaving the neutralizer, the aerosol entered the top of 6 in. (15.24 cm) dia. aerosol tunnel, where it was diluted by the N_2 gas jets directed upward from holes on a 1/4 in. (0.635 cm) dia. copper tube concentric with the tunnel.

The contraction tunnel (that is, the lower part of the aerosol tunnel) was designed to provide a uniform flow field. The diameter of the contraction tunnel shrank from 6 in. (15.24 cm) at the top to 1.5 in. (3.81 cm) at the lower end. Immediately below the contraction tunnel was the experimental filter bed, made of a Plexiglas cylinder with 1 9/16 in. (3.97 cm) ID and a height of 4 in. (10.16 cm). The actual packing height of the experimental filter varied from 0.21 to 3.0 cm, depending upon the filter grain size. Four different sizes of filter grains were used in this study. The influent and effluent aerosol concentrations were determined using a Climet Particle Counter (Climet Instrument Co., Model 208, Redlands, CA). One sampling probe was placed before the inlet and another beyond the outlet of the experimental filter. The pressure drop across the filter was measured using a manometer.

Experimental conditions

A substantial number of experimental runs were made using the apparatus described above under constant flow conditions. The experimental conditions of the bulk of the measurements are summarized in Table 1.

A typical set of measurements is shown in Figures 2 and 3. In Figure 2, the effluent-to-influent concentration ratio is given as a function of the total number of aerosol particles entering the bed, $\int_o^t u \cdot c_{in} \cdot dt$. The pressure drop data are shown in Figure 3. The data shown in these figures were obtained from several experiments carried out under identical conditions. The differences in results of the separate experiments are similar to the scattering of data points in a given experiment, attesting to the reproducibility of the experimental work.

Interpretation of Experimental Data

The purpose of this study was to determine experimentally the effect of aerosol deposition in granular filtration, specifically, the changes in collection efficiency and pressure gradient as functions of the specific deposit. As shown earlier, predicting the dynamic behavior of granular filtration requires knowing λ (or η) and $(\partial p/\partial z)$ for the entire filtration period. To account for the effect of derposition, it is customary to write

$$F_1 = \frac{\eta}{\eta_o} = \frac{\lambda}{\lambda_o} = F_1(\alpha, \sigma) = 1 + \alpha_1 \sigma^{\alpha_2} \quad (6)$$

$$F_2 = \frac{(\partial p/\partial z)}{(\partial p/\partial z)_o} = F_2(\beta, \sigma) = 1 + \beta_1 \sigma^{\beta_2} \quad (7)$$

The extent of particle deposition throughout a filter is generally not uniform. Consequently, in order to obtain a relationship

Table 1. Experimental Conditions

	Properties of Aerosol Particles			
Substance	Polyvinyltoluene			
Diameter, d_p	2.02 μm			
Density	1.027 g/cm^3			
Concentration	Up to 10^3 particles/cm			
	Properties of Experimental Filters			
Substance	Glass			
Grain size, μm	99	255	505	1,170
Height, cm by grain size	—	0.215	0.42	1.0
	—	0.43	0.84	2.0
	—	0.645	1.26	3.0
	Operating Conditions			
Gas velocity	5.85 ~ 22.6 cm/s			
Stokes number	1.43×10^{-3} to 3×10^{-2}			
Relative size parameter	2×10^{-3} to 8×10^{-3}			
Experiment duration	Up 15 h			

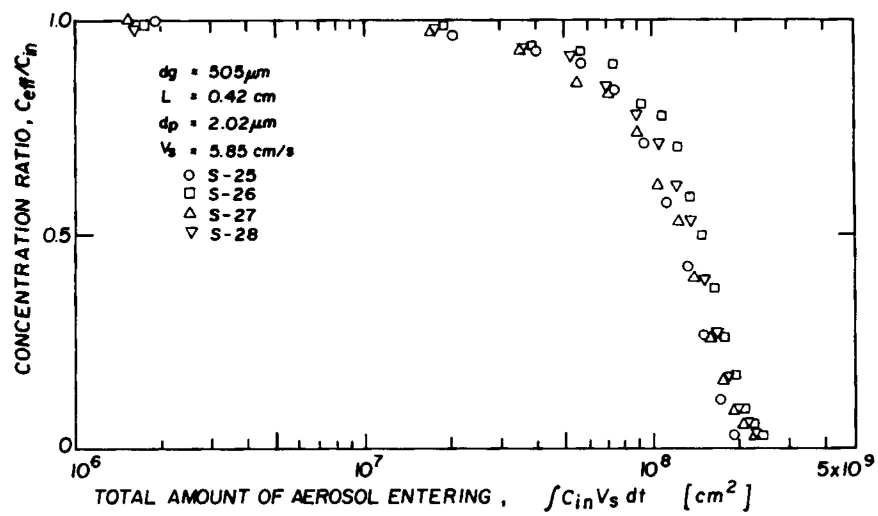

Figure 2. Experimental data of effluent concentration.

such as Eq. 6 or 7 from measured effluent concentration and pressure drop data, special procedures must be employed. A comparative study by Walata et al., (1984) showed that the most consistent approach is to apply the extrapolation method, the principle of which is briefly described below.

Consider that a granular bed is composed of a number of unit bed elements (unit collectors) connected in series. Let c_{i-1} denote the aerosol concentration in the stream of the ith element. The effluent-to-influent concentration ratio of a granular filter, $c_{\text{eff}}/c_{\text{in}}$, can be expressed as

$$\frac{c_{\text{eff}}}{c_{\text{in}}} = 1 - E = \frac{c_1}{c_{\text{in}}} \cdot \frac{c_2}{c_1} \cdot \cdot \cdot \frac{c_{\text{eff}}}{c_{N-1}} = \prod_{i=1}^{N} (1 - \eta_i) \tag{8}$$

where η_i deontes the efficiency of the ith unit collector and N is the total number of the unit collectors in series. For a bed of height L, N is given as

$$N = \frac{L}{\ell} \tag{9}$$

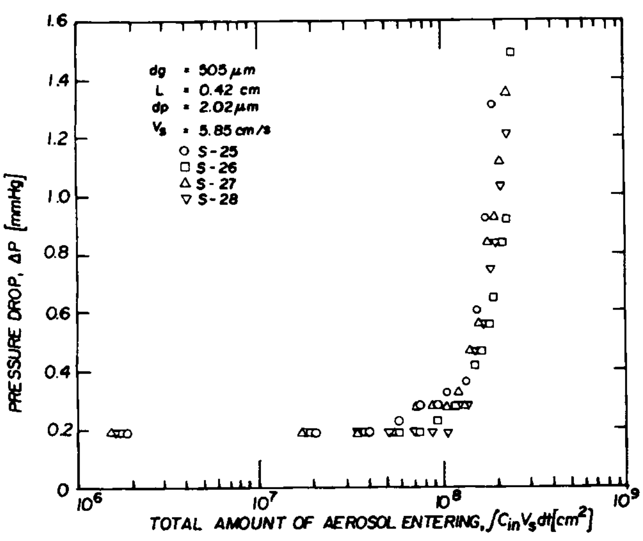

Figure 3. Experimental data of pressure drop.

If the extent of deposition is uniform throughout the filter, all η_i's are the same. Accordingly, the unit collector efficiency, η, becomes

$$\eta = 1 - \left(\frac{c_{\text{eff}}}{c_{\text{in}}}\right)^{1/N} \tag{10}$$

corresponding to a specific deposit given as

$$\sigma = \frac{1}{L} \cdot \int_o^t (c_{\text{in}} - c_{\text{eff}})\, u \cdot dt = \frac{1}{L} \int_o^t (c_{\text{in}})\, E\, u \cdot dt \tag{11}$$

Note that both Eqs. 10 and 11 hold if the assumption of uniform deposition is valid.

Based on experimentally determined values of c_{in} and c_{eff} and by using the uniform deposition assumption, one can obtain the values of η (or $F_1 = \eta/\eta_o$) corresponding to various values of σ which can be calculated from Eqs. 10 and 11. Based on the F_1 vs. σ results, the empirical constants α_1 and α_2 can be determined. By applying this procedure to data obtained from experimental filters of different heights, different values of α_1 and α_2 can be obtained. As the validity of the uniform deposition assumption improves with decreasing filter bed height, one may plot the values of α_1 (and α_2) against the filter height, L, and obtain their limiting values at zero bed height (or more appropriately $L = \ell$). These limiting values may be considered correct for expressing the effect of aerosol deposition on unit collector efficiency. The same principle can also be applied to estimate the constant β_1 and β_2 for the effect of aerosol deposition on pressure gradient.

Results

Initial collection efficiency and pressure gradient

Determining F_1 (and F_2) from experimental data, as outlined above, requires the values of the initial (or clean-filter) unit collector efficiency (or pressure gradient). The initial collection efficiency was taken to be the average of the values calculated from Eq. 10, using the effluent concentration data obtained 5 min after beginning to take filtration measurements. All conditions were similar except filter height. Similar procedures were

Table 2. Experimental and Predicted Initial Values of Unit Collector Efficiency, η_o

	Filter Grain Diameter, d_g, μm [Aerosol dia., d_p = 2.02 μm]							
	99		255		505		1,170	
u cm/s	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.	Exp.	Pred.
5.85	—	—	1.75×10^{-2}	2.51×10^{-2}	1.20×10^{-2}	1.29×10^{-2}	—	—
11.3	1.31×10^{-1}	8.11×10^{-2}	3.03×10^{-2}	3.25×10^{-2}	1.20×10^{-2}	1.74×10^{-2}	4.08×10^{-3}	8.65×10^{-3}
22.6	—	—	1.25×10^{-1}	4.95×10^{-2}	4.70×10^{-2}	2.80×10^{-2}	4.49×10^{-3}	1.56×10^{-2}

used to calculate the clean-bed pressure gradient. The results are summarized in Tables 2 and 3.

The experimentally determined η_o and predictions from the correlation of Pendse and Tien (1982a) were compared, as shown in Table 2. Generally speaking, the correlation gave good estimates of η_o except for $N_{St} \leq 6 \times 10^{-3}$ (namely, d_g = 1,170), where the correlation tended to overestimate.

The experimentally determined clean-filter pressure gradient was compared against the Ergun (1952) equation and the more recent correlation proposed by MacDonald et al. (1979). As shown by the results given in Table 3, the correlation of MacDonald et al. gave better agreement with data than did Ergun's equation.

Establishment of correlations of the increase in η and $(\partial p/\partial z)$ vs. σ

Empirical expressions were obtained relating the increase in the unit collection efficiency and pressure gradient vs. the specific deposit in the form of Eq. 6 or 7. The procedure used can be described as follows. First the effluent concentration (or pressure drop) data for a given set of conditions were used to obtain α_1 and α_2 (or β_1 and β_2) based on the uniform deposition assumption; see Figure 4 for illustrations. It was found that the variations in α_2 (or β_2) corresponding to the three different bed heights but at the same gas velocity and grain size are much less than those in α_1 (or β_1). Accordingly, the arithmetic average of the three α_2 (or β_2) was taken to be the correct value of α_2 (or β_2). On the other hand, the values of α_1 (or β_1) were plotted against the bed height, and the limiting value at $L = 0$, Figure 5, was taken to be the correct values of α_1 (or β_1). The results are summarized in Table 4.

Table 3. Experimental and Predicted Initial Values of Pressure Gradient, $(\partial p/\partial z)_o$, mm Hg/cm

	Filter Grain Diameter, d_g, μm [Aerosol dia., d_p = 2.02 μm]								
	255			505			1,170		
		Pred.			Pred.			Pred.	
u cm/s	Exp.	(1)	(2)	Exp.	(1)	(2)	Exp.	(1)	(2)
5.85	1.52	1.34	1.61	0.40	0.41	0.57	—	—	—
11.3	3.40	2.64	3.14	0.82	0.89	1.13	0.12	0.11	0.13
22.6	7.51	5.45	6.47	1.72	2.02	2.39	0.32	0.25	0.29

Prediction (1) based on Ergun's equation, (2) based on correlation of MacDonald et al. (1970). SI conversion: kPa = mm Hg × 0.133.

Correlation of empirical constants with relevant dimensionless parameters

In order to apply the results obtained in this study to simulate the dynamic behavior of granular aerosol filtration in general, expressions must be developed to estimate the empirical constants (α_1, α_2, β_1, and β_2) under specified conditions. The previous work on the transient behavior of fibrous filtration (Emi et

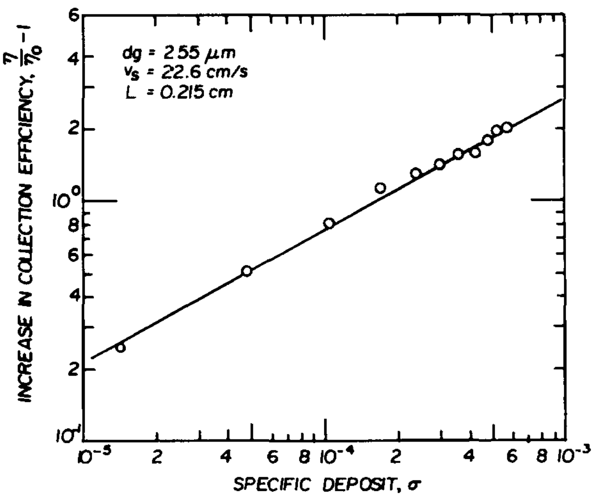

Figure 4a. Data based on uniform deposition assumption: increase in collection efficiency vs. specific deposit.

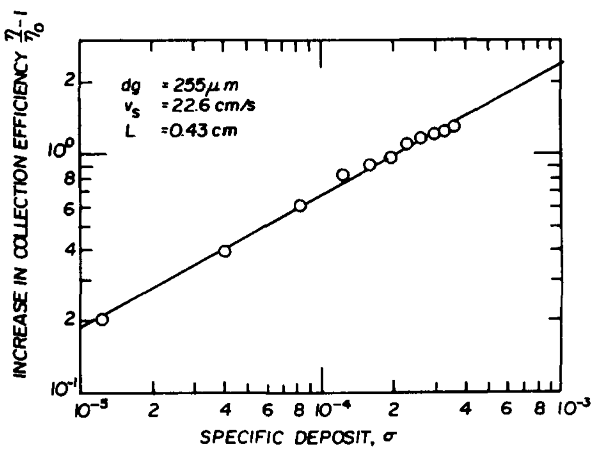

Figure 4b. Data based on uniform deposition assumption: increase in pressure gradient vs. specific deposit.

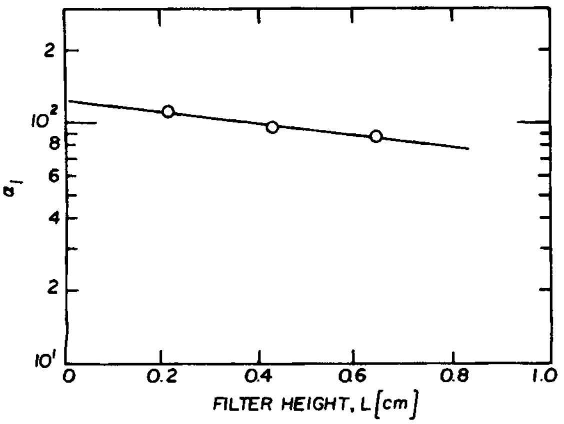

Figure 5. Extrapolation of α_1 vs. L.

al., 1982) and on the stochastic simulation of granular filtration (Pendse and Tien, 1982b) has shown that the increases in collection efficiency and pressure gradient resulting from deposition, for a given value of σ, are strongly affected by the deposit morphology. For cases in which the dominant mechanism of collection is inertial impaction, the important relevant dimensionless parameters are the Stokes number, N_{St}, and the relative size parameter, N_R, respectively defined as

$$N_{St} = \frac{c_s \rho_p D_p^2 u}{9 \mu d_g} \tag{12}$$

$$N_R = d_p / d_g \tag{13}$$

The ranges of the experimental variables covered in this work are not extensive enough for a general correlation. On the other hand, they are sufficient for at least an initial attempt. The tentative conclusions obtained are as follows.

Table 4. Values of Empirical Constants α_1, α_2, β_1, β_2 Obtained from Effluent Concentration and Pressure Drop Data

d_g	u, cm/s		
μm	5.85	11.3	22.6
		α_1	
99	—	2.90×10^2	—
255	4.15×10^4	4.70×10^3	1.23×10^2
505	2.70×10^5	2.50×10^4	1.60×10^3
1,170	—	7.80×10^3	4.10×10^3
		α_2	
99	—	0.710	—
255	1.12	0.867	0.540
505	1.27	1.06	0.860
1,170	—	0.879	0.664
		β_1	
99	—	1.29×10^3	—
255	1.02×10^4	7.20×10^3	1.25×10^5
505	7.20×10^4	4.50×10^3	6.30×10^2
1,170	—	4.10×10^3	1.20×10^3
		β_2	
99	—	1.05	—
255	1.19	1.24	1.79
505	1.34	1.15	0.945
1,170	—	0.982	0.890

The empirical constants α_1 and α_2 are assumed to be a function of both N_{St} and N_R. In Figures 6a and 6b, values of α_1 (or α_2) were plotted against N_{St}. It is rather obvious that except for the data obtained using the largest filter grain (d_g = 1,170 μm), all the data follow very similar trends. Furthermore, the consistency that the data exhibit can be improved if the effect of the relative size parameter, N_R, is included. After a number of attempts, the following empirical expression of α_1 and α_2 were found:

$$\alpha_1 = [3.42 \times 10^{-5} + 0.292 N_R^{1.5}] \cdot N_{St}^{-3.8} \tag{14}$$

$$\alpha_2 = 0.26 \ln \frac{1}{N_{St}} - 0.23 \tag{15}$$

The slope of the line α_2 vs. ln $(1/N_{St})$ was chosen in such a manner that the dependence of α_2 on N_{St} for the three smaller filter grain cases is qualitatively similar to that displayed by the data for the case of d_g = 1,170 μm. Equation 15 reflects this choice.

The fact that the results obtained using d_g = 1,170 μm failed to agree with those of other cases is puzzling. The predicted values of α_1 and α_2 for d_g = 1,170 μm from Eqs. 14 and 15 differ significantly from experimental values. One possible reason for this deviation is the reentrainment of deposited particles and their subsequent redeposition, behavior not considered in the present study. Accordingly, the validity of Eqs. 14 and 15 must be restricted to $N_R \geq 0.004$.

Similar results were observed in correlating the coefficient β_1 and β_2 with the relevant dimensionless groups, as shown in Figures 7a and 7b. The data corresponding to the case of d_g = 1,170 μm failed to agree with the rest of the data. The correlations that hold true for $N_R > 0.004$ are

$$\beta_1 = [1.84 \times 10^{-5} + 4.32 \times 10^{-2} N_R^{1.5}] N_{St} \tag{16}$$

$$\beta_2 = 0.52 + 0.14 \ln \frac{1}{N_{St}} \tag{17}$$

Since no similar experimental studies have been reported in the literature, there is as yet no basis on which to compare the results presented above. To provide some indication as to the validity of the correlations, the increases in the unit collection efficiency based on the correlations established in this study were compared to the results from stochastic simulation (Pendse and Tien, 1982b). As shown in Figure 8, these predictions are at least consistent with each other.

Acknowledgment

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Notation

- c = aerosol concentration
- c_i = aerosol concentration in the effluent of the ith unit bed element
- c_{eff} = effluent aerosol concentration
- c_{in} = influent aerosol concentration
- c_s = Cunningham's correction factor
- d_g = filter grain diameter
- d_p = aerosol diameter

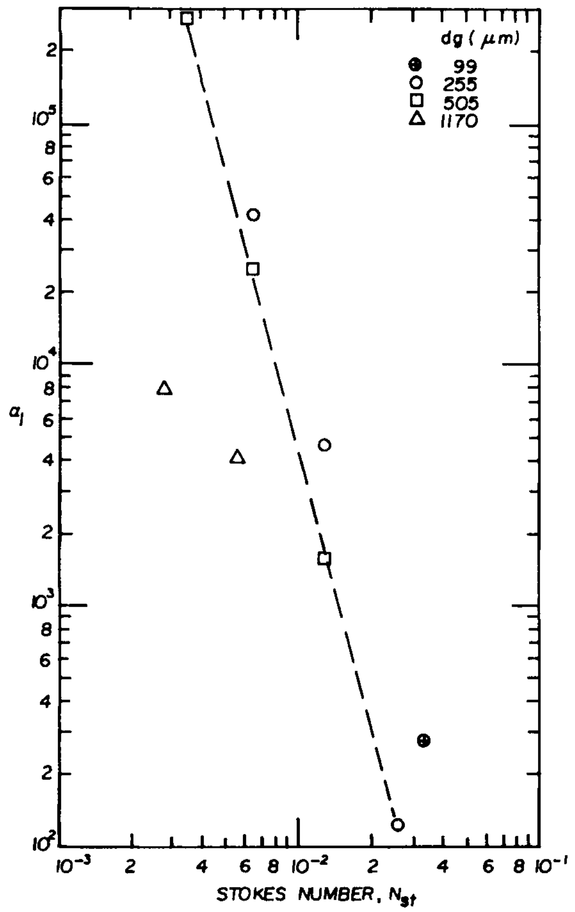

Figure 6a. Dependence of α_1 on N_{St}.

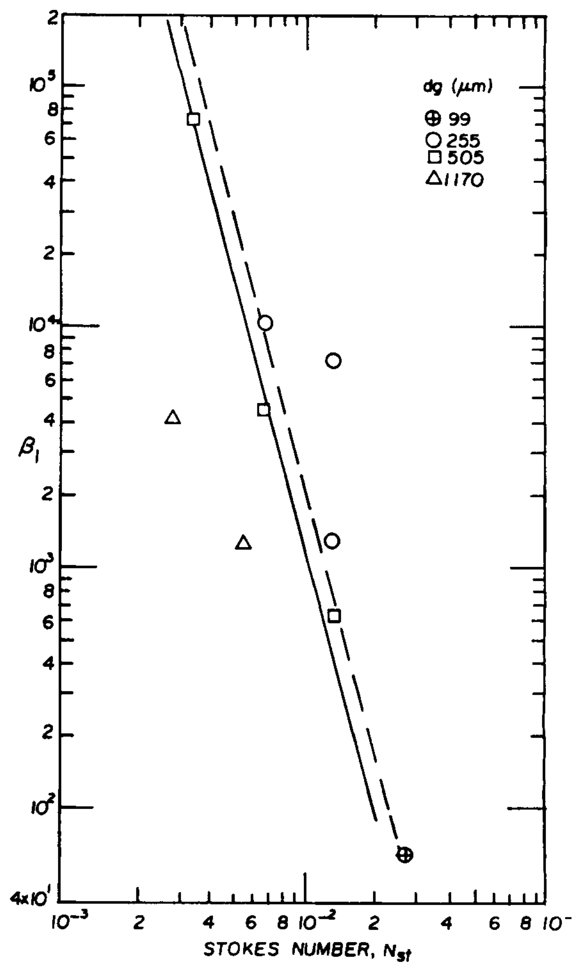

Figure 7a. Dependence of β_1 on N_{St}.

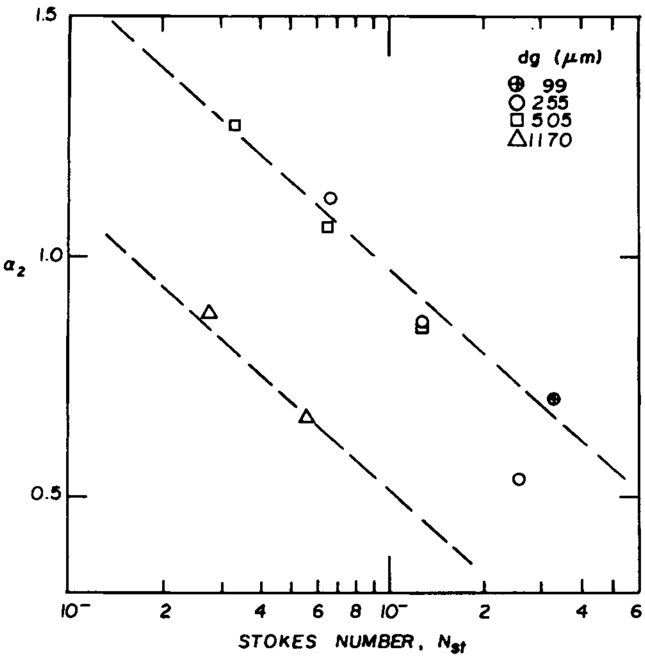

Figure 6b. Dependence of α_2 on N_{St}.

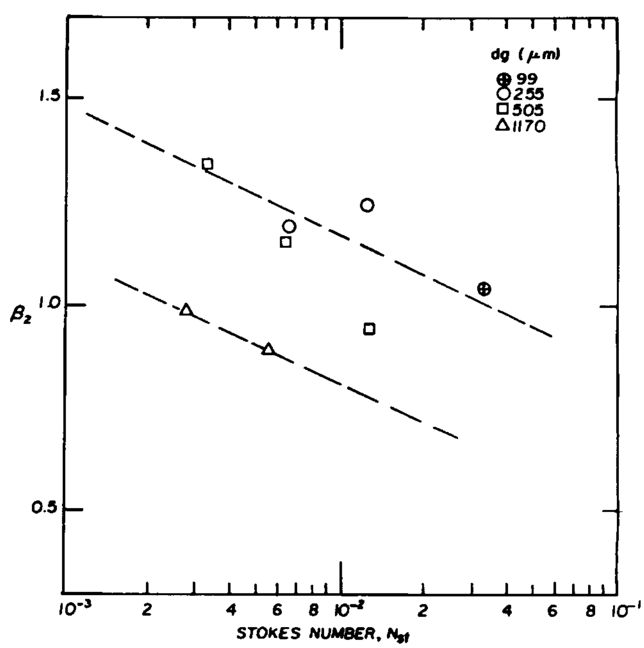

Figure 7b. Dependence of β_2 on N_{St}.

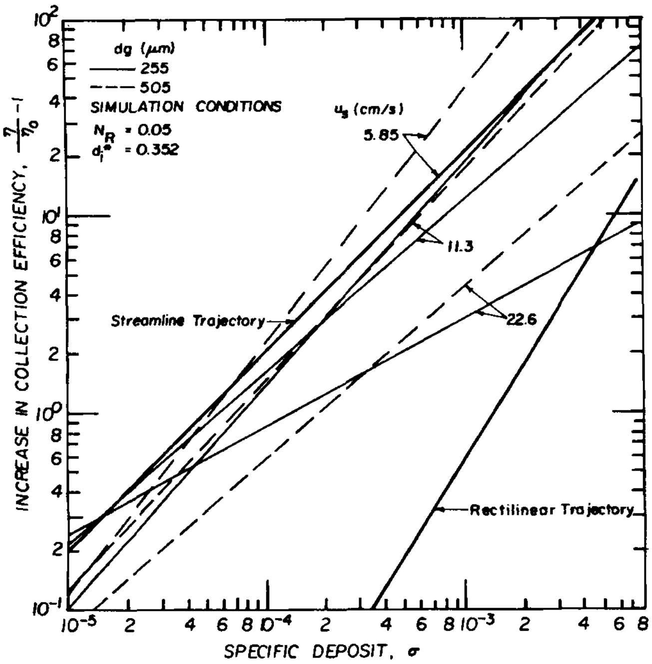

Figure 8. Comparison between prediction from this study and stochastic simulation (Pendse, 1979).

E = total collection efficiency of filter
F_1, F_2 = defined as λ/λ_o amd $(dp/dz)/(dp/dz)_o$, respectively
L = filter height
ℓ = axial distance of a unit bed element
N = total number of unit bed elements in series
N_R = relative size parameter
N_{St} = Stokes number
P = pressure
u = superficial velocity
z = axial distance

Greek letters

α, β = vectors parameter of F_1 and F_2, respectively
α_1, α_2 = empirical constants of Eq. 6
β_1, β_2 = empirical constants of Eq. 7
Δp = pressure drop
ϵ = bed porosity
λ = filter coefficient
λ_o = initial value of λ
η = unit collector efficiency
η_i = efficiency of the ith unit collector
η_o = initial value of η
ρ_p = particle density
σ = specific deposit
θ = corrected time
μ = fluid viscosity

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