Metcalfe, C. I., and J. R. Howard, "Fluidization and Gas Combustion in a Rotating Fluidized Bed," *Appl. Energy*, 3, 65-74 (1977).
Murray, J. D., "On the Mathematics of Fluidization. Part I. Fundamental Equations and Wave Propagation, "*J. Fluid Mech.*, 21, 465-493 (1965).
Richardson, J. F., "Incipient Fluidization and Particulate Systems," in *Fluidization*, J. F. Davidson and D. Harrison, ed., pp. 25-64, Academic Press, New York (1971).
Roschke, E. J., "Experimental Investigation of a Confined Jet-Driven Water Vortex," Jet Propulsion Lab. Tech. Rep. No. 32-982, NASA CR 78550 (1966).
Schrage, D. L., and H. C. Perkins, Jr., "Isothermal Bubble Motion Through a Rotating Liquid," *J. Basic Eng.*, 94, 187-192 (1972).
Siekmann, J., and K. Dittrich, "Über die Bewegung von Gasblasen in einem rotierenden Medium," *Ingenieur Archiv*, 44, 131-142 (1975).
Turner, J. S., "The Constraints Imposed on Tornado-Like Vortices by the Top and Bottom Boundary Conditions," *J. Fluid Mech.*, 25, 377-400 (1966).

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Electrically Stimulated Aerosol Filtration in Packed Beds

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Since charged particles are quite mobile in an electric field, charge is often added to aerosol particles to facilitate capture; indeed, provision for such charging is an indispensable part of electrostatic precipitators. Nevertheless, calculations disclose that a very slight amount of charge may suffice when the distance the aerosol particle must travel to the collector surface is small, contrary to the usual situation. In the experiments described here a model aerosol containing 0.5 μm polystyrene particles passed through a radioactive charge neutralizer to deliberately reduce the charge as much as practicable and then through a packed bed under the influence of a fairly large external electric field. Filtration efficiencies approaching 100% were obtained owing to the influence of the field on small amounts of residual charge.

SCOPE

It is well known that aerosol particles with diameters in the range 0.2 to 1 μm are difficult to remove by filtration, since such particles are too large for diffusion to be effective but are too small for efficient inertial capture. Electrical effects, however, enhance the rate of capture of such particles by three mechanisms: coulombic attraction between a charged particle and a collector, attraction between dipoles induced in a particle and a collector by an externally imposed field, and through the force on a charged particle due to an external electric field. For the capture of submicron size particles, the charged particle-electric field interaction can be especially effective. Estimates of the amount of charge required for efficient filtration using a packed bed suggest that very small amounts may suffice, and the experiments described here were used to test this hypothesis. In the experiments, the charge levels on a model aerosol were deliberately reduced using a radioactive source neutralizer. Coarse metal screens placed perpendicular to the flow were used to impose an electric field across the glass bead packing.

CONCLUSIONS AND SIGNIFICANCE

High filtration efficiencies were achieved which were due primarily to the influence of the field on a small amount of residual charge on the particles. This was deduced from the following observations and calculations. First, comparison of aerosol concentrations measured by electrical and mechanical methods indicates that the average charge level on the aerosol after passing through the neutralizer was small, close to the average of two to three elementary charges reported by Whitby and Liu (1968) for a similarly neutralized aerosol. This is also consistent with the amount necessary to produce the observed rates by the external field charged particle force which, according to the computations reported here, ranged from one to four elementary units per particle. Since, in addition to the fact that the coulombic interaction is independent of the external field, the charge levels themselves appear too small to create significant coulombic interactions, this sort of electrical effect was discounted. On the other hand, estimates of the collection rates expected from polarization effects show that this effect is weak and not the primary cause of the high capture rates observed. Finally, lower efficiencies were observed in the upper portions of the bed, and this is consistent with the effect of an external field on an aerosol with a distribution of charge. Thus, the charged particle-external field force emerges as the dominant cause of the high collection rates.

Whitby and Liu (1966) have shown that the natural average charge levels on many particles are fairly large, suggesting that the natural charge on respirable aerosols may be adequate for filtration, thereby eliminating the need for a separate charging unit in some instances. This would further reduce the operating costs for what already appears to be a very economical filter, since the pressure drop across the bed is low and the current small.

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Filtration with packed beds is widespread, sand filters are common in water and sewage purification systems and coke boxes have long been used to remove mists from sulfuric acid plants. In all these devices, diffusive, gravitational, and inertial forces drive the particulate matter to the surface of the packing, thereby removing it from suspension. With aerosols, as with most suspensions, the size of the particle controls, to a large extent, the nature of the collection process. When the particle diameter is smaller than, say, 0.2 μm, diffusion to the packing is the primary collection mechanism. On the other hand, gravity and particle inertia dominate the capture of particles greater than 1 μm.

Gebhardt et al. (1973), for example, studied the filtration of polystyrene aerosol in beds of glass beads and demonstrated that high filtration efficiencies may be obtained in both the diffusive and gravitational-inertial regions. However, neither diffusion, gravity nor inertia are particularly effective for particles in an intermediate range (for example, 0.2 to 1 μm) and markedly poorer filtration results. While it is possible to achieve any degree of collection by lengthening the bed, doing so increases the pressure drop across the filter and thereby affects operating costs. Fortunately, it is also possible to improve the filtration by adding a suitable force, such as an electrical one, between the particle and the collector. In an investigation of electrical effects in packed bed filters, Anderson and Silverman (1958) used charged polystyrene granules as collectors, and the coulombic attraction between the particles and the packing produced a noticeable improvement in the filtration.

More recently, Alexander and Melcher (1977) and Zahedi and Melcher (1977) have continued the investigation of electrical effects, placing greater emphasis on modeling the electrical enhancement. To ensure a large and constant quantity of charge on the particles, the aerosol is passed through a corona before being filtered, and since the static charge within the bed, upon which Anderson and Silverman relied, is difficult to model or control, it was deliberately eliminated. An external electric field across the bed polarized the surface of the packing, and the poles induced on each packing element served as enhanced collection sites for the highly charged aerosol. This procedure gave reproducible, predictable results. Overall collection efficiencies close to 100% were obtained for a 0.4 μm diameter di-octyl phthalate aerosol in beds of 1 mm sand particles less than 10 cm deep. This is substantially better filtration than that of a standard packed bed under these conditions. They also emphasized the advantages of the low pressure drop and the much smaller size of these units compared to the bag filter or electrostatic precipitator, the two most common particulate removal devices currently in use.

Related work by Kirsch (1972) with fibrous filters indicates that electrical effects can also improve the filtration of neutral particles. Under the influence of an electric field, both the particle and collector polarize, and the attraction between poles of opposite charge enhances the capture. In one set of experiments, Kirsch measured the collection of a neutral aerosol in a filter constructed of fibers 25 μm in diameter which had a void fraction of 98%. The filter efficiency was 99.9% for 2.66 μm diameter particles at a field strength of 10.8×10^5 V/m. However, since the polarization force is proportional to the volume of the particle, the efficiency dropped off to 53% for 0.12 μm diameter particles. Although Kirsch obtained highly consistent results, his data and the theory for polarization capture suggest that it will be most effective when the aerosol particles are large and the collectors small. Accordingly, polarization will probably play a minor role in the filtration of submicron particles in packed beds where the collectors tend to be millimeter size. Of course, it is possible to decrease the size of the packing, but smaller packing increases the pressure drop.

THEORY

Theories which suffice for the present are reviewed in the monographs by Hidy and Brock (1970) or Davies (1973), and so most of the details can be omitted here. The purposes of this section are simply to set down the relevant formulas and discuss their implications for this study.

The collection efficiency of an array of collector units, a packed bed for example, can be estimated from knowledge of the efficiency of a single representative unit. The efficiency of a single isolated unit is simply the ratio of two areas: the upstream area of the flow swept free of particles and the projected area of the collector. When this efficiency η_c is combined with a conservation equation for the particles in suspension, the fraction of the particles removed by the bed is

$$\eta_B = 1 - \exp\left[\frac{3(\phi - 1)h}{4R_c}\eta_c\right] \tag{1}$$

The efficiency of a single collector η_c depends on the capture mechanisms, and, as a first approximation, collection efficiencies for different mechanisms are often assumed to be additive. For charged particles under the influence of an external field, the single-particle efficiency in the absence of all other capture forces is (Zebel, 1968)

$$\eta_c = (1 + 2\gamma_c)\, G(1 + G)^{-1} \tag{2}$$

where

$$\gamma_c = (\epsilon_c - \epsilon_f)/(\epsilon_c + 2\epsilon_f)$$

and

$$G = Q_p\, E_\infty/6\pi\mu\, U\, R_p$$

The parameter denoted as G is, in essence, the electrically engendered velocity of a single aerosol particle compared to the speed of the suspending fluid.

The premise under investigation here is that the action of a strong external electric field can produce a high collection efficiency even when the aerosol particles are weakly charged. For a particle typical of those used in this study, $G = 1.5 \times 10^{-2}$, $\gamma_c = 0.55$ and so $\eta_c = 0.03$. The collection efficiency of a bed packed with glass beads to a height of 10^{-1} m is 0.95.*

According to this calculation, some 95% of the entering particles would be collected. Even though the particles are only weakly charged, the field causes them to move at a velocity of about 10^{-3} m/s, roughly one collector diameter per second relative to the flow. Thus, since an aerosol particle spends roughly 1 s in the bed, it is obvious that the probability of capture by the packing is high, since the average distance to be traversed for capture is roughly one particle diameter.

There are, of course, other mechanisms for capture: inertial capture, interception, electrical polarization and coulombic interactions. Estimates indicate far smaller roles for all of them. Inertial effects and interception are negligibly small, and polarization effects are roughly an order of magnitude smaller than the charged particle-external field effect. An estimate for the coulombic effect requires knowledge of the charge on the packing, but for an effective charge of the order of 10^4 electrons per collector, the collection efficiency is still negligible.

Based on the calculation outlined above, it should be possible to remove almost all the particles from an aerosol, even though the typical charge per particle is small. An experimental investigation of this premise is described next.

EXPERIMENTAL APPARATUS

Figure 1 is a schematic diagram of the apparatus. Air supplied by a compressor first flows through a coarse filter then up through a bed of silica gel to be dried before the final purification stage of an absolute (0.3 μm DOP test) glass filter. The flow then splits, roughly 3 l/min goes to the aerosol generator and the remainder rejoins the aerosol flow later to dry the particles as well as to extend the range of flows investigated.

A Thermo-Systems atomizer (model 3075) produces the aerosol from a hydrosol of 0.5 μm polystyrene spheres (Liu and Lee, 1975). This hydrosol was synthesized by emulsion-free polymerization of styrene in distilled water at 65°C using $K_2S_2S_8$ as an initiator. The immediate product of the reaction was a suspension of polystyrene in water which

* $R_p = 0.25 \times 10^{-6}$ m, $U = 10^{-1}$ m/s, $E_\infty = 4 \times 10^5$ V/m, $Q_p = \pm 3.2 \times 10^{-19}$ C (± 2 electrons), $\mu = 1.8 \times 10^{-5}$ kg/m-s, $\epsilon_c = 4.6\ \epsilon_0$, $\phi = 0.33$, $R_c = 5 \times 10^{-4}$ m.

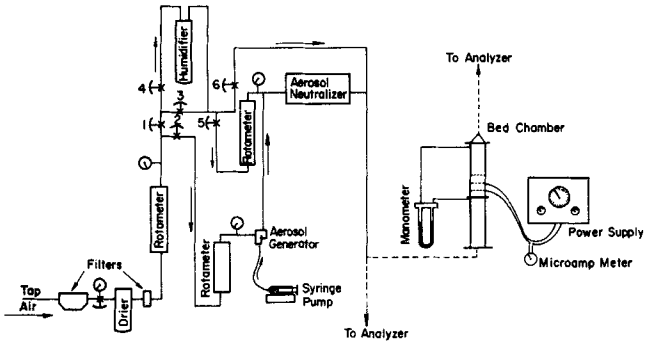

Fig. 1. Apparatus diagram.

was then diluted by a factor of 3:100 to facilitate operation of the atomizer. In order to reduce contamination, the dilution water was distilled and then filtered through a 0.45 μm filter.

As mentioned above, the aerosol stream from the atomizer mixes with a large flow of dilution air which serves to dry the aerosol and provide the desired range of flow rates. The resulting number concentration was of the order of $10^9/m^3$. Since the humidity of the aerosol stream has a strong influence upon the electrical properties of the glass bead packing, a simple bubbler was installed in the dilution air line to control humidity in the bed. The water filling the humidifier is also filtered to reduce contamination of the aerosol, and the amount of air bubbling through the humidifier is controlled so that the relative humidity of the air stream entering the bed is 34% at room temperature. Finally, a set of wet and dry bulb thermometers was used to measure the stream humidity. Although Melcher and his colleagues found a relative humidity of 80% or greater desirable to suppress static electrification, they performed the majority of their studies on fluidized beds where the constant friction between packing elements is normally a fertile source of static charges. Except for charges created while filling, the packed bed ought not to generate static charges, and therefore it is more important that the humidity in these experiments be constant rather than high.

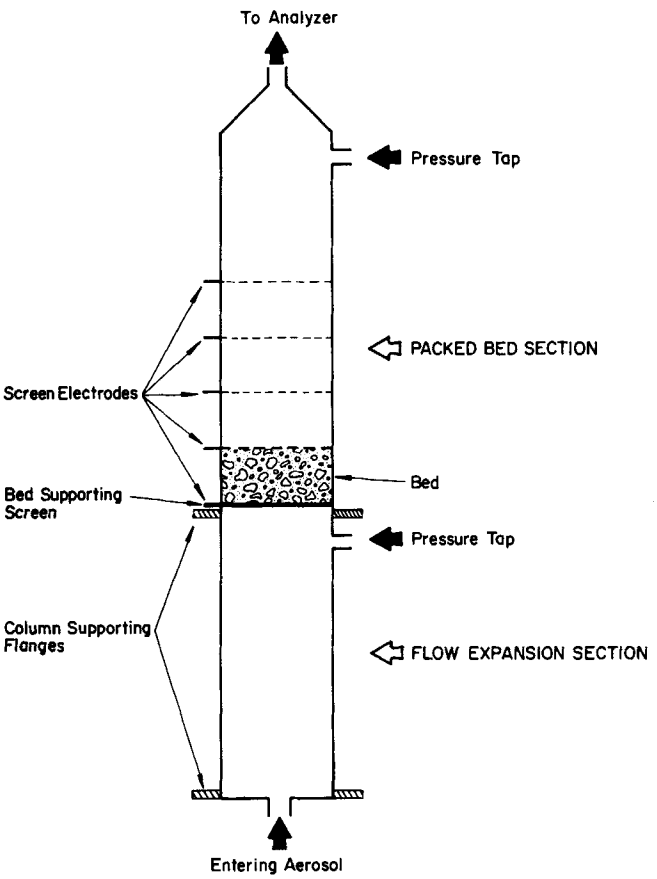

Fig. 2. Schematic diagram of the packed bed filter.

In addition to being wet, the polystyrene carries a large surface charge when it leaves the atomizer (Whitby and Liu, 1968). To reduce this charge the stream is sent through a radioactive neutralizer (Thermo Systems model 3012). It is impossible to eliminate all charge on the particles in an ionized atmosphere, and the theoretical bipolar distribution limit corresponds to the Boltzmann equilibrium (Whitby and Liu, 1966). The aerosol exiting from the neutralizer should carry a charge distribution close to the Boltzmann equilibrium, where nearly 20% of the 0.5 μm particles are neutral, and the absolute value average charge is 1.7 units. Whitby and Liu (1968) were unable to measure the low charge levels which resulted after passing polystyrene aerosol through a similar radioactive neutralizer, but they estimated that the absolute value average charge on 0.557 μm particles was two to three units. In a more thorough study, Liu and Pui (1974*a*) found that the charge distribution on di-octyl phthalate aerosols which had been treated in a radioactive neutralizer mapped quite well to the Boltzmann equilibrium. Since this neutralizer is designed for a maximum flow of 30 l/min, excess dilution air joins the aerosol stream after it leaves the neutralizer. At this point the aerosol stream is ready to be measured or sent to the filter.

A Thermo Systems model 3030 electrical aerosol analyzer measures the concentration of the aerosol stream before or after passing through the bed. Liu and Pui (1974*b*) have described the analyzer in detail, and therefore only a summary of its operation will be given here. In the analyzer, particles are charged and then sent through an electrostatic precipitator. The aerosol's mobility after leaving the charger is dependent upon particle size; hence applying selected electric fields across the precipitator results in the capture of different size particles. The aerosol not caught by the precipitator exits into an absolute filter and is trapped there while its charge drains off into an electrometer. A low pass filter converts the resulting current into a voltage which is displayed on a chart recorder.

Despite the efforts to reduce contamination, 0.1 μm and smaller particles are present in the aerosol. However, if the precipitator field is set at 6 600 V/m, these tiny contaminants are trapped in the precipitator while the 0.5 μm particles pass to the absolute filter/electrometer and are recorded. By using this precipitator field strength, we were able to measure the concentration of the monodisperse 0.5 μm particles alone.

A fairly rigorous test of the neutralizer's efficiency and the analyzer's accuracy is to compare the concentration measured using the neutralizer/analyzer with that obtained from an impactor. In order to obtain an accurate concentration measurement from the analyzer, the charge on the entering aerosol must be known or insignificant compared to that added by the instrument. We measured the concentration with the analyzer and a four-stage impactor simultaneously over a period of 6 hr. At a flow rate of 24 l/min, the concentration calculated from the voltage output, assuming neutral particles, exceeded that measured using the impactor by only 9%. When we consider the accuracy of the impactor ($\pm$ 12% when four plates are used), this represents excellent agreement. From this result we again estimate that the average charge on the aerosol was $\pm$ 2 electrons.

After being measured in the analyzer, the aerosol stream is sent to the bed, a diagram of which is shown in Figure 2. The column is constructed from 6.35 mm Plexiglas and has a square cross section 5 cm on a side. It is comprised of two parts. The lower section is 30 cm long and allows the entering jet (~4 mm diameter) to expand evenly over the entire cross section. Glass beads 0.2 mm in diameter fluidized uniformly across the bed indicating that the 30 cm expansion length is adequate.

The main section of the column is roughly 35 cm long and contains the bed which is supported by a fine stainless steel screen. Glass beads of 0.15 (lime glass), 0.051 and 0.024 cm (borosilicate glass) diameter are used as packing. To promote a consistent packing configuration, the bed was tapped lightly before the start of each run at a new bed height. The electric field is applied between four grids (0.5 cm wire spacing) which span the bed's cross section and are constructed from 1 mm tinned copper alloy. The lowest grid is covered with the bed supporting screen, and the distances from it to screens higher in the bed are 4.7, 9.8 and 14.9 cm.

The power supply generates positive d.c. potentials from 0 to 30 kV on one wire with the second wire grounded. Thus, the maximum bulk field strength is 6.4×10^5 V/m. A microamp meter of range 0 to 50 μA is connected in series with the positive lead to note the total current drawn. The column sections are joined with 1 cm brass bolts and sealed with silicone rubber which gave an airtight bond. The pressure drop across the bed is measured by a water manometer driven from pressure taps near the top of the expansion and packed sections of the column. A

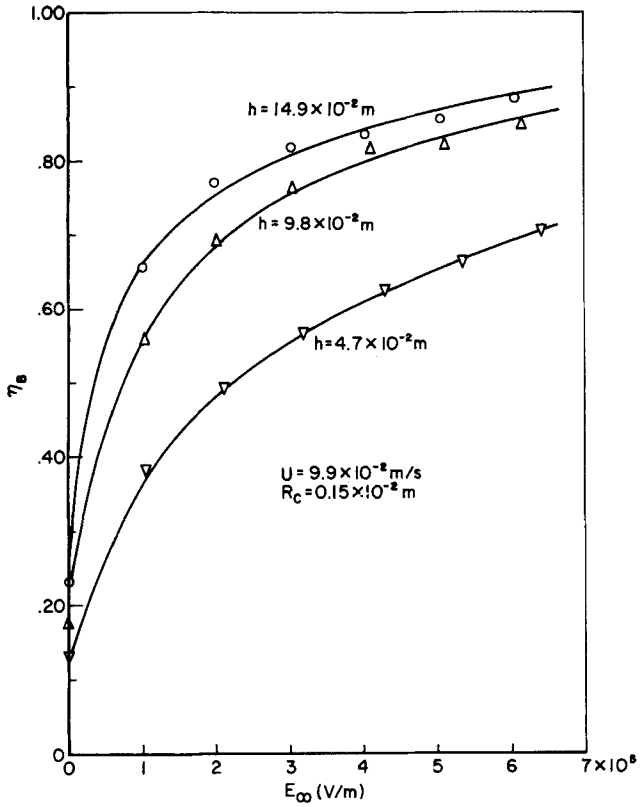

Fig. 3. Effects of field strength and bed height on filtration efficiency.

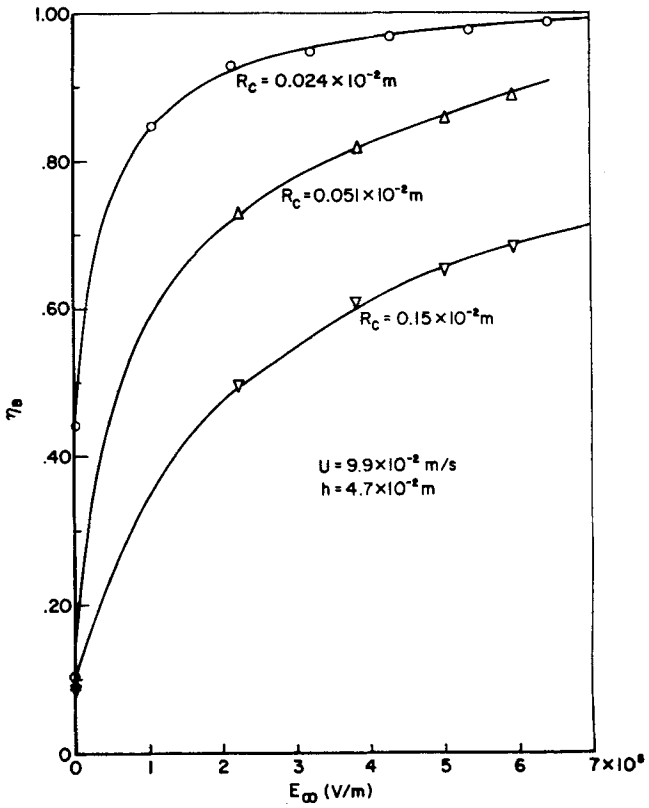

Fig. 4. Effects of field strength and collector size on filtration efficiency.

safety screen covered the entire column when the electric field was present.

For purposes of completeness, it was necessary to consider whether the particles acquired charge in passing through the bed. A change in the degree of charge on the particles could distort the analyzer output and cause apparent changes in the concentration. The packing does intensify the field, and the current drawn by the electrodes often increased sharply at the higher fields studied, suggesting a corona. The presence of corona in the empty bed chamber was investigated by applying a potential across the screens and observing the system in the dark. While the leads from the screens protruding from the bed glowed lightly and occasionally discharged between themselves at potentials up to 30 kV, the inside of the chamber remained dark. Only once, at the maximum field of 6.4×10^5 V/m, did a violent blue discharge occur between the two lowest screens, lasting until the field was reduced below 5.7×10^5 V/m. When filled with glass beads, the chamber exhibited no corona, despite the continued presence of a corona on, and between, the screen leads on the outside. As a final test, a few runs were repeated in which

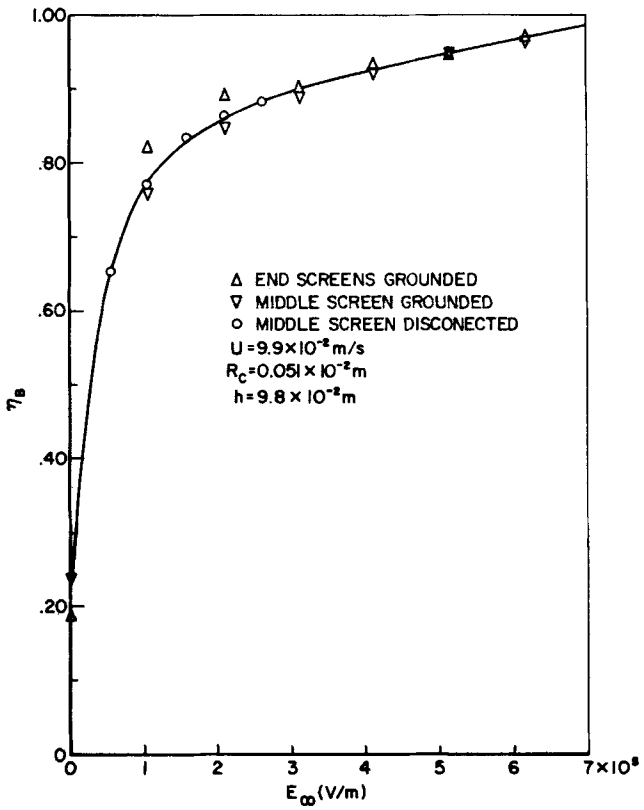

Fig. 5. Effects of field configuration on filtration efficiency.

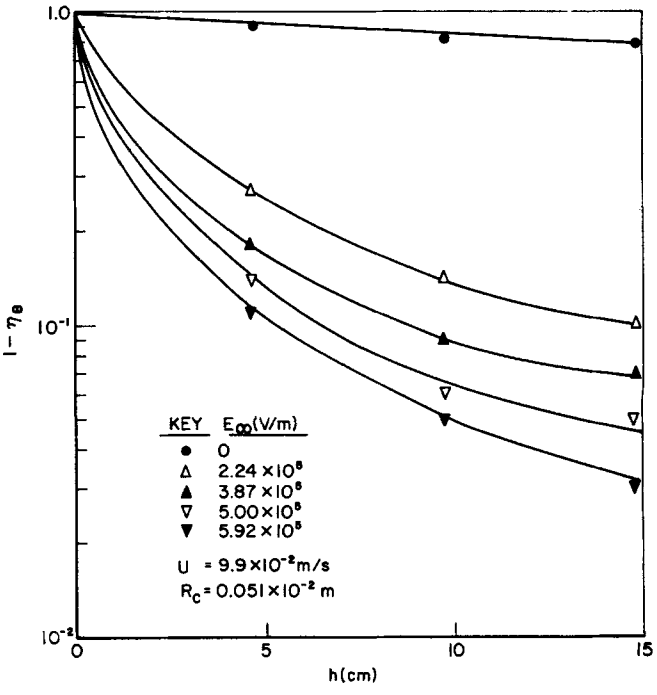

Fig. 6. Effects of bed height and field strength on filtration efficiency.

TABLE 1. ESTIMATED CHARGE LEVELS*

(a) $R_c = 0.15 \times 10^{-2}$ m, $U = 9.9 \times 10^{-2}$ m/s

Field strength, V/m	Bed height 4.7×10^{-2} m	9.8×10^{-2} m	14.9×10^{-2} m
2.24×10^5	4.9	2.7	3.5
3.87×10^5	4.0	2.9	2.4
5.00×10^5	3.5	2.5	2.0
5.92×10^5	3.2	2.5	1.9

(b) $R_c = 0.05 \times 10^{-2}$ m, $U = 9.9 \times 10^{-2}$ m/s

2.24×10^5	2.8	2.5	1.9
3.87×10^5	2.3	1.9	1.3
5.00×10^5	2.1	1.6	1.2
5.92×10^5	2.0	1.5	1.1

* Charge levels computed from Equations (1) and (2) in units of $1.6 \times 10^{-19} C$ (1 electron).

the analyzer output was recorded over a wide range of precipitator voltages. No change in the distribution of output was noticed, confirming the data's validity and indicating that the analyzer was an acceptable instrument for these experiments.

RESULTS

Figures 3 and 4, which typify the experimental results from nearly one hundred runs, show that the action of an electric field greatly improves filtration. Such enhancement cannot result from coulombic capture, as the coulombic force is independent of field strength. Reversing the field had no appreciable effect upon the collection, suggesting either that polarization forces were responsible for the capture or that the aerosol was charged bipolarly. Occasionally, the middle screens were disconnected in the 9.8 and 14.9 cm deep beds and the field generated between screens at the top and bottom of the bed. Identical bulk field strengths resulted in the same filtration efficiency which demonstrated the uniformity of the field. An example of these tests on a 9.8 cm bed is shown in Figure 5. As the theory based on the single spherical collector predicts, greater filtration results from smaller beads, stronger fields and deeper beds. Nevertheless, Figure 6 indicates that the customary inverse exponential height dependence was absent (Gebhardt et al., 1972).

The bed efficiencies computed earlier demonstrate that the charged particle-electric field interaction is the main factor producing the large efficiencies observed. The particles are too small for major polarization effects under the conditions studied, and the theory for filtration by polarization forces fails to correlate the data. Assuming the filtration to be entirely caused by the charged particle field interaction, and neglecting any intensification of the field due to the packing, we solved for the charge necessary to produce the observed collection using Equations (1) and (2). This charge corresponds to a representative charge for those particles caught by the bed, and, as Table 1 shows, it is surprisingly low. The charge levels calculated in Table 1 differ from the average charge at the Boltzmann equilibrium (± 1.7 electrons) by only one or two units.

If the aerosol is charged, then it is likely to contain a distribution of charges. Those particles with a high level of charge will be captured most readily at lower field strengths, on larger collectors, in shorter beds or in the lower sections of longer beds. Farther into the bed the charge of the remaining particles diminishes, lowering the efficiency in the upper reaches of the bed. Similar arguments apply for the field strength and collector size, and the results anticipated are borne out in the tables: the effective charge level declines with increasing h and E_∞ and with decreasing R_c. Charge levels close to unity in the longer beds imply that neutral particles make up a substantial fraction of the aerosol in the higher regions of the filter. An estimate of the single collector efficiency from dipole forces reveals that it is of the same magnitude as the bead efficiencies in the upper sections, and it seems likely that the aerosol is captured largely by polarization forces here. Although polarization capture occurs in the lower sections of the bed as well, its contribution there is dwarfed by the collection of charged particles.

Most aerosols carry charges of at least several elementary units per particle, acquired by various mechanisms, making them highly vulnerable to this method of filtration (Whitby and Liu, 1966). Even if the charge is as low as the Boltzmann equilibrium, it should be possible to increase filtration rates dramatically using an external electrical field.

ACKNOWLEDGMENT

Messrs Harold Lambert and Harry Buvel rendered their usual competent assistance with the fabrication and assembly of the apparatus.

NOTATION

E_∞ = bulk field strength, V/m
G = $Q_p E_\infty / 6\pi\mu U R_p$
h = bed height, m
Q_p = charge per aerosol particle, coulombs
R_p = aerosol particle radius, m
R_c = collector particle radius, m
U = superficial gas velocity, m/s

Greek Letters

ϵ_c = dielectric constant of collector particle, dimensionless
ϵ_f = dielectric constant of fluid, dimensionless
ϵ_0 = permittivity of a vacuum, 8.85×10^{-12} Farads/m
η_c = single collector efficiency, dimensionless
η_B = bed collection efficiency, dimensionless
μ = gas viscosity, kg/m-s
ϕ = bed porosity, dimensionless

LITERATURE CITED

Anderson, M. D., and L. Silverman, "Mechanisms in Electrostatic Filtration of Aerosols with Fixed and Fluidized Beds," Air Cleaning Laboratory, School of Public Health, Harvard University, Report on Contract AT(30-1)841 (Aug., 1958).

Alexander, J., and J. R. Melcher, "Alternating Field Electrofluidized Beds in the Collection of Submicron Aerosols," *Ind. Eng. Chem. Fundamentals*, **16**, 311-317 (1977).

Davies, C. N., *Air Filtration*, Academic Press, New York (1973).

Gebhardt, J., C. Roth, and W. Stahlhofen, "Filtration Properties of Glass Bead Media for Aerosol Particles in the 0.1-2 μm Size Range," *Aerosol Sci.*, **4**, 335-371 (1973).

Hidy, G. M., and J. R. Brock, *The Dynamics of Aerocolloidal Systems*, Pergamon Press, Oxford, England (1970).

Kirsch, A. A., "The Influence of an External Field on the Deposition of Aerosols in Fibrous Filters," *Aerosol Sci.*, **3**, 25-29 (1972).

Liu, B. Y. H., and K. W. Lee, "An Aerosol Generator of High Stability," *J. Amer. Industrial Hygiene Association*, 861-865 (1975).

Liu, B. Y. H., and D. Y. H. Pui, "Equilibrium Bipolar Charge Distribution of Aerosols," *J. Colloid Interface Sci.*, **49**, 305-312 (1974*a*).

Liu, B. Y. H., and D. Y. H. Pui, "On the Performance of the Electrical Aerosol Analyzer," *Aerosol Sci.*, **5**, 465-472 (1974*b*).

Whitby, K. T., and B. Y. H. Liu, "The Electrical Behavior of Aerosols," in *Aerosol Science*, C. N. Davies, ed., pp. 59-86, Academic Press, New York (1966).

Whitby, K. T., and B. Y. H. Liu, "Polystyrene Aerosols, Electrical Charge and Residual Size Distribution," *Atmosphere Environment*, **2**, 103-116 (1968).

Zebel, G., "Capture of Small Particles by Drops Falling in Electric Fields," *J. Colloid Interface Sci.*, **27**, 294-304 (1968).

Zahedi, K., and J. R. Melcher, "Collection of Submicron Particles in Bubbling Electrofluidized Beds," *Ind. Eng. Chem. Fundamentals*, **16**, 248-254 (1977).

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