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Gas Filtration in Granular Moving Beds — An Experimental Study

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An experimental study was conducted of gas filtration in cross-flow moving-bed granular filters. Variables examined included both the gas and solid velocities as well as filter-grain size. The triboelectric effect was found to play an important role in determining the extent of particle collection.

On a mené une étude expérimentale sur la filtration du gaz dans des filtres granulaires en lit mobile et en écoulement croisé. Les variables étudiées comprennent les vitesses de gaz et de solides ainsi que la taille des pores de filtres. On montre que l'effet triboélectrique exerce un rôle prépondérant pour évaluer l'importance de la récupération.

Keywords: granular bed filtration, moving-bed filtration, aerosol filtration, triboelectric effect.

Among various particulate emission-control processes, granular filtration is known for its relatively high collection efficiency for particles of widely ranging size and for its simplicity in operation. Other advantages of granular filtration include the abundance of granular substances which can be used as filter grains and the fact that many available granular substances are immune to high-temperature, high-pressure, and/or chemically corrosive environments. As a result, granular filtration has been widely used in gas cleaning and dedusting, with applications in practically every industrial segment (Juvinall et al., 1970).

Granular filtration is commonly conducted in the fixed-bed made. Fixed-bed filtration, however, is inherently nonsteady in nature. Initially free of any deposited matter, a filter bed becomes increasingly clogged with deposited particles during the course of filtration. Clogging, in turn, increases the pressure drop necessary to maintain a constant gas throughput. Ultimately, the pressure drop across the filter becomes so excessive that one must stop the filtration process to replace or regenerate the filter medium.

One alternative for overcoming the disadvantages arising from fixed-bed clogging is to use a moving bed. In one such approach, cross-flow moving-bed filtration, the flow of the gas suspension is transverse to the flow of the filter grains. This arrangement, which combines the advantages of granular filtration and the benefits of continuous operation, has been seriously considered for use in hot gas cleaning and, indeed, is the basis for a patent granted more than sixty years ago (Klarding, 1921).

Despite its potential, cross-flow moving-bed granular filtration needs to be examined much more rigorously before its true value can be assessed. The present work represents the first phase of a systematic study in cross-flow moving-bed granular filtration aimed at developing a comprehensive framework that accurately describes the essential features of the process. The specific aims of this work are:

(1) to determine the extent of particle collection achieved and the effect of various operating variables on particle collection;
(2) to examine the possible operational complexities arising from the interaction between solids flow and gas flow;
(3) to delineate the essential difference between fixed-bed and moving-bed filtration.

Experimental work

Apparatus

A schematic diagram of the experimental apparatus is shown in Figure 1. The moving bed was made of a brass sheet (1/16 inch in thickness) with three sections (entry section, filter section, and discharge section) flanged together. The entry section began with a hopper (for solids storage) which had a cross section of 127 mm by 82.6 mm and a height of 470 mm. The hopper tapered into a duct of rectangular cross section measuring 20.3 mm by 82.6 mm by 308 mm high. The discharge section was 635 mm high with a cross section similar to that of the entry section.

The filter section was composed of a solids flow duct (280 mm high) and a gas flow duct (140 mm long). Both ducts had identical cross sections (20.3 mm by 82.6 mm). They were joined perpendicularly at their midsections. To prevent any loss of filter grains into the gas flow duct, mesh wire screens (with 150 μm openings) were placed on the two sides of the solids flow duct to which the gas flow duct was joined. The gas flow duct was preceded by a divergent flow section and followed by a discharge duct. Provisions were made to sample both the influent and effluent gas streams and to measure the pressure drop between the upstream and downstream side.

Downward movement of the filter grains was maintained at a velocity of 0.2 to 2 mm/s with a DC motor (1/6 HP and 1750 rpm, Boston Gear Co.) and a worm gear reducer (Model 001, Boston Gear Co.) controlled by a DC motor controller. Details of the moving bed are shown in Figure 2.

The apparatus used for preparing the test suspensions is shown in Figure 1. All the suspensions were prepared using a collision atomizer (BGI Inc., Waltham, MA) and monodispersed polyvinyltoluene latex particles (Dow Chemical Co., Indianapolis, IN). Bottled nitrogen gas at 35 psig or 70 psig was passed through the atomizer's aspirators to create a spray. The spray was first passed through a heating tube (namely, a glass tube of 5/8 in. i.d. with heating tape wrapped around the tube) in order to vaporize the water on particle

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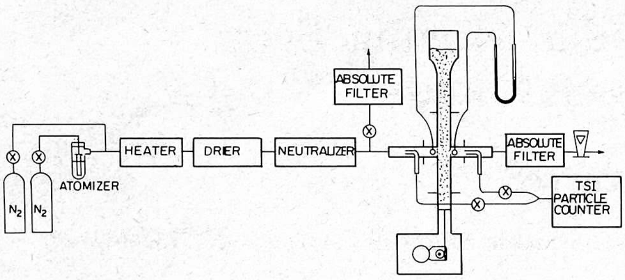

Figure 1 — Generation of aerosol suspension and its filtration.

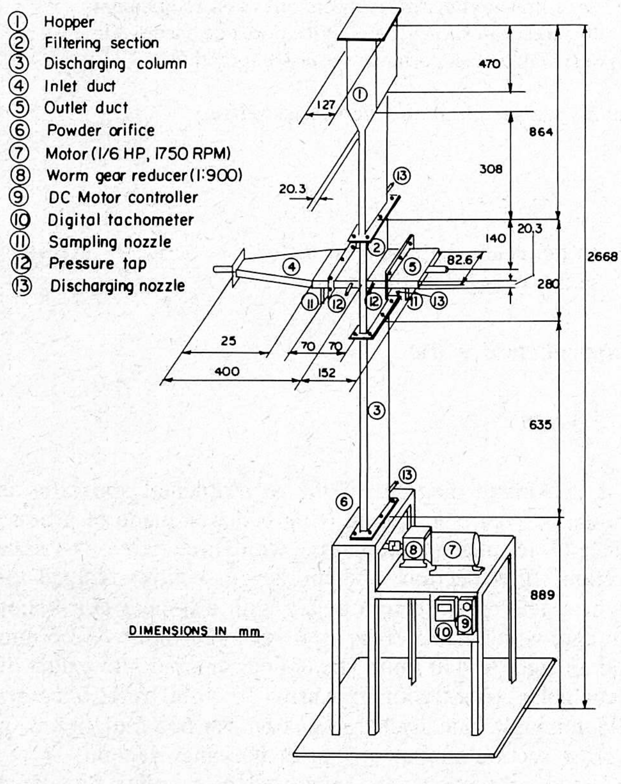

Figure 2 — Schematic diagram of moving-bed filter.

surface. The spray was then sent through a diffusion dryer to remove the water vapor before entering a neutralizer (Model 3012, TSI, St. Paul, MN), where the electrostatic charge was reduced to a minimum. The test suspension entered the filter through the upstream side of the gas entry section, which, as shown in Figure 2, was placed ahead of the gas duct of the cross-flow filter.

The experimental work measured the concentrations of the influent and effluent gas suspensions and the pressure drop associated with the gas flow. A particle counter (Model APS 3300 TSI, St. Paul, MN) was used to give the number concentrations of the monodispersed latex particles in the gas streams, and a manometer provided the pressure-drop readings.

Experimental systems

The filter grains used were nearly mono-sized glass spheres with average diameters of 280 μm and 525 μm and magnetite particles with an average diameter of 367 μm. Under microscopic examination, the glass spheres were found to be nearly uniform in geometry and with smooth surfaces

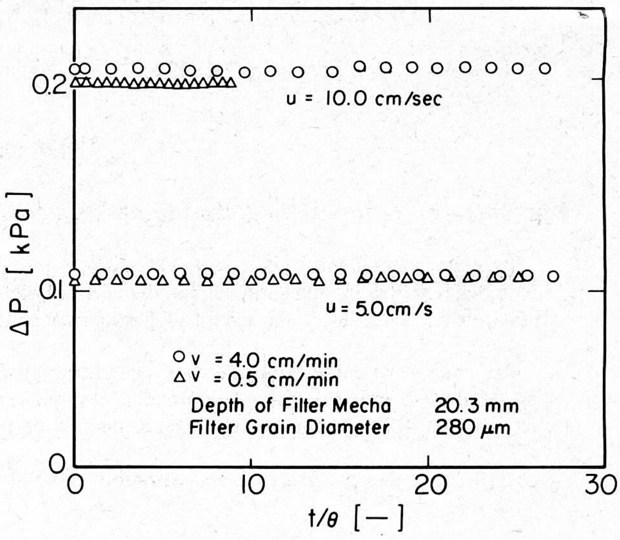

Figure 3 — Pressure drop in the direction of gas flow.

(Chiang and Tien, 1985). The latex particles used had a diameter of 2.02 μm.

Experimental conditions

The conditions used in carrying out the experiments were:

Filter grain diameter	280 μm, 367 μm and 525 μm
Particle diameter	2.02 μm
Filter width	82.6 mm
Solids velocity	up to 16 cm/min
Gas velocity	>5 cm/s
Filter grain residence time	>7.5 s
Time duration of measurement	$\leq 62/v$ when v is the solids velocity in cm/min

Results

A substantial number (over thirty) of experimental runs were made to obtain data on filter performance (c_{eff} and p vs. time). The salient features of the results are given below.

Possible interaction between gas and solid flow

For proper operation of cross-flow moving-bed filters, transverse gas flow must not impede solid flow. Otherwise, as shown by previous investigators (Bridgwater, 1982; Ginestra and Jackson, 1985), for high gas velocities, granular particles constituting the filter medium may be pinned against the downstream boundary of the moving bed. Under extreme conditions, solid flow may cease totally.

For the present work, it was important to take measurements when such gas–solid interaction was absent. To insure that the necessary experimental conditions were maintained, gas pressure-drop data over a period of time and corresponding to two different solid velocities were obtained. These data are shown in Figure 3. The fact that the pressure drop was independent of the solid velocity and time indicates that the conditions used for conducting the measurements were indeed proper.

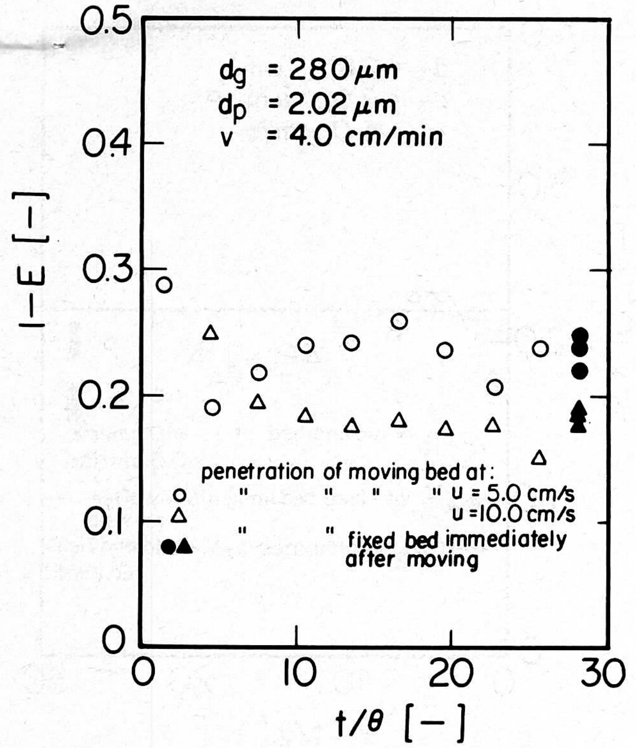

Figure 4 — Aerosol penetration at two gas velocities.

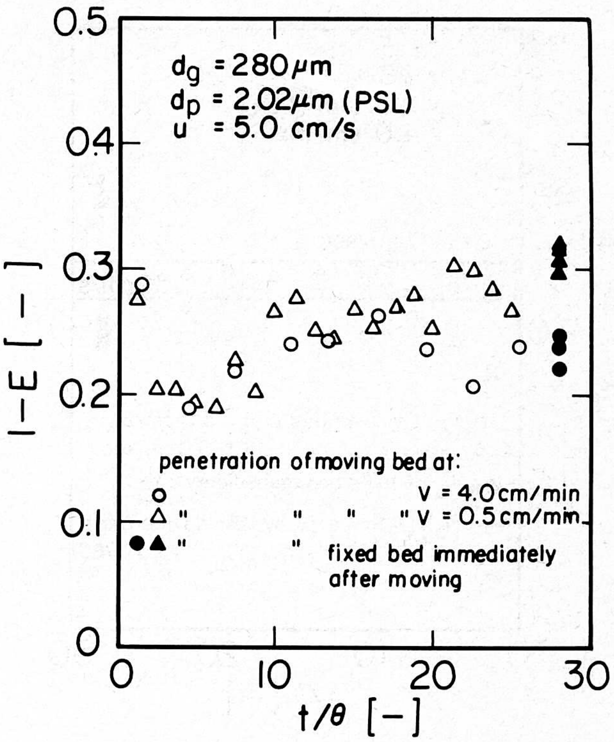

Figure 5 — Aerosol penetration at two filter grain velocities.

PARTICLE COLLECTION

Filter performance is usually described by the so-called total collection efficiency, E, defined as

$$E = \frac{c_{in} - c_{eff}}{c_{in}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where c_{in} and c_{eff} denote, respectively, the influent and effluent concentrations.

Typical results which demonstrate the extent of particle collection achieved in the experimental moving-bed filters are shown in Figures 4 and 5. In both figures, the results are presented in the form of $1 - E$ or P, (the penetration, defined as c_{eff}/c_{in}) vs. the dimensionless time, t/θ, where θ is the average residence time of the filter grain, defined as

$$\theta = H/v \quad \ldots\ldots\ldots\ldots \quad (2)$$

where v is the solid velocity and H is the height of the moving-bed filter. Note that H is not the same as the depth of the filter medium.

The results shown in Figure 4 were obtained at two gas velocities (u = 5.0 and 10.0 cm/sec) and at a fixed solid velocity (v = 4 cm/min). The extent of penetration observed for the case of u = 10 cm/s was lower than the penetration for the case of u = 5 cm/s, which is consistent with the expectation that particle collection attributable to inertial impaction increases with the increase of gas velocity. The effect of solid velocity on particle collection was found to be negligible, as shown by the results displayed in Figure 5.

Both the results showed some scattering in the values of $1 - E$. However, they do not exhibit any definite trend, as was also the case for all of the other results collected. Equally important is the fact that the pressure drop associated with gas flow was essentially constant. This behavior is in marked contrast to that observed in fixed-bed granular filtration. For fixed-bed filtration, both the collection efficiency of a filter and the pressure drop necessary to maintain a given flow rate through the filter increase with time because of the progressive clogging taking place in the bed. In a moving-bed filter, the filter grains are renewed continuously. Furthermore, since the filter grains are in motion, it becomes more difficult for deposits to form on adjoining or neighboring filter grains. Consequently, the effect of deposition on particle collection can be expected to be small. As an approximation, one may assume that the unit collector efficiency of the filter grains along the gas-flow path is constant and equal to the initial unit collector efficiency, η_0. The relationship between η_0 and E is given as (Pendse and Tien, 1982).

$$\eta_0 = \frac{d_g}{L}\left[\frac{\pi}{6(1-\epsilon)}\right]^{1/3} \ln(1 - E) \quad \ldots\ldots\ldots \quad (3)$$

where d_g, L and ϵ are the grain diameter, the depth of filter medium (along the direction of gas flow), and the bed porosity, respectively.

The unit collector efficiency provides a meaningful indicator of the grain's intrinsic ability to capture particles. For example, η_0 is independent of the filter depth, while E is strongly influenced by it. Because of this consideration, values of η_0 corresponding to those shown in Figures 4 and 5 were obtained and presented in Figures 6 and 7.

A number of empirical expressions have been proposed and can be used to estimate the initial unit collector efficiency of granular fixed-beds. The correlation proposed by Yoshida and Tien (1985) is given as

$$\eta_0/B = 100N_{St}^2 + 0.19\left(4 - \frac{4N_R}{d_c^*} + \frac{N_R^2}{d_c^{*2}}\right)^{1/2} \times \frac{N_R^{1.041}}{d_c^*} \qquad N_R \leq 0.002 \quad \ldots\ldots\ldots \quad (4a)$$

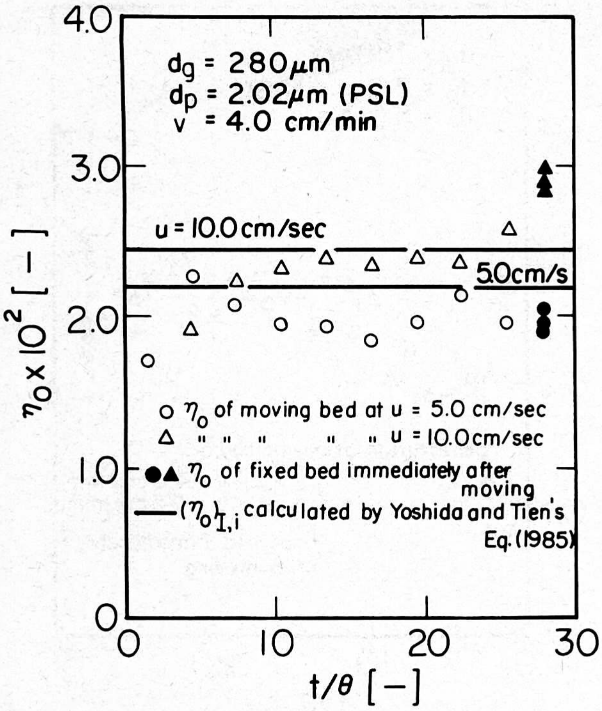

Figure 6 — Unit collection efficiency of moving-bed filtration-effect of gas velocity.

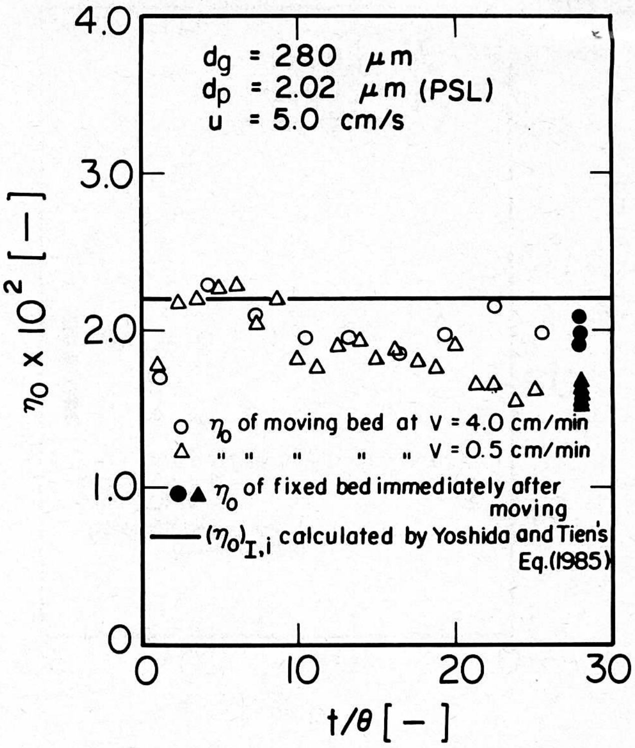

Figure 7 — Unit collection efficiency of moving-bed filtration-effect of filter grain velocity.

$$\eta_0/B = N_{St} + 0.48\left(4 - \frac{4N_R}{d_c^*} + \frac{N_R^2}{d_c^{*2}}\right)^{1/2} \times \frac{N_R^{1.041}}{d_c^*} \qquad N_R \geq 0.002 \quad \text{(4b)}$$

and

$$B = 7 - 6\exp[-0.0065 N_{Re_s}] \quad \text{(4c)}$$

where

$$N_R = d_p/d_g \quad \text{(5a)}$$

$$N_{Re_s} = d_g u \rho/\mu \quad \text{(5b)}$$

$$N_{St} = d_p^2 u \cdot \rho_s C_s / 9\mu d_g \quad \text{(5c)}$$

where d_p is the particle diameter; u, the gas velocity (superficial); and ρ, μ, and ρ_s, the gas density, gas viscosity, and particle density, respectively. C_s is the Cunningham correction factor, and d_c^* is the dimensionless average pore constriction diameter, which can be taken to be 0.35 for beds packed with nearly monosized grains.

The values of η_0 obtained experimentally and those estimated from Equations (4a) through (4c) were compared, with the results also shown in Figures 6 and 7. The comparisons clearly indicate that the extent of particle collection achieved in moving-bed filters is comparable to that of clean fixed-bed filters. In this connection, one should bear in mind that in estimating the unit collection efficiency, empirical correlations (including that given by Equations (4a) through (4c)), are usually accurate within a factor of two.

Another important aspect in moving-bed granular filtration is the triboelectric effect resulting from the relative motion between filter grains themselves and that between filter grains and the filter bed boundary. Tardos et al. (1983) found in fluidized filter studies that the triboelectric effect significantly enhances particle collection.

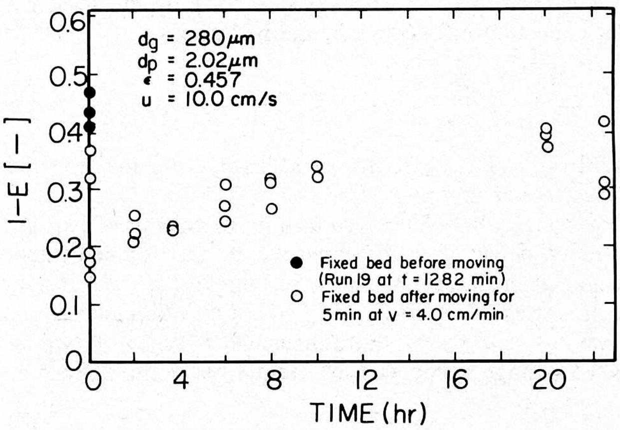

Figure 8 — Aerosol penetration change with time.

The presence of the triboelectric effect was observed in several ways. During the initial phase of the study, when trial experiments were performed, it was rather difficult to obtain reproducible results. It was then found that discrepancies in collection efficiency obtained under seemingly identical conditions could largely be attributed to whether or not filter grains were in motion prior to the data collection. That presence or absence of movement, determines, of course, the presence of the triboelectric effect.

One series of experiments to demonstrate the presence of the triboelectric effect was performed as follows: The moving bed was first set in motion for five minutes at a downward velocity of 4 cm/s; it was then stopped. The bed was then operated as a fixed-bed filter, with the total collection efficiency determined over a period of time. A set of data obtained is shown in Figure 8, in which the total collection efficiency is plotted as a function of time.

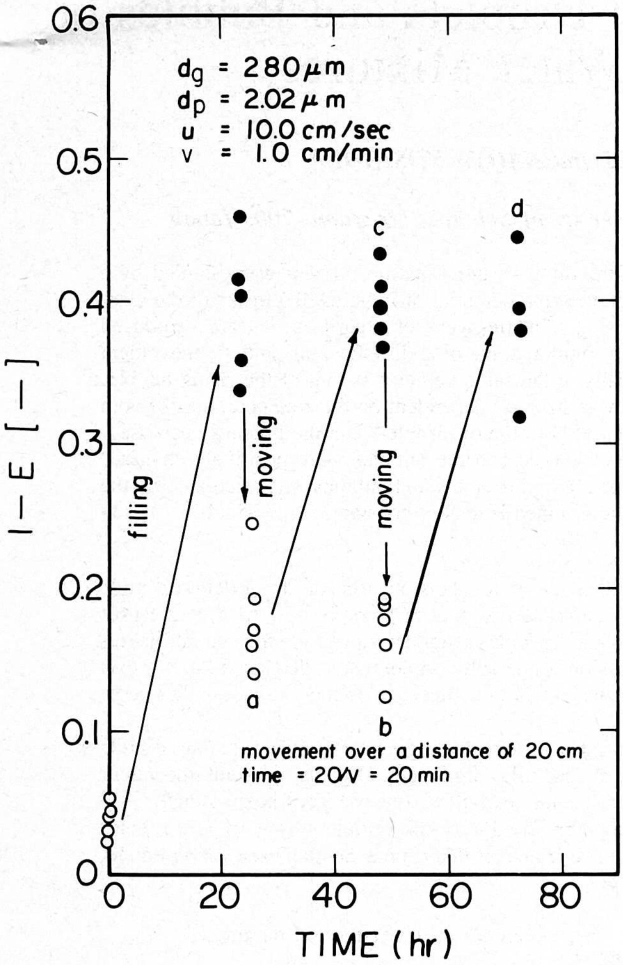

Figure 9 — Experimental evidence on the generation and dissipation of electrical charges.

The $(1 - E)$ vs. time shown in Figure 8 exhibits a decrease in E (or an increase in penetration, $1 - E$) with time. It is also shown that a significant difference in E occurs before and after particle motion. The results also indicate that after sufficient time had elapsed after the cessation of particle motion, E becomes comparable to those values obtained before particle motion. The behavior observed over all agrees with the facts that (a) inter-particle friction and particle-wall friction caused by particle motion generate electrostatic charges; (b) the charge is greatest immediately after motion stops but declines with time; and (c) electrostatic charge enhances particle collection.

A further evidence of the presence of the triboelectric effect can be seen from the data shown in Figure 9. The data for Figure 9 were compiled from measurements collected in the following manner. Initially, the filter was empty, and filter grains were poured into it. Immediately after the bed was filled, filtration (in the fixed-bed mode) measurements were made and collection efficiencies determined. The bed was then allowed to stand for 24 hours before another filtration measurement was taken. Immediately after the second measurement, the bed was set in motion for 20 minutes. Another fixed-bed measurement was taken. The bed was then allowed to stand for 24 hours, and the procedures were repeated.

The results shown in Figure 9 indicate that the collection efficiencies achieved immediately after the filter grains had been set in motion were consistently greater than those measured after the bed had been at rest for 24 hours. The contribution of electrostatic charge is obvious.

Conclusions

The experimental work carried out in this study demonstrates clearly that under conditions where solid flow rate is kept moderately low (≤ 6 cm/min), the solid motion does not interfere with gas flow in the operation of cross-flow moving-bed filters. Both the collection efficiency and pressure drop do not exhibit time-dependent behavior, and the extent of particle collection can be estimated using the simple collection efficiency correlation recently proposed by Yoshida and Tien.

Acknowledgement

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Nomenclature

c_{in} = influent concentration, number of particles/cm^3
c_{eff} = effluent concentration, numbers of particles/cm^3
C_s = Cunningham's correction factor
d_g = filter grain diameter, mm
d_p = aerosol particle diameter, μm
E = total collection efficiency
H = height of filter, mm
L = filter width, mm
N_R = dimensionless group defined by Equation (5a)
N_{Re_s} = dimensionless group defined by Equation (5b)
N_{St} = dimensionless group defined by Equation (5c)
t = time, s
u = gas velocity, cm/s
v = solid velocity, cm/min

Greek Letters

ϵ_0 = bed porosity
ρ = gas density, kg/m^3
ρ_s = particle density, kg/m^3
η_0 = unit collector efficiency
θ = defined as H/v, min
μ = gas viscosity, Pa · s

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