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Removal of Fine Particles from Gases in a Magnetically Stabilized Fluidized Filter

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ABSTRACT

A magnetically stabilized fluidized filter has been used to remove aerosols from gaseous streams, and its performance has been compared to that of an equivalent fixed bed. The filter grains were magnetite particles in the 250 to 795 μm size range. Talc powder was used to prepare the test aerosols. The mode in which a number of variables, including the collector size, the applied magnetic field, the gas velocity, and the aerosol size, affect the degree of agreement between experimental and predicted data has been analyzed. The comparisons yielded good results, suggesting that the behavior of these filters may be predicted from the existing theory initially developed for fixed beds.

INTRODUCTION

The separation of fine particles from gases is a common practice in the chemical and process industries either to recover a product or because a gas has to be cleaned. Methods of separation have been developed during the past century, but because of increased demands for better performances by the separators, more reliable methods for selection and layout are needed.

Granular fixed filters have been successfully applied in gas cleaning over the years (1–3). In general, they provide high collection efficiency and a relatively large gas throughput. They have a disadvantage however: The pressure drop across the bed increases as it becomes increasingly clogged with collected aerosols and, finally, the filter grains have to be regenerated or replaced with clean ones. One possible way of overcoming these limitations is to operate the filter in the fluidized-bed mode (4–6). However, fluidized filters inevitably operate in a bubbling regime, and since gas bubbles offer a bypass for gas flow, the collection efficiency of the filter decreases. It follows that if fluidized bed filters could be stabilized by external forces, a significant improvement of the collection efficiency would be expected.

The use of external magnetic fields to stabilize fluidized beds of magnetizable particles is relatively recent. After Rosensweig's pioneering work (7), a number of authors (8–10) suggested aerosol filtration as a possible application of the phenomenon. More recently, Tien and coworkers (11–13) and Geuzens and Zoenes (14) examined the various aspects of aerosol filtration in magnetically stabilized fluidized filters (MSFFs). Their investigations were mostly concerned with the dynamic performance of this type of filters, i.e., with the evolution of collection efficiency and pressure drop across the filter during relatively long periods of operation. In contrast, in work by Rincón and Tien (15), the behavior of MSFFs during the initial stage of the filtration process was analyzed and a correlation for collection efficiency in such filters was developed.

In this paper the behavior of MSFFs is further examined and compared to identical filters operated in the fixed-bed mode. Specifically, the aim of our work was 1) to determine if the performance of a MSFF can be predicted from correlations developed for fixed-bed filters, and 2) to analyze the manner in which a number of variables, such as collector size, magnetic field strength, gas velocity, and aerosol size, affect agreement between experimental data and those predicted for an equivalent fixed bed.

EXPERIMENTAL

The experimental setup used in this work is shown schematically in Fig. 1. Basically it consists of the air supply system, the aerosol generator, the experimental filter itself (a fluidized bed of magnetizable particles that was stabilized by a magnetic field provided by two magnetic coils surrounding the bed), and the sampling system (two sampling probes connected to a TSI Aerodynamic Particle Size Analyzer interfaced with an Apple IIc Microcomputer).

The experimental systems were a talc powder (ρ_a = 2.14 g/cm^3, d_a = 0.5–2 μm) used to prepare the aerosol suspensions, and four different sized fractions of magnetite particles (ρ_c = 4.16 g/cm^3; d_c = 795, 595, 385, and 250 μm) used as filter grains. The minimum fluidization velocity of these particles was experimentally determined and found to be, respectively, 0.69, 0.42, 0.24, and 0.102 m/s.

The operating variables included the gas velocity ($1.25 \leq u/u_{mf} \leq 2.5$), the magnetic field strength (100 oersteds $\leq B \leq$ 200 oersteds), the collector size (250 μm $\leq d_c \leq$ 795 μm), and the aerosol size (0.5 μm $\leq d_a \leq$ 2.0 μm).

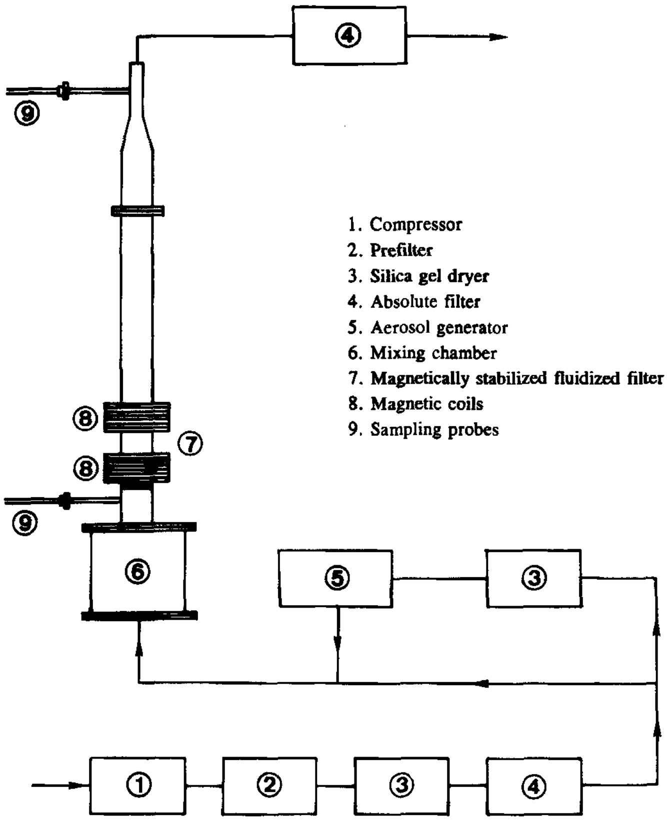

FIG. 1 Diagram of the experimental facility.

The operating procedure can be briefly described as follows. The air supply from the compressor was filtered and dried, then split into two parts, one of which was used to operate the aerosol generator. Next, the air stream from the generator and the other part were combined before entering at the mixing chamber and allowed to enter into the experimental filter with the magnetic field turned on. The experiments lasted approximately 40 minutes. During this time period the influent and effluent concentrations, c_{inf} and c_{eff}, were analyzed by connecting the proper probe to the Aerodynamic Particle Size Analyzer interfaced with the microcomputer. The overall collection efficiency was experimentally determined from these measurements according to its definition:

$$\eta = (c_{inf} - c_{eff})/c_{inf} \quad (1)$$

RESULTS AND DISCUSSION

Previous Considerations

The mode in which the classical theory of gas filtration in granular beds can be applied to predict the performance of a magnetically stabilized fluidized filter will be shown below.

In a magnetically stabilized bed, upon defluidization, bed height and porosity remain constant with decreasing air velocity. The gas flow rate–pressure drop data can be represented by the Karman-Kozeny equation (16). Both facts suggest that fixed beds may be formed at air velocities in excess of u_{mf} when a stabilizing magnetic field is applied. Therefore, as an approximation, a MSFF may be considered to be a fixed-bed filter of uniform voidage.

If one assumes a MSFF to be a fixed bed, the classical filtration theory (17) should be applicable to the description of the filter performance. This theory postulates that a fixed-bed filter consists of a number of unit bed elements and that similar phenomena occur on any of them. Therefore, the capacity of the bed to remove aerosols, η (overall collection efficiency), can be obtained by integrating the collection efficiency of each filter element, E (unit collector efficiency), over the whole bed.

According to this, the overall collection efficiency may be obtained either from its definition, given by Eq. (1), or from the expression proposed by Tien and Payatakes (1):

$$\eta = 1 - \exp(-HE/l) \tag{2}$$

where l is the thickness of the unit collector and can be expressed as

$$l = (\pi/[6(1 - \epsilon)])^{1/3} d_c \tag{3}$$

where d_c is the collector diameter and ϵ is the porosity of the bed.

The unit (or single) collector efficiency, E, is usually assumed to be the summation of the collection efficiencies due to several operative collection mechanisms of particle collection:

$$E = E_{i,I} + E_D + E_G \tag{4}$$

where $E_{i,I}$, E_D, and E_G are, respectively, the individual collection efficiencies due to inertia + interception, diffusion, and gravity. Over the years a number of correlations have been proposed to estimate these efficiencies. Among them, we used the following:

$$E_D = 4A_s^{1/3} N_{Pe}^{-2/3} \tag{5}$$

$$E_G = (1 - \epsilon)^{2/3} N_G \tag{6}$$

$$E_{i,I} = B\left[N_{St} + 0.48\left(4 - \frac{4N_R}{d_c^*} - \frac{N_R^2}{d_c^{*2}}\right)^{1/2} \frac{N_R^{1.0412}}{d_c^*}\right] \tag{7}$$

for $N_R \geq 0.002$ and $N_{St} < 0.01$, and

$$E_{i,I} = B\left[100N_{St}^2 + 0.19\left(4 - \frac{4N_R}{d_c^*} - \frac{N_R^2}{d_c^{*2}}\right)^{1/2} \frac{N_R^{1.0412}}{d_c^*}\right] \tag{8}$$

for $N_R \leq 0.002$ and $N_{St} < 0.01$, where

$$B = 7 - 6 \exp(-0.0065 N_{Re}) \tag{9}$$

The above expressions have been given by Rajagopalan and Tien (2) and Yoshida and Tien (18). A_s, N_{Pe}, N_G, N_{St}, N_R, d_c^*, and N_{Re} are dimensionless numbers whose definition is given in the Notation Section. As an approximation, d_c^* may be assumed to be 0.35 (5).

On the other hand, it is well known that at high particle inertia the impacting aerosols may bounce off the filter grains after colliding with them, and, therefore, not all impacting particles will be collected upon contact. Since the experiments were performed under the inertial-impaction-dominated-regime in this work, we could not ignore this effect and, to account for this possibility, the collection efficiency was expressed as

$$E_{i,I} = \gamma(E_{i,I})_{\gamma=1} \tag{10}$$

where γ is the adhesion probability (or sticking efficiency) and $(E_{i,I})_{\gamma=1}$ is the collection efficiency due to inertia + interception when all impacting particles are collected. An approximate estimation of γ can be made from the correlation proposed by Yoshida and Tien (18):

$$\gamma = 0.00318 N_{St}^{-1.248}, \qquad N_{St} > 10^{-2} \tag{11}$$

Collection Efficiency in Magnetically Stabilized Fluidized Filters

Although there have been some attempts to compare the performance of a MSFF to that of an equivalent fixed-bed filter (11, 12, 14), little attention has been given to well-defined filtration measurements in order to test if theoretical predictions agree, and up to what extent, with experimental results. In this work, both the overall collection efficiency obtained in a MSFF, η_{exp}, and the efficiency that would be obtained in an identical filter operated in the fixed-bed mode, η_{cal}, are evaluated from measurements collected for each experiment using Eq. (1) for η_{exp}, and Eqs. (2) through (11) for η_{cal}; then they are compared. For consistency of comparison, when using Eq. (2) to estimate η_{cal}, H is taken to be the bed height corresponding to the condition of incipient fluidization H_{mf}. The difference between the actual bed height and H_{mf} is too small to be significant.

Two sets of preliminary runs were conducted to determine both the reproducibility of the data and the optimal bed height under which experiments should be performed. Results of the runs made to examine the reproducibility of the data are shown in Fig. 2, where the experimentally determined overall collection efficiency is represented as a function of the aerosol size for two different experimental conditions. It can be seen in Fig. 2 that the data reproducibility is good in both cases.

The second set of preliminary runs, i.e., the experiments to calculate the optimal bed height, showed that the experimental collection efficiency was close to 100% even at low bed heights (H = 1.75 cm). However, it is well known that, for an accurate estimation of the unit collector efficiency from experimental measurements, the total collection efficiency should be significantly smaller than 100%. This value may be reduced by decreasing the bed height so the experiments can be performed under conditions of minimum individual collector efficiency. Nonetheless, it was found that for the experimental conditions in this work, the smallest bed height required to prevent bed bubbling and/or spouting was 1.5 cm. This value of the variable was therefore used in subsequent experiments.

The mode in which such variables as collector size, magnetic field strength, gas velocity, and aerosol size affect the agreement between experimental results and predictions is shown in Figs. 3 through 5, where the overall collection efficiency is plotted against the aerosol diameter. However, before discussing these figures, it should be noted that when using

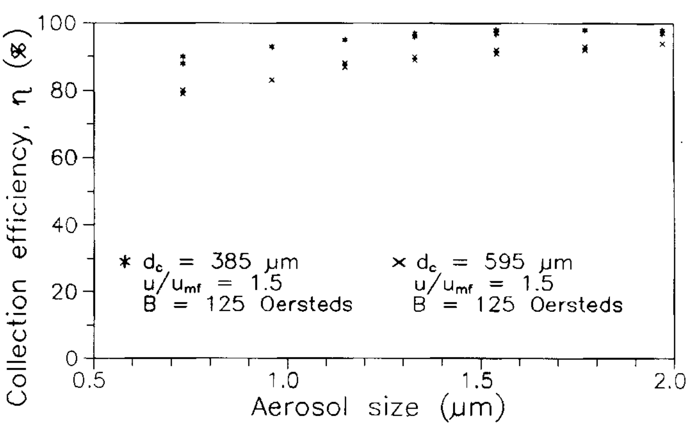

FIG. 2 Reproducibility of the experimental data.

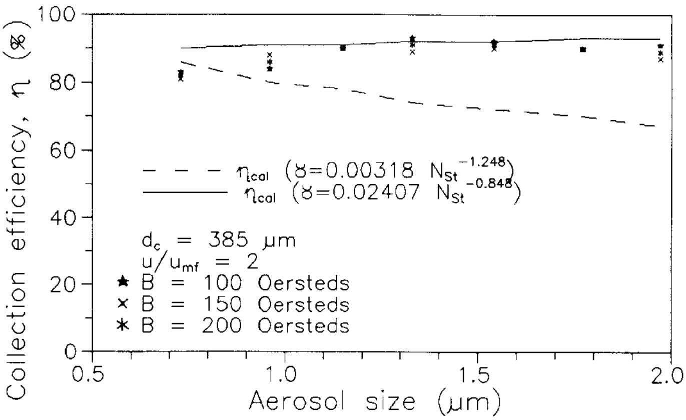

FIG. 3 Influence of the magnetic field strength on the agreement between experimental and predicted data (d_c = 385 μm).

Eq. (11) to estimate the adhesion probability (γ), the predicted collection efficiency (dashed line in Figs. 3 through 5) is significantly smaller than the experimental value, indicating that either the adhesion probability is underestimated or that the bounced particles are being collected again. The last statement seems improbable or, at least, of negligible effect since all experiments were conducted in beds of small thickness. The disagreement is most probably due to an inaccurate estimation of γ.

Important factors affecting this parameter, i.e., the probability of adhesion of impacting particles on collectors, are the characteristics of the aerosol and collector particles, and the kinetic energy of the aerosol particles. Although a number of investigators have examined the problem (18–20), none of the adhesion criteria available is exact (17). It follows that there is need of a new correlation for calculating γ in MSFFs.

Such a correlation was attempted, and, following Yoshida and Tien (18), the result is expressed as a function of the Stokes number:

$$\gamma = \frac{(E_{i,I})_{\exp}}{(E_{i,I})_{\gamma=1}} = 0.02407 N_{St}^{-0.848}, \qquad N_{St} > 1.25 \times 10^{-2} \tag{12}$$

where $(E_{i,I})_{\gamma=1}$ is the collection efficiency when all impacting particles are collected (estimated from Eqs. 7 and 8), and $(E_{i,I})_{\exp}$ is the experimental value of $E_{I,i}$. It was obtained as follows: first, the individual collection efficiency (E) was calculated from Eq. (2), using Eqs. (1) and (3), respectively, to evaluate γ and l; then $(E_{i,I})_{\exp}$ was calculated by subtracting from E the values of E_D (from Eq. 5) and E_G (from Eq. 6).

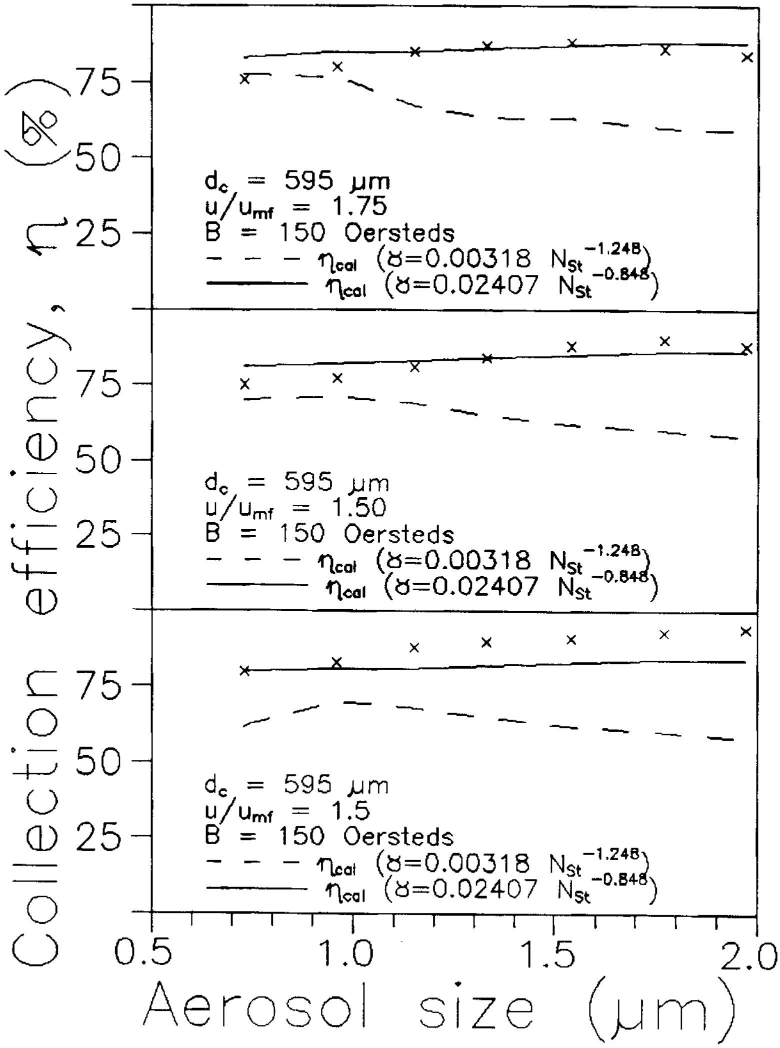

FIG. 4 Influence of the fluidization velocity on the agreement between experimental and predicted data (d_c = 250 μm).

As can be seen in Figs. 3 through 5, the agreement between experimental data and theoretical predictions increased significantly (solid lines in Figs. 3 through 5) when the adhesion probability was estimated by Eq. (12). Therefore, in the discussion that follows, the new value of the adhesion probability ($\gamma = 0.02407N_{St}^{-0.848}$) was used.

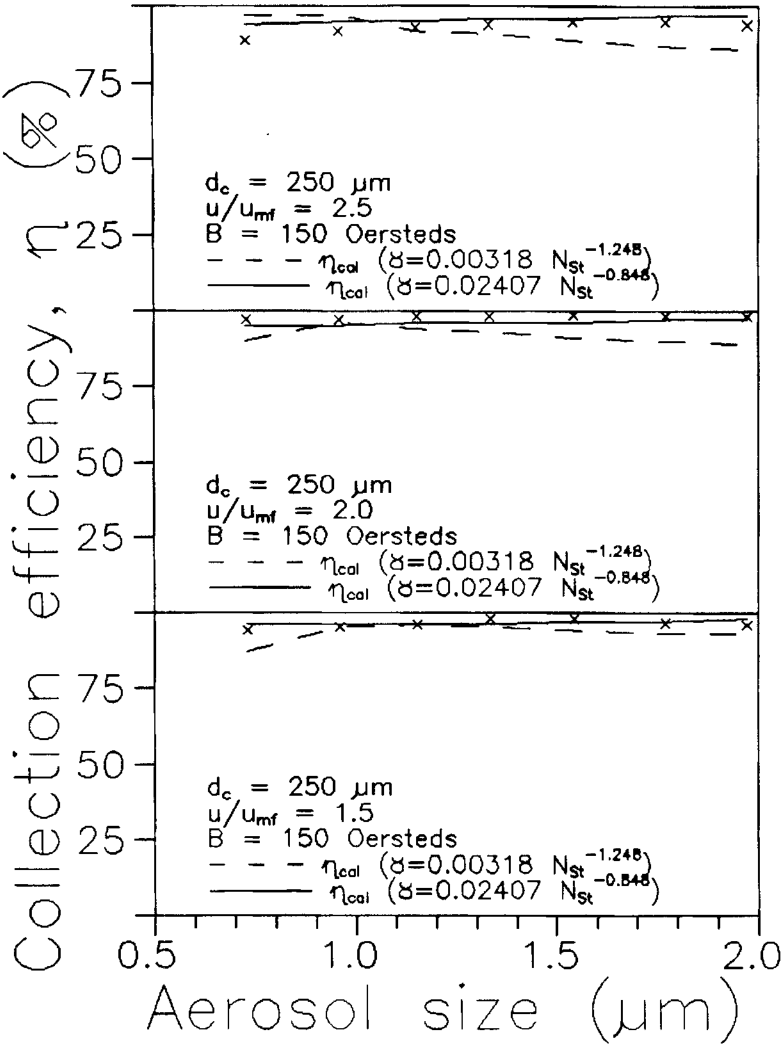

FIG. 5 Influence of the fluidization velocity on the agreement between experimental and predicted data (d_c = 595 μm).

The influence of magnetic field strength is presented in Fig. 3 for the 385-μm collector. It can be observed that the experiments plotted in Fig. 3, i.e., those performed under identical conditions but with higher magnetic field strengths, yield similar results which indicate that increasing magnetization beyond that required to stabilize the bed has no further effect.

The degree of agreement between experiments and predictions was, on the average, quite good and almost independent of aerosol size. Similar results were found for the other collector sizes.

Figures 4 and 5 show the effect of fluidization velocity for two collector sizes (250 and 595 μm). For the 595-μm collector the degree of agreement increased slightly with fluidization velocity (or u/u_{mf} ratio) and was not affected by aerosol size. For the smallest collector (250 μm), very good agreement that depended slightly on the u/u_{mf} ratio was found. Thus, theory slightly overpredicted experimental data at the highest ratio ($u/u_{mf} = 2.5$) and underpredicted at $u/u_{mf} = 2$. Experiment and predictions were similar at the smallest ratio ($u/u_{mf} = 1.5$). For other collector sizes (385 and 795 μm), agreement was almost independent of this ratio and, therefore, of the fluidization velocity. Aerosol size did not seem to affect the agreement either.

From this sequence of results, one may conclude:

(1) The agreement between experimental and predicted results increases significantly when the correlation developed in this paper for the adhesion probability (γ) is used. The new correlation should be useful for estimating this parameter in MSFFs and is expressed as follows:

$$\gamma = 0.02407 N_{St}^{-0.848}, \qquad N_{St} > 1.25 \times 10^{-2} \tag{12}$$

(2) In the experimental range of the variables studied, the performance of a magnetically stabilized fluidized filter can be predicted reasonably well based on classical filtration mechanisms and assuming that the stabilized filter behaves as a fixed bed of uniform voidage. The degree of agreement between experimental and predicted data is almost independent of all the variables studied (collector size, magnetic field strength, gas velocity, and aerosol size).

NOTATION

A_s	dimensionless number defined as $2(1 - \alpha'^5)/\alpha''$
B	magnetic field (oersteds)
C	Cunningham's correction factor (dimensionless)
c_{eff}	effluent particle concentration (kg/m^3)
c_{inf}	influent particle concentration (kg/m^3)
D	diffusion coefficient (μm)
d_a	aerosol diameter (μm)
d_c	collector diameter (μm)
d_c^*	dimensionless constriction diameter of constricted tube, d_p/d_c, where d_p is the average pore constriction diameter.

E single collection efficiency (dimensionless)
H bed height (m)
H_{mf} minimum fluidization bed height (m)
l thickness of a unit bed element as defined by Eq. (3) (dimensionless)
N_G dimensionless number of sedimentation, $2d_a^2(\rho_a - \rho)gC/9u\mu$ (dimensionless)
N_{Pe} Peclet number, ud_c/D (dimensionless)
N_{St} Stokes number, $ud_a^2\rho_aC/\mu$ (dimensionless)
N_R relative size parameter, d_a/d_c (dimensionless)
N_{Re} Reynolds number, $ud_c\rho/\mu$ (dimensionless)
u superficial gas velocity (m/s)
u_{mf} minimum fluidization velocity (m/s)

Greek Letters

α solids fraction, $(1 - \epsilon)$ (dimensionless)
α' dimensionless constant, $(1 - \epsilon)^{1/3}$
α'' dimensionless constant, $2 - 3\alpha' + 5\alpha'^5 - 2\alpha'^6$
γ adhesion probability (dimensionless)
ϵ bed porosity (dimensionless)
μ gas viscosity (kg/m·s)
η total collection efficiency (dimensionless)
ρ gas density (kg/m^3)
ρ_a aerosol density (kg/m^3)
ρ_c collector density (kg/m^3)

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