Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Rincón, J. , Guardiola, J. and Romero, A.(1992) 'Gas Filtration in Binary Fluidized Beds', Separation Science and Technology, 27: 15, 2171 — 2185
To link to this Article: DOI: 10.1080/01496399208019473
URL: http://dx.doi.org/10.1080/01496399208019473

SEPARATION SCIENCE AND TECHNOLOGY, 27(15), pp. 2171–2185, 1992

Gas Filtration in Binary Fluidized Beds

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Abstract

A systematic experimental study of aerosol filtration in a binary fluidized bed of dielectric material is carried out. Measurements of the collection efficiency when such parameters as gas velocity, bed height, collecting mixture, and column diameter are varied over a wide range have been made. Experimental evidence is given to show that charges generated naturally by triboelectrification of the bed dielectric particles can considerably increase the efficiency of such beds. Furthermore, it is demonstrated that a proper choice of the fluidized mixture can significantly improve the performance of such filters.

INTRODUCTION

The idea of using a fluidized bed for particulate removal dates back to the late 1940s (*1*). Since then, because of the operational advantages offered by fluidized filters (namely, continuous operation and the possibility of working under severe conditions), a number of authors have examined the various aspects of their operation and application (*2–5*). The major drawback is that they inevitably operate in a bubbling regime and, since the bubble phase offers a bypass for gas flow, the overall collection efficiency is reduced. This disadvantage may be overcome in two possible ways: (a) suppressing bubble formation through the use of internal buffles, neutrally buoyant bubble brakers (*6*), or magnetic stabilization (*7–9*); and (b) in-

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creasing the particle removal efficiency on the dense phase by stimulating electrostatic collection either by applying an external magnetic field (*10–12*) or by boosting electric charge generation by triboelectrification of the bed collector particles (*13–16*).

The last type of charging—triboelectrification—occurs naturally and is almost unavoidable in a fluidized bed of insulating material. On the other hand, recent experimental work by Gradon (*17*) has shown that the charge generated may be higher when the bodies brought into contact have different dielectric constants and high surface resistivity. Consequently, one can readily see the advantages of operating with a binary fluidized filter, i.e., with a fluidized bed consisting of mixtures of two different dielectric materials.

In this paper a systematic experimental study of aerosol filtration in binary fluidized beds (BFB) is carried out. The objective of the work is to gain understanding on the performance of such filters, specifically to determine if theoretical models for monocomponent fluidized filters can be used to predict their behavior. The experimental data are used to test the validity of existing theories. Finally, both the superficial charge density on the bed dielectric medium and the contribution of the electrostatic collection mechanism to the overall collection efficiency are evaluated.

EXPERIMENTAL SECTION

Apparatus

The experimental facility used in this work is shown schematically in Fig. 1. Briefly, it consists of the following: *The binary fluidized filter* itself, a binary mixture of plastic and glass spherical particles supported by a perforated plate distributor (A_L = 4.5%, d_o = 1.5 mm) inside a perspex column.

The aerosol generator, a fluidized bed of glass ballotini into which the carbon fines are fed through a rotating brush screw. In this device the bed particles and the carbon fines are, respectively, fluidized and elutriated by the air stream used to operate the generator. The exit aerosol suspension is allowed to enter into a settling chamber where the largest particles are removed.

The sampling system consisted of (a) sampling probes, attached at both ends of the BFB filter; (b) filter holders, which housed the membrane filters where the sampled aerosol particles were retained; and (c) an electronic particle counter (Coulter Counter, model ZM) where both particle size and particle concentration were determined.

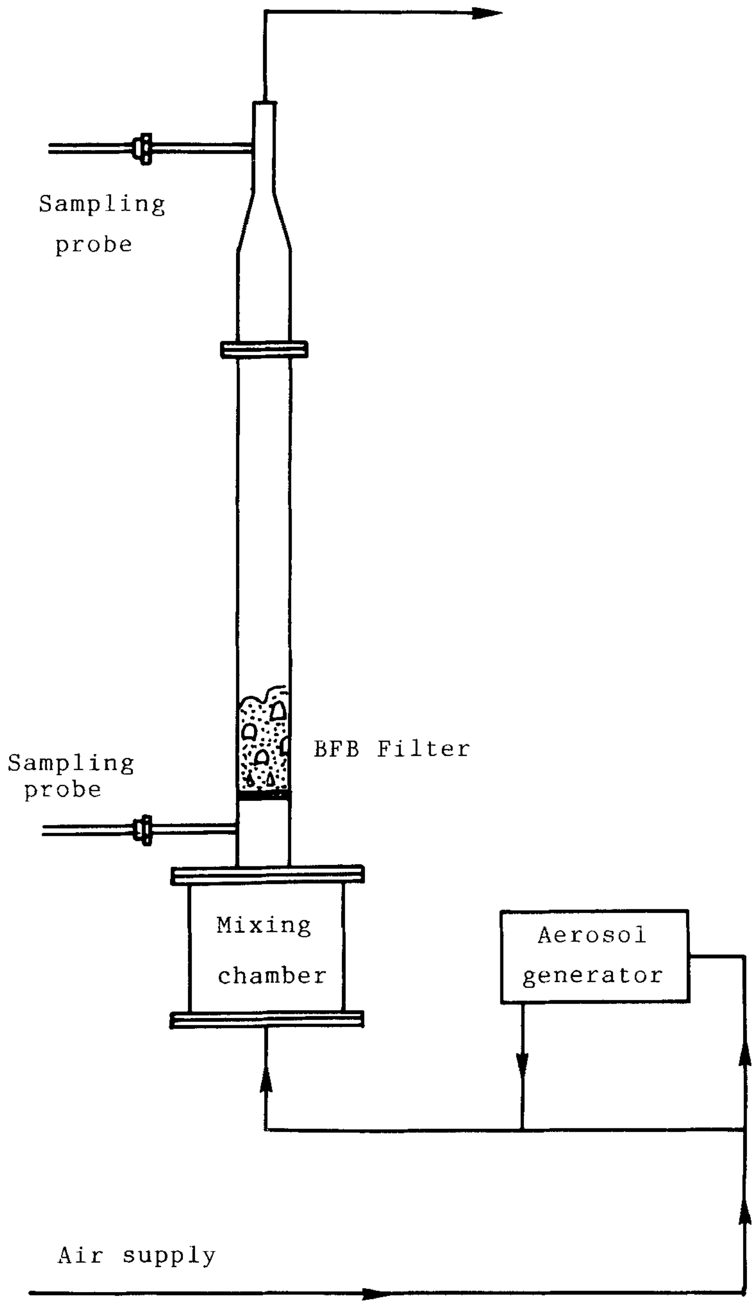

FIG. 1. Experimental facility.

Experimental Systems and Variables

The experimental systems were: (a) mixtures of glass beads (d_g = 460–1090 μm, ρ_g = 2.7 g/cm^3) and plastic spherical granules (d_p = 3100 μm, ρ_p = 0.98 g/cm^3) that were used as collector particles, and (b) carbon fines (d_a = 4.4–14 μm, ρ_a = 1.85 g/cm^3), a dark powder of low cohesiveness that was used to prepare the aerosol suspensions.

The experimental variables included gas velocity, bed height (expressed in column diameter units), aerosol size, column diameter, and type of collecting mixture. Each mixture was designed by M with a superscript and a subscript. The superscript refers to the volumetric proportion of glass used in the mixture (30, 50, and 70%) and the subscript to their size with the numbers 1, 2, 3, 4, and 5 being assigned to glass particle diameters of 1090, 775, 665, 550, and 450 μm. For example M_2^{70} refers to a mixture of plastic and glass particles where the average size of the glass is 775 μm and its volumetric proportion is 70%. A summary of the experimental conditions is given in Table 1. The data are tabulated in Reference *15*.

Procedure

Preliminary steps included the washing, drying, and mixing of the particles that would make up the bed. Then the binary mixture was introduced into the column, the air supply was switched on, and the aerosol generator was started.

The air stream supplied by the compressor was divided into two parts, one of which was used to operate the aerosol generator. The exit aerosol suspension from the generator was then combined with the rest of the air at the mixing chamber and, finally, allowed to enter the BFB filter.

Each experiment lasted 20 minutes. Aerosol samples were taken simultaneously at both the inlet and the exit of the filter during this time period. The samples were later analyzed in an electronic particle counter.

TABLE 1
Experimental Variables

D_c (cm)	5.5	9.0	11.5
H_0/D_c	1	2	3
u (m/s)	0.50	0.75	1.00
d_a (μm)	From 4.4 to 14.0		
Mixture	M_i^j; i = 1, 2, 3, 4, 5; j = 30, 50, 70		

Analysis of the Data

The performance of a fluidized bed filter may be described by its overall collection efficiency, η, defined as

$$\eta = 1 - c_e/c_i \quad (1)$$

where c_i and c_e are, respectively, the particle concentration of the influent and effluent streams. In the experiments carried out in this work, both concentrations were measured and, therefore, the overall collection efficiency could be obtained experimentally from its definition.

On the other hand, from experimental measurements of the design and operating variables and using a macroscopic fluidized bed filter model, the overall collection efficiency can be theoretically predicted. Since the use of a model and its comparison with experimental data can either illuminate the way in which BFB filters behave or indicate new areas for investigational work, the overall collection efficiency obtained experimentally is compared against that predicted from two models (*22*, *23*). The experimental results are discussed later in the light of the comparison.

The models were proposed by Clift et al. (*22*) and Warrior and Tien (*23*). They have been successfully applied to interpret experimental data of aerosol collection in monocomponent fluidized filters (*14*, *15*, *24*). In the following we will refer to them as the C-Model and the WT-Model.

The C-Model evaluates the overall collection efficiency, η, from the expression

$$\eta = 1 - [X(m_2 e^{-m1} - m_1 e^{-m2}) - (1 - \beta)m_1 m_2(e^{-m1} - e^{-m2})/X(m_2 - m_1)] \quad (2)$$

where m_1 and m_2 are the square roots of the equation

$$(1 - \beta)m^2 - [X + (1 - \beta)k]m + KX(1 - \beta e^{-Y}) \quad (3)$$

Thus, the collection efficiency is calculated as a function of four parameters (X, β, k, Y) whose definition is given in the notation.

The WT-Model proposes the following equation for η:

$$\eta = 1 - [\beta(c_B^*)_{H^*=1} + (1 - \beta)(c_P^*)_{H^*=1}] \quad (4)$$

where c_B^* and c_P^* are complicated functions of several parameters (k, ϵ_B, H, u, and λ) also defined in the notation. H^* is a dimensionless bed height

TABLE 2
Correlations to Calculate the Individual Collection Efficiencies

Mechanism	Correlation	Remarks	Author
Inertia	$E_i = 0.2589 N_{St.eff}^{1.3437}$	$N_{St.eff} = [A(\epsilon) + 1.14 N_{Re}^{1/2} \epsilon^{-3/2}] N_{St}$ $A(\epsilon) = \frac{6 - 6(1-\epsilon)^{5/3}}{6 - 9(1-\epsilon)^{1/3} + 9(1-\epsilon)^{5/3} - 6(1-\epsilon)^{6/3}}$	Jung et al., 1989 (*19*)
Diffusion	$E_D = 4A(\epsilon)^{1/3} N_{Pe}^{-2/3}$		Rajagopalan and Tien, 1976 (*18*)
Gravity	$E_G = (1-\epsilon)^{2/3} N_G$		Rajagopalan and Tien, 1976 (*18*)
Interception	$E_I = 1.5 N_I^2 f^3(\epsilon)$	$f(\epsilon) = 1.09/\epsilon$	Gutfinger and Tardos, 1979 (*20*)
Electrostatic attraction	$E_E = (15\pi K_E/8)^{0.4}$	$K_E = \frac{(\epsilon_D - 1) 2 C d_a^2 Q_s^2}{(\epsilon_D + 2) 3 \mu d_M u \epsilon_0}$	Kraemer and Johnstone, 1955 (*21*)

defined as h/H, where H is the expanded bed height and h is the bed height at a given level above the distributor.

According to Expressions (2) through (4), the single collection efficiency, E (defined as the collection efficiency that may be imputed to a single particle), should be evaluated prior to applying the models. This magnitude is usually assumed to be the addition of various separate efficiencies due to each operative mechanism of particle collection. Therefore one may write

$$E = E_D + E_i + E_I + E_E + E_G \quad (5)$$

where the subscripts D, i, I, E, and G refer, respectively, to the collection efficiencies due to diffusion, inertia, interception, electrostatic attraction, and sedimentation. They may be estimated from the expressions listed in Table 2.

RESULTS AND DISCUSSION

Selection of a Model for the Binary Fluidized Bed Filter

Earlier attempts to simulate fluidized bed filters (*1–3*) were largely confined to mechanisms by which aerosol particles were collected, but they lacked the appropriate hydrodynamic framework and thus could not reliably predict the performance of such filters. Only in the past decade have the proper descriptions of both mechanics of fluidization and mechanisms of particle collection been considered (*22–26*).

Models presented by Clift et al. (*22*) and Warrior and Tien (*23*) apply the two-phase theory to describe bed hydrodynamics and use empirical correlations to evaluate the collection of aerosol particles. They differ in the way that gas interchange between phases is described. Although initially developed for monocomponent beds (the particles in the bed are uniform in size and density), they can be applied to binary mixtures if an average size, d_M, and density, ρ_M, are introduced to characterize the bed particles. Here they are defined as follows:

$$\rho_M = \rho_p\rho_g/(x_p\rho_g + x_g\rho_p) \quad (6)$$

$$d_M = [(x_p\rho_g + x_g\rho_p)/(x_p\rho_g d_g + x_g\rho_p d_p)]d_p d_g \quad (7)$$

where the subscripts g and p refer, respectively, to the glass and plastic particles.

It should be noted at this point that, although simplified, these models are accurate enough to be used in preliminary design calculations of monocomponent filters. Furthermore, several authors have claimed recently (*27, 28*) that very often relatively simple models do as well as more complex models (*24–26*) and require less computational effort. In this section the ability of these simpler models to predict the behavior of binary fluidized filters is tested against the experimental data collected.

In order to make the comparison, the superficial charge density on the bed dielectric medium, Q_s, should be known before obtaining the overall collection efficiency from the models. To estimate such a charge, we proceeded as follows: For each experiment—and for different values of the superficial charge—the electrostatic collection was evaluated from the expression proposed with this regard in Table 2 (namely, Q_s was supposed to be 1.5, 2.0, 2.5, and 3.0 orders of magnitude less than the maximum value for surfaces charged in air, Q_{max}). Then the collection efficiencies due to the other mechanisms of particle collection were also determined from the appropriate expressions in the table. Next, η_{cal} was obtained—for all superficial charge levels—from the corresponding equations (namely, Eq. 2 for the C-Model and Eq. 4 for the WT-Model) and compared against the experimental value, η_{exp}, calculated from Eq. (1). From this comparison, the value of Q_s that, on the average, best fitted all the experimental data would be taken as representative of the superficial charge on the bed particles.

Obviously, both models should have led to the same value of Q_s. However, it was found that the C-Model better fitted the experimental data when Q_s was 10^{-8} C/m^2 while the WT-Model did it for $Q_s = 10^{-7}$ C/m^2. Nevertheless, since the WT-Model yielded the best agreement when the charge density on the dielectric bed medium was two orders of magnitude less than the maximum value (Q_{max}) for surfaces charged in air, which is an assumption widely accepted (*24–26, 29*), the experimental results will be discussed in the light of this method.

A general feature of the agreement between predictions based on these models and experiments conducted in this work is shown in Figs. 2 and 3. It can be seen that both methods yield essentially correct predictions for the values of Q_s mentioned above and that, for most data points, the difference between experimental and predicted results is within the range of accuracy of the data. The comparison demonstrates that, even if the degree of agreement observed does not necessarily constitute a validation of the methods, it does provide some confidence in their use for predicting the performance of BFB filters. However, since the charge density on the bed dielectric particles had to be estimated, thereby introducing uncertainties, to go further into their relative merits would be risky and will not be done here.

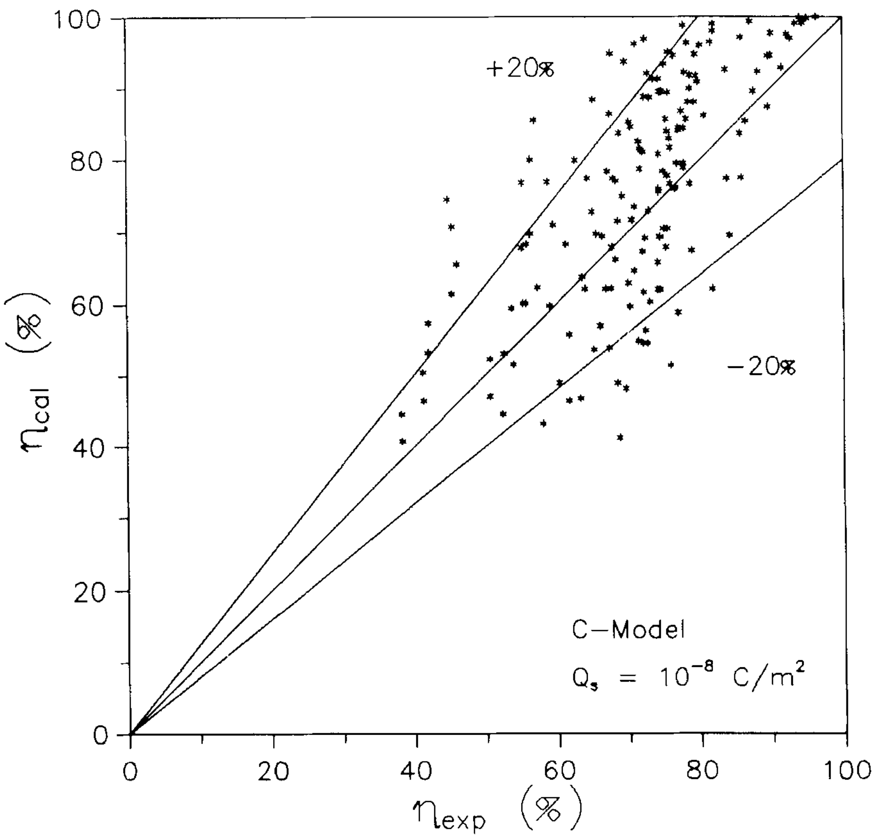

FIG. 2. Comparison between experimental and predicted data of the overall collection efficiency. Model by Clift et al. (22).

Superficial Charge Density on the Bed Dielectric Medium. Effect of Several Variables

As stated above, in the absence of experimental data, the charge density on the bed dielectric particles is usually taken as two orders of magnitude less than Q_{max}. Obviously, this constitutes a first approximation. Actually, the magnitude of this charge will be a function of the degree of triboelectrification of the bed particles which, in turn, will depend on the values of the experimental variables. In this section the superficial charge density was taken as that value among those mentioned above (1.5, 2.0, 2.5, and 3.0 orders of magnitude less than Q_{max}) that, using the WT-Model and the

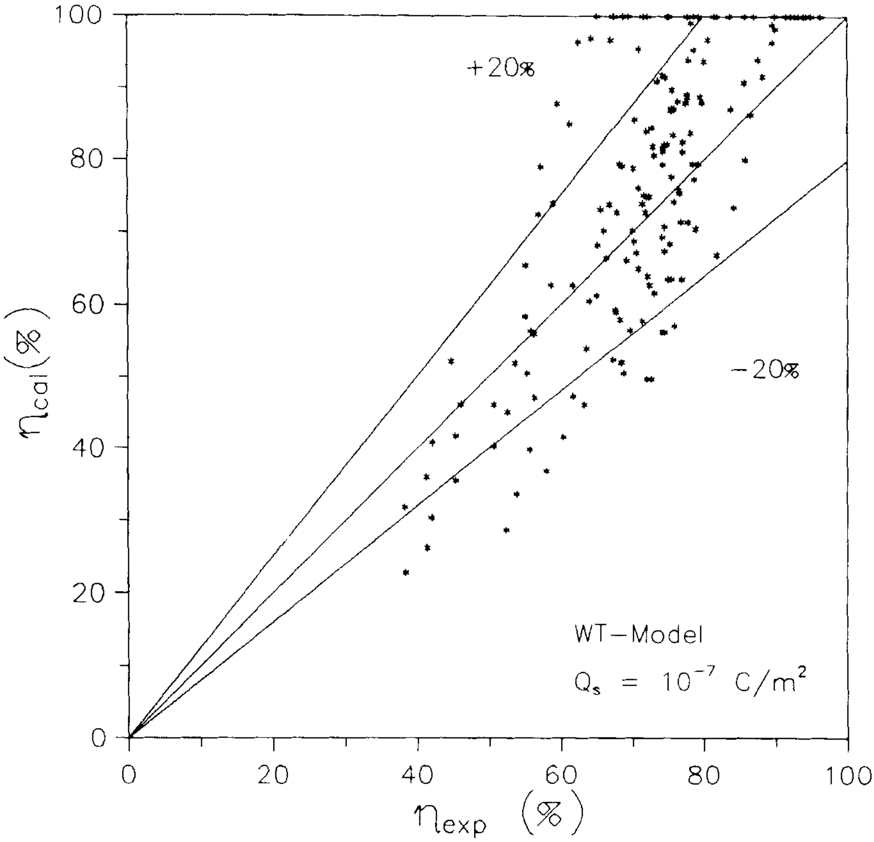

FIG. 3. Comparison between experimental and predicted data of the overall collection efficiency. Model by Warrior and Tien (*23*).

correlations listed in Table 2, best fitted the experimental data for each experiment considered individually. In the following, the mode in which such variables as collecting mixture, gas velocity, bed height, and column diameter affect to the magnitude of this charge is discussed.

The influence of the collecting mixture has been studied through both the size of the glass used and its volumetric proportion in the mixture. The experimental results are presented in Table 3. In relation to the glass size effect, it was found that, for the three different proportions of glass in the mixture, the superficial charge density decreased with increasing particle diameter. This result may be explained by taking into account that the

TABLE 3
Superficial Electric Charge (in C/m²) on the Dielectric Bed Medium. Effect of Collecting Mixture (D_c = 5.5 cm, H_0/D_c = 2, μ = 0.75 m/s)

Glass size (μm)	Glass percentage 0	30	50	70	100
1090	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²
775	10^{-8}	10^{-7}	10^{-7}	10^{-8}	10^{-8}
655	10^{-8}	10^{-7}	10^{-7}	10^{-7}	10^{-8}
550	10^{-8}	5×10^{-7}	5×10^{-7}	10^{-7}	10^{-8}
460	10^{-8}	5×10^{-7}	5×10^{-7}	10^{-7}	10^{-8}

total particle surface available for rubbing in a fluidized bed decreases with particle size and, therefore, the electric charge as well.

To study the effect of the glass proportion, experiments with binary mixtures containing glass volumetric percentages of 0, 30, 50, 70, and 100% were conducted. Table 3 shows the experimental results. It can be observed that in a binary fluidized bed the charge density is larger than in a monocomponent bed, and also that the magnitude of this charge presents a maximum for a glass volumetric ratio between 30 and 50%. This result seems to be related to the quality of contact, i.e., to the number of contacts between particles of different natures. It confirms that in a fluidized bed of insulating materials, as expected, the charge generated is greater when the bodies brought into contact have different dielectric constants (*17*). The shift of the maximum to the smaller proportions of glass may obey the belief that bed segregation is smaller for these ratios and, therefore, the amount of charge generated is larger.

Table 4 shows the effect of gas velocity, bed height, and column diameter for the binary mixture M_4^{30}. It can be observed in the table that 1) the smallest superficial charge density was always obtained at a gas velocity of

TABLE 4
Superficial Electric Charge on the Dielectric Bed Medium. Effect of Bed Height, Fluidization Velocity, and Column Diameter (Mixture: M_4^{70}, *D_c = 5.5 cm, †D_c = 9.0 cm, ‡D_c = 11.5)

u (m/s)	H_0 (cm) 5.5*	11.0*	16.5*	9.0†	18.0†	5.7‡
0.50	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²	10^{-8} C/m²
0.75	5×10^{-7}	5×10^{-7}	5×10^{-7}	10^{-7}	10^{-7}	10^{-7}
1.00	5×10^{-7}	5×10^{-7}	5×10^{-7}	10^{-7}	10^{-7}	10^{-7}

0.5 m/s, independent of bed height and column diameter; and 2) for a given column, the order of magnitude of the electric charge was similar at 0.75 and 1.00 m/s.

These results may be explained by bearing in mind that bed triboelectrification is affected by the regime of fluidization (*30*). In a bubbling regime (up to 0.75 m/s in this work), at increasing gas flow rates, bubbles are larger and cause a bigger motion and friction of the bed particles and, ultimately, an increase of the charge level on such particles (*31*). The reason why similar results were found at 0.75 and 1.00 m/s should be imputed to a change in the regime of fluidization (from a bubble to a slug regime). Since bubbles placed at a constant bed height become bigger with gas velocity (*32*), if the gas flow rate is large enough, bubbles become slugs with a lower rise velocity than free bubbles of the same volume and, therefore, the motion of the bed particles as well as the charge generated in the fluidized bed do not increase with gas velocity.

According to Table 4, bed height did not affect the charge density on the bed particles in the range that the variable was varied. This result may be explained by considering that no net effect on the variation of charge density with bed height should be observed if one assumes that processes causing electrostatic charges to vary in a fluidized bed (namely, charge generation and charge dissipation) increase with bed height at a similar rate (*16*).

In relation to the effect of column diameter, no influence was noticed at 0.50 m/s. However, by comparing Columns 1, 2, and 3 of Table 4 with columns 6, 4, and 5 of the same table, which express the results of experiments performed in different columns but at approximately similar heights, it is seen that at 0.75 and 1.00 m/s the charge density decreased with column size. This may be due to friction between bed particles and column walls decreasing with column diameter and, therefore, bed triboelectrification and charge density on the dielectric particles decreasing as well.

Contribution of the Electrostatic Collection to the Overall Collection Efficiency

To end this work it seems important to determine, at least approximately, how the contribution of E_E to the overall collection efficiency varies with experimental conditions. By using the expressions listed in Table 2 to evaluate the collection efficiency due to each mechanism and calculating the percentage contribution of the electrostatic collection, it was found:

(1) The percentage contribution of E_E to η ranged from 0 to 5% for plastic alone and from 5 to 30% for glass alone.

(2) For binary mixtures, in the range of variables studied, the contribution of E_E was affected by glass size and fluidization velocity but it was almost independent of bed height and glass proportion.

Experiments performed to determine the influence of the collecting mixture showed that the largest contribution of E_E was found for the mixture containing glass of 550 μm (the percentage contribution ranged from 70 to 85%), followed by those with glass of 460 μm (40–80%), 655 μm (35–55%), 775 μm (25–40%), and 1090 μm (5–10%).

Experiments conducted to analyze the effect of fluidization velocity and bed height showed that, almost independently of bed height, the contribution of E_E increased from 0–20% (at a fluidization velocity of 0.50 m/s) to 40–80% (at fluidization velocities of 0.75 and 1.00 m/s).

These results are an immediate consequence of the charge level of the bed particles and need no further comment. However, it is worth noting that charges generated naturally by triboelectrification of the bed dielectric mixtures can considerably increase the efficiency of BFB filters. Furthermore, a proper choice of both fluidized mixtures and fluidization conditions can significantly improve the performance of such filters.

NOTATION

A_L	free area (dimensionless)
C	Cunningham's correction factor (dimensionless)
c_B	average aerosol concentration in the bubble phase (kg/m^3)
c_B^*	dimensionless concentration, c_B/c_i
c_e	average effluent aerosol concentration (kg/m^3)
c_i	average influent aerosol concentration (kg/m^3)
c_P	average aerosol concentration in the particulate phase (kg/m^3)
c_P^*	dimensionless concentration, c_P/c_i
D	molecular or Brownian diffusivity (m^2/s)
D_c	column diameter (m)
d_a	aerosol diameter (μm)
d_g	glass particle diameter (μm)
d_M	average diameter of the particles of a binary mixture (μm)
d_o	orifice diameter of the distributor plate (mm)
d_p	plastic particle diameter (μm)
E	single collection efficiency (dimensionless)
g	gravity (m/s^2)
H	expanded bed height (m)
H^*	dimensionless bed height, defined as h/H where h is the bed height at a given level above the distributor

H_{mf}	minimum fluidization bed height (m)
H_0	packed bed height (m)
K	filtration rate constant, $3E(1 - \epsilon_{mf})H/2d_M$ (dimensionless)
k	interchange coefficient (s^{-1})
K_E	electrostatic attraction parameter, as defined in Table 2 (dimensionless)
l	axial distance of a unit collector, $[\pi/6(1 - \epsilon_{mf})]^{1/3}d_M$ (dimensionless)
N_G	dimensionless number for sedimentation, $2d_a^2(\rho_a - \rho)gC/9\mu u$
N_I	relative size parameter, d_a/d_M (dimensionless)
N_{Pe}	Peclet number, ud_m/D (dimensionless)
N_{Re}	Reynolds number, $ud_M\rho/\mu$ (dimensionless)
N_{St}	Stokes number, $\rho_a d_a^2 uC/9\mu d_M$ (dimensionless)
Q_{max}	maximum value of the superficial charge density for surfaces charged in air (C/m^2)
Q_s	surface density of electric charges (C/m^2)
u	gas velocity (m/s)
u_{mf}	minimum fluidization velocity (m/s)
X	crossflow factor, $HK\epsilon_B\beta/u$ (dimensionless)
x	weight fraction of a component in the mixture (dimensionless)
Y	group describing transfer from bubble phase to a single layer of collector, $\alpha d_M X/H$ (dimensionless)

Greek Symbols

α	group describing filter bed associated with a single layer of collector particles, $[\pi/6(1 - \epsilon_{mf})]^{1/3}$ (dimensionless)
β	fraction of fluidizing gas passing through the bed in bubble phase, $1 - [u_{mf}(1 - \epsilon_B)/u]$ (dimensionless)
ϵ	bed porosity (dimensionless)
ϵ_B	volume fraction of the bubble phase (dimensionless)
ϵ_D	relative permittivity of the aerosol particles (dimensionless)
ϵ_{mf}	bed porosity at minimum fluidization conditions (dimensionless)
ϵ_0	electric permittivity of free space (8.85×10^{-12} F/m)
η	overall collection efficiency (dimensionless)
λ	filter coefficient, $[\ln (1/(1 - E))]/l$ (dimensionless)
μ	gas viscosity (kg/m·s)
ρ	gas density (kg/m^3)
ρ_a	aerosol density (kg/m^3)
ρ_g	glass density (kg/m^3)
ρ_M	average density of the particles of a binary mixture (kg/m^3)
ρ_p	plastic density (kg/m^3)

Subscripts

D diffusion
E electrostatic
G gravity
I interception
i inertia

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Received by editor February 20, 1992