

Electrostatically augmented granular gas filters: A solution in search of a problem?

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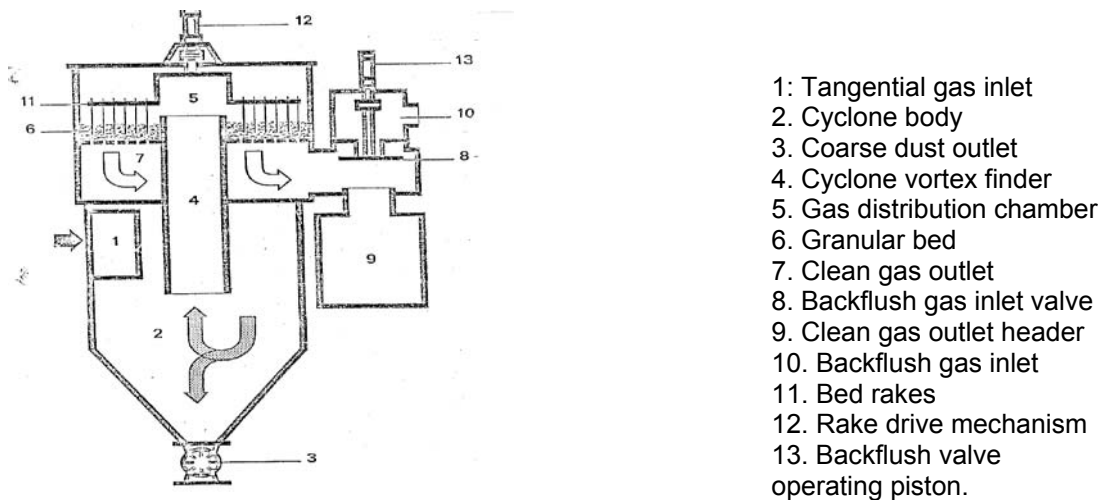
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1. Introduction

The filtration of liquids and gases through a bed of granular medium developed as an industrial process during the 19th century. Early applications to gas filtration are summarized by Squires and Pfeffer [1] and Tien [2]. The first granular bed gas filters were of the horizontal type, operated in the fluidized bed mode. Non-fluidized, periodically backflushed units were developed during the 1950's and were widely used, for instance in the cement industry (see figure 1).

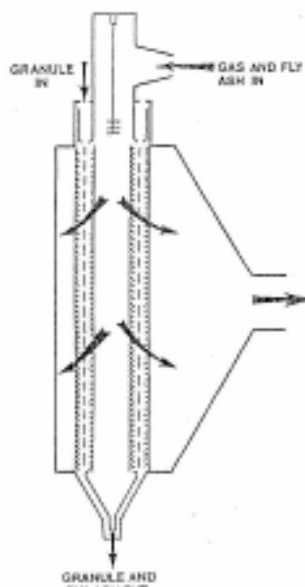
Fig. 1: Stationary bed granular filter (Drallschicht type) in filtration mode.



- 1: Tangential gas inlet
- 2: Cyclone body
- 3: Coarse dust outlet
- 4: Cyclone vortex finder
- 5: Gas distribution chamber
- 6: Granular bed
- 7: Clean gas outlet
- 8: Backflush gas inlet valve
- 9: Clean gas outlet header
- 10: Backflush gas inlet
- 11: Bed rakes
- 12: Rake drive mechanism
- 13: Backflush valve operating piston.

Continuously cleaned vertically moving beds are described in the standard chemical engineering compendia of Perry [3] and Elvers *et al.* [4]. The medium moves vertically by gravity between retaining screens of varying shapes. The vertical flow rate of the medium is controlled by rotating valves or pneumatic removal of the filtration medium at the bottom of the bed (see fig 2 below).

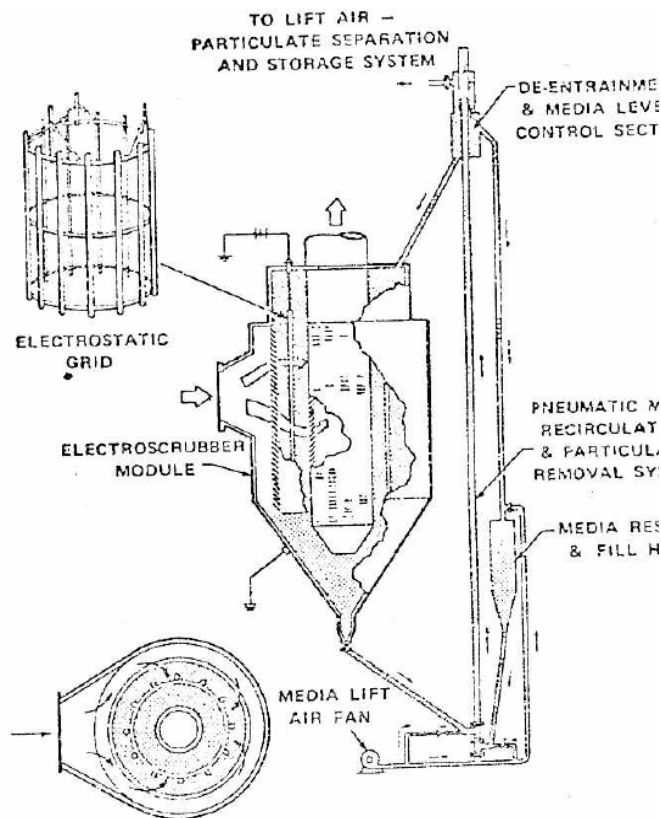
Fig. 2: Moving granular bed (EPB Inc./GE)



Electrostatic augmentation of moving granular beds was utilised commercially from the 1970s by applying an electric direct current potential between an electrode placed vertically in the centre of the bed and the retaining screens. Dust particles are charged triboelectrically and by the applied field within the bed and migrate to the granule surfaces under the influence of the field, thus augmenting the mechanical filtration mechanisms. A parametric study by Snaddon [5] shows that with the application of a sufficiently intense field ($> 10^5$ V/m) the particles may be charged to such an extent that electrostatic capture mechanisms become predominant for the particles of less than approximately $5 \mu\text{m}$ in diameter. This type of filter has been applied commercially to particulate control in industrial wood-fired boilers and in sinter plants in the metallurgical industry (see fig 3). In both cases, the dust contains high percentages of potassium and sodium chloride and is hygroscopic. It therefore "clings" to bag filters and EP plates, while the high shear forces in the granule cleaning loop removes it very efficiently from the granular medium into a small, concentrated gas stream. The title of this paper refers to similar applications where the classical particle removal classes of apparatus (bag filters, EPs and wet scrubbers) fail for one reason or another, and where the particular properties of granular bed filters might be utilized.

Pre-charging of particles, to enable much thinner beds to be used, has however not been studied experimentally. In such thin beds, bed movement and its effects on particle capture has to be studied in more detail as the capacity to hold dust is much lower. Lately, some studies of the pattern of movement of granules in vertically moving beds have also appeared (Henriquez and Macias-Martin [6]) but the influence of the bed movement on particle capture efficiency or particle re-entrainment has not been studied. In this paper, a model for the efficiency of electrostatically augmented moving granular beds with precharging of the particles is proposed and tested, and empirical values for the particle re-entrainment efficiency due to bed movement are proposed.

Fig 3: Moving bed electrostatic filter (CPC)



2. Particle capture mechanisms.

In industrial gas cleaning practice, particles larger than $10\ \mu\text{m}$ are readily collected using simple mechanical collectors such as cyclones or settling chambers and their collection will therefore not be discussed further here. For smaller particles, the gravel bed filter acts as a depth filter and the mechanisms that have been identified as playing a role in this are the following (see fig 4):

Direct interception, where dust particles follow a gas streamline that passes the granule within a distance of half a particle diameter or less ("grazing distance") and is captured .

Inertial interception, where the inertia of a particle is such that it leaves the streamline where the latter changes direction to pass around the granule, and hence impacts on the granule surface.

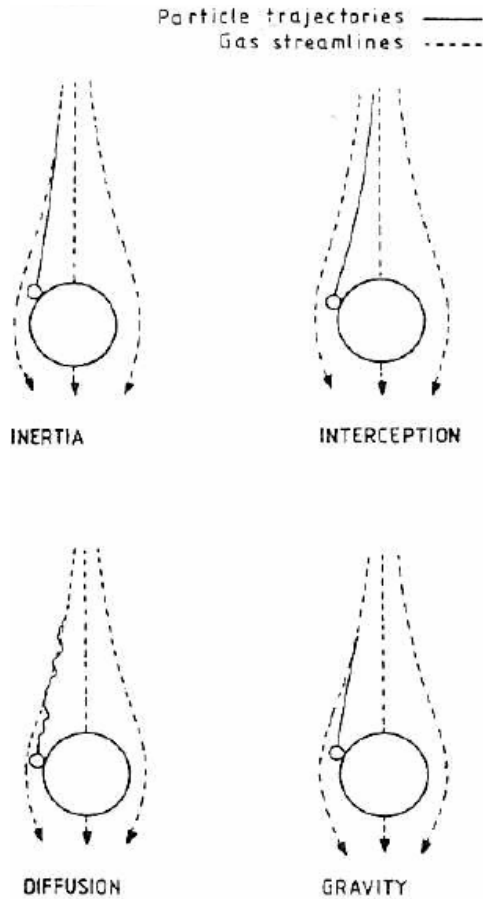
Diffusion, where the concentration gradient which exists between the bulk of the gas and the granule surface causes a particle flux towards the granule surface.

Electrostatic capture. Electrostatic forces may take a number of forms. It has been shown by a parametric analysis by Shapiro et al. [7] that the Coulombic force due charge movement in an electrostatic field is at least an order of magnitude larger than any of the other forces in this category under conditions used in present industrial practice, which are those used in this work.

A large number of equations describing the mechanisms have been published. Kornelius and Grimsehl [8] offer a summary, and reasons for the selection of specific equations for the experimental conditions used in this work. Typical efficiency values for capture by a single granule are shown in fig. 5, with the heavy line indicating the total efficiency of the flow mechanics-driven mechanisms. It is evident that impaction is the dominant of these for particles from 2 micrometer upwards.

A number of authors have indicated that not all particles that collide with a granule are retained. Retention of particles is due to van der Waals forces or, in the case of electrostatically enhanced beds, to Coulombic forces, and if the energy associated with plastic deformation during collision exceeds the retention energy, the particle will not be retained. Prediction methods for specific pairs of materials (of the granule and the particle) based on this approach have met with limited success. Yoshida and Tien [9] have however produced an empirical correlation for the reduction in capture efficiency due to particle "bounce". The applicability of this correlation where Coulombic forces are present is tested in the present work.

Fig. 4: Particle capture mechanisms



Deposition of dust on bed granules influences both bed efficiency and pressure drop. For stationary beds, it was shown by particle trajectory calculations by Payatakes et al. [10] and Pendse and Tien [11] that deposition does not occur as a uniform coating on the granules, but as a combination of a uniform coating and dendrites or "tree growths" on the granules. This has a profound influence on the porosity of the deposit and requires empirical determination of the influence of the operating parameters although generally a monotonously increasing relationship is observed between efficiency and specific deposit [12], as in the example of experimental results of fig.6 (where the parameter indicates specific bed load, or volume of dust collected per unit volume of the bed) until an upper limit in efficiency improvement is approached, probably due to particles being re-entrained as the interstitial gas flow increases in velocity. The onset of this phenomenon will be determined by specific conditions of bed loading and filtration velocity, and in this work the effect is included in the determination of the effect of bed loading on capture efficiency.

An additional mechanism for the release of particles from granule surfaces operates in moving beds. This is the mechanical force generated by slippage between granules [13]. The magnitude of this force will be determined by the same variables that determine shear stresses within the bed such as the intra-bed friction coefficient. Tsubaki and Tien [14] have shown that the deterioration in moving-bed efficiency with an increasing load of collected dust reaches an equilibrium condition, independent of the downward velocity of the bed.

Fig. 5: Calculated single-sphere efficiency of the "mechanical" mechanisms

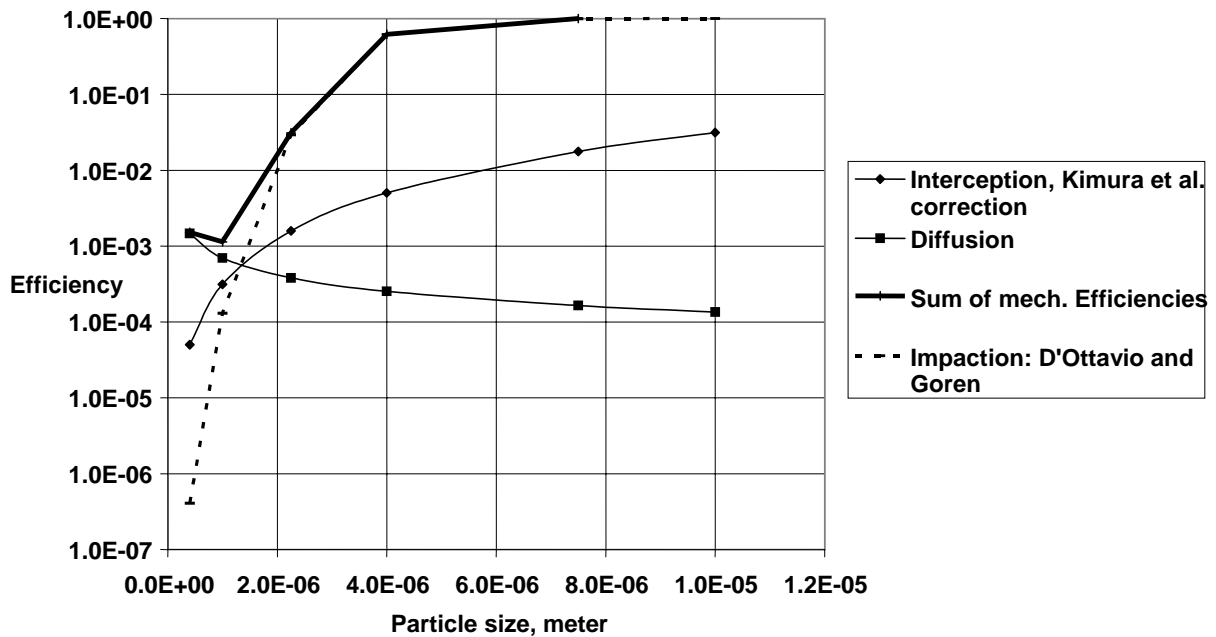
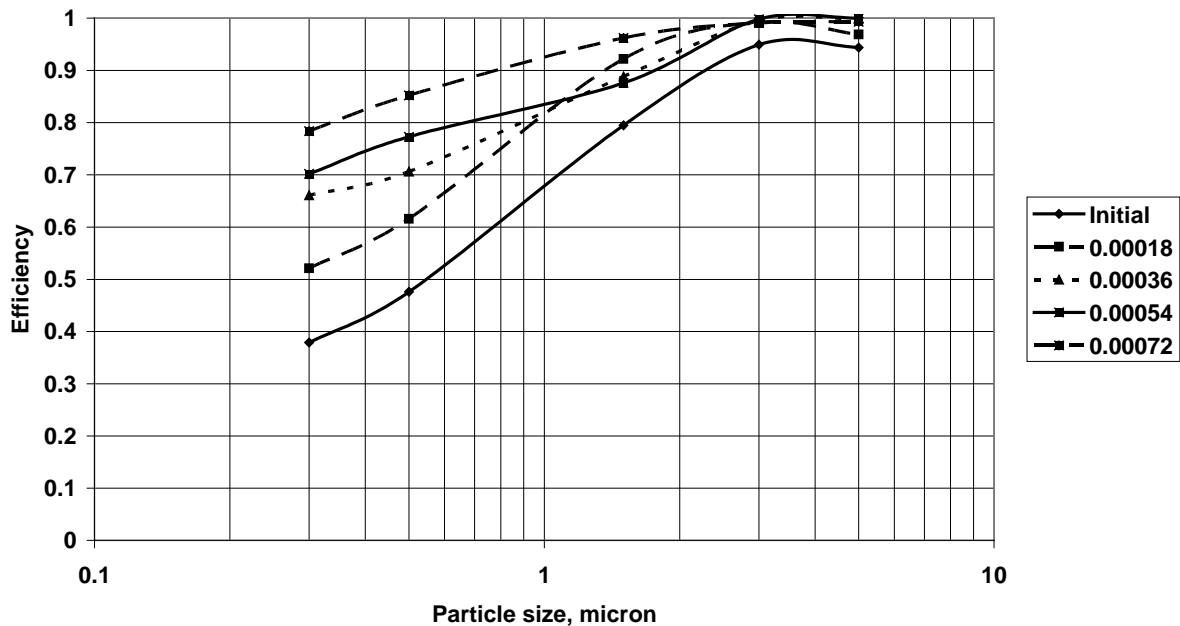


Fig. 6: Efficiency history for 3cm glass bead static bed, 20 kV applied potential



In this work, this mechanism is represented by re-entrainment efficiency which is determined empirically.

3. Particle charging

Forced electrostatic charging of particles, which takes place both in the pre-charger and in the bed itself, has been studied in considerable detail because of its importance in the design of electrostatic precipitators, especially for the electric power industry. Standard texts have appeared [15,16] and the charging rate equations given there were used in this work. It is generally agreed that charging takes place by two mechanisms:

- For particles less than approximately 0,1 micrometer in diameter, particle charging occurs predominantly by diffusion of ions to the surface of the particle. As ions accumulate on the particle, a repulsive field is set up and the charging rate slows down because increasingly higher thermal energy is required to overcome this.
- For particles above approximately 1 micrometer in diameter, the particles are sufficiently large to act as targets for the ions moving in the electrostatic field between the (negative) discharge electrode and the positive one. Charging occurs by impaction of charged ions on the particles and is described as field charging. Collection of ions by the particle ceases when the field set up by the cumulatively collected ions prevents further impaction. This condition is referred to as a saturation charge.

Between the two particle sizes, neither of the mechanisms is predominant, which gives rise to the characteristic minimum in the collection efficiency of EPs between 0,1 and 2 micrometer.

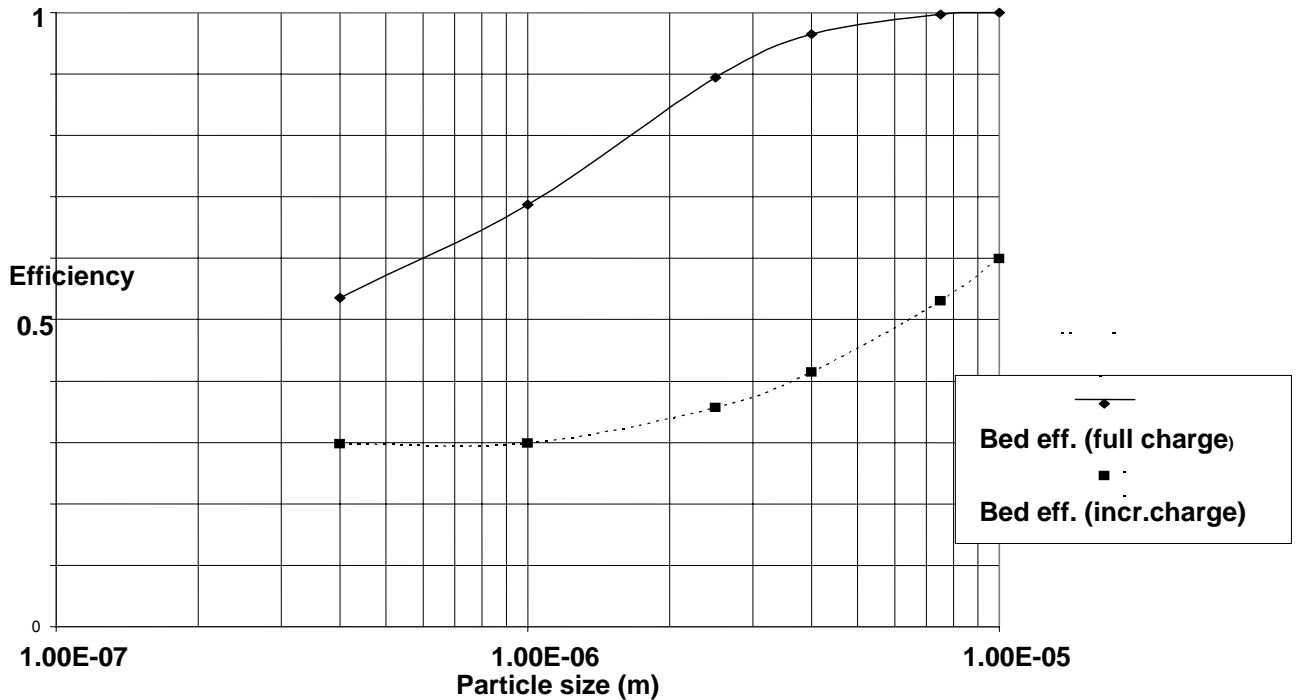
The strength of the field within which the particle is charged is influenced by the medium over which the field is applied. The presence of a granular medium reduces the effective field strength by a factor of between 2 and 8 from the applied field (depending on di-electric properties of the medium and its porosity). Particles are thus charged at a much slower rate when travelling in a bed than they would be travelling in the same applied field in air. This is illustrated in fig. 7, showing calculated efficiency for particles being charged while travelling through a granular bed compared to the efficiency when pre-charged in a 10 MV/m field.

4. Cumulative efficiency of the collection mechanisms

Many authors have accepted as self-evident that the different capture mechanisms should be additive. [17, 18 ,19] . On the other hand, Peters et al. [20] argue that at least direct interception, impaction and electrostatic mechanisms should be regarded as independent events, for which the penetrations should be multiplied instead of efficiencies being added. In practice, the results according

to the above-mentioned summation methods often differ by small margins only. This is due to two reasons

Fig. 7: Comparative calculated electrostatic bed efficiency



- Under given conditions of flow velocity, size ratio between particle and granule, and other process parameters, one of the mechanisms is dominant
- Efficiencies calculated for single granules are often relatively small so that simple addition is a reasonable approximation (Coury *et al.* [21])

Conditions may however occur, mainly where one of the mechanism approaches unity and is obviously dominant, where addition of efficiencies introduces errors and multiplication of penetrations should be used.

5. Total bed efficiency

The efficiency of the bed, E , or alternatively the penetration, P , is defined by

$$E = 1 - P = 1 - C_{out}/C_{in} \quad (1)$$

[22] with the subscripts referring to the particle concentrations on the inlet and outlet side of the bed respectively. This is related to the single-granule efficiency by

$$E = 1 - \exp[-K_1 \eta (1 - \epsilon) L / d_g] \quad (2)$$

with K_1 given alternatively by 1,5 [23]; $1,5/\epsilon$ [24,25] or $(6/(\pi(1 - \epsilon)))$ [22]. In the latter case, a characteristic dimension of the unit cell instead of the granule diameter d_g is used in the defining equation. Conversion between the efficiencies calculated by different authors is therefore possible, provided that one converts η values obtained at one value of K_1 to those based on other values.

6. The effect of previously collected dust:

The parameter characterising the variation in collecting ability of a granular bed is the filter coefficient λ , which is related to the extent of deposition and is a local function [2,22]. The change in filter coefficient is related to the filter coefficient by the equation

$$F = \lambda/\lambda_0 = \eta/\eta_0 = 1 + \alpha_1 \sigma \exp \alpha_2 \quad (3)$$

with σ the specific deposit (i. e. volume of dust deposited per unit granular bed volume). The equation contains two empirical constants, values of which are given by for monodisperse aerosols by

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the first reference above, and for polydisperse aerosols by the other, in all cases valid for specific types of materials in the absence of electrostatic fields. In practice, poly-dispersed dusts are of course collected, which would require cross-coefficients between all the particle size classes. In addition, the presence of the electrostatic fields may well have a strong influence on the coefficients, and they have therefore been determined experimentally in this work.

7. Experimental

Experimental work was carried out to determine the effect of the electrostatic field on the bed loading parameters and the influence of bed movement on particle re-entrainment

7.1 Bed configurations and materials.

For measurements under different condition the following variations in granular bed configuration were used:

Basic filtration mechanism without electrostatic augmentation: The stationary bed used here consists of a cylindrical section of Perspex or stainless steel 143 mm in diameter and 30 or 60 mm long, flanged at both ends. The granules are retained by stainless steel screens with 0,5 mm dia wire and 2,0 mm square apertures. Compressed air is supplied via a droplet separator and a control valve. Flow is measured by a calibrated rotameter. Air is distributed over the face of the filter bed using conical inlet and outlet sections with a 7° included angle to ensure even velocity distribution over the filter face.

Initial experiments were carried out using uniform glass spheres 3 mm in diameter and also commercially available media such as silica sand, crushed granite and dolomite chips screened on 2,35 mm, 2,75 mm and 3,35 mm screens with rectangular apertures.

Moving bed: A schematic diagram of this apparatus is shown in fig 8. The bed retaining silo is 500 mm high and 110 mm wide. It is manufactured from Celeron, a fibre-reinforced synthetic resin that is electrically non-conducting and mechanically stable at the temperatures used in this work (<200°C). Bed thickness is 30 or 60 mm and the active filtration area is 100 mm wide and 200 mm high. The moving bed is retained by a stainless steel mesh similar to the one in the stationary bed. Electrical short circuiting of metal parts such as connecting bolts is eliminated by the use of suitable isolating material.

The bottom of the bed retaining silo is tapered to allow the bed material to rest on a vibrating feeder. Vertical bed movement is controlled by adjustment of the vibrating feeder frequency. As extended experimental runs require re-use of the medium, a pneumatic transport system is used between the vibrating feeder outlet and the top of the apparatus. A separation chamber at the top of the bed allows transport air and dust to exit to the laboratory fume exhaust system, while the medium falls onto the top of the bed for re-use. Test runs using coloured granules and a transparent silo wall showed substantial mass flow in this configuration.

Filtration media: Dolomite and granite gravel screened as indicated in table 3 below were used as filter medium for this part of the work. In order to determine equivalent diameters for the mixed particles, the pressure drop was determined over a static bed of each of the materials, using a flow of dry nitrogen. A bed of 5 mm spherical beads was used as a calibration and check measurement and calculation, using the methods of Ergun [26] and Leva [27]. It was found that the method of Leva provided better prediction of pressure drop, and sphericities of 0,7 to 0,8 were found.

Di-electric constants (permittivity values) for the various types of granules and test dusts used were obtained from literature sources [28-31]. Estimates had to be made using chemical composition where values were not available for specific materials used here.

7.2 Particle charging

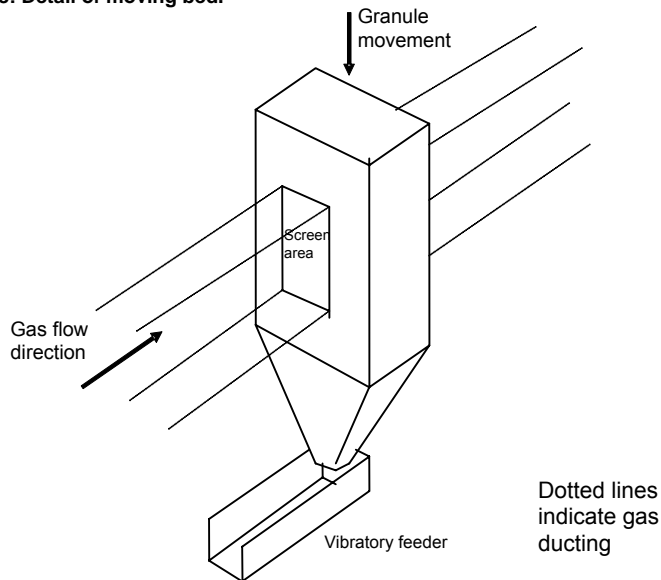
To investigate the electrostatic mechanism under both static and moving bed conditions, a high voltage direct current source (Hipotronics model 50B) generating a maximum potential of 50 kV was used in conjunction with the apparatus of fig 1, connected to the inlet and outlet screens.

A particle precharger is installed upstream (in the gas flow direction) of the moving bed. This consists of vertical stainless steel plates and discharge wire electrodes providing a residence time in the pre-charger sufficient for the particles to reach saturation charge by the field charging mechanism at a bed superficial gas velocity of up to 2 meter per second. A separate direct current source with a maximum potential of 40 kV was used to energise the particle precharger.

7.3 Test dusts

Several types of dust were used during the different phases of the work. A standard fly ash (no 10: Ultrafine fly ash) was obtained from the Association of Powder Process Industry and Engineering (APPIE) in Japan. The dust has an approximate log-normal distribution with a mass geometric mean particle size of 4,8 μm . A metallurgical alumina powder (Boshoff Alumina) was also obtained.

Fig. 8: Detail of moving bed.



The mass geometric mean particle size of this dust is 1,8 μm . Dust feed was via a screw feeder directly into the inlet side of the filters, using a glidant where necessary, through a dispersion nozzle. Dust concentration on both the inlet and outlet side of the beds were measured using a HIAC/ Royco visible light particle counter, which consists of separate sensor (model 1200) and counter (model 4100) units. For this work, the particle sizes of 0,3; 0,5; 1,5; 3,0; 5,0 and 10,0 micron were chosen. This choice gives a high accuracy in the size range where, under most experimental conditions, a minimum in efficiency may be expected and a high accuracy is required.

8. Results – static bed

8.1 The effect of bed loading with dusts of mixed particle size - direct measurement

The only variable influencing the electrostatic and diffusion collection mechanisms that changes with bed load is ϵ , the bed porosity. In the range of bed load values investigated here (and of practical concern), the porosity change is so small as to fall within the range of experimental variability. It can therefore be argued that the increase in collection efficiency with increased bed loading must be due only to the influence on the impaction and direct interception mechanisms as described by the Takahashi/Jung model [32,22]. (Electrostatic enhancement can of course have an influence on these mechanisms by changing the morphology of the deposited dust). Values for α_1 and α_2 applicable to the direct interception and impaction mechanisms only under varying experimental conditions were therefore calculated as follows:

Single granule efficiency due to all mechanisms was calculated for each particle size from the “no load” experimental bed efficiency. The theoretical single granule interception and impaction efficiencies were then calculated. An objective function $\sum[\eta_{\sigma i, \text{exp}}/\eta_{0, \text{exp}} - \eta_{\sigma i, \text{calc}}/\eta_{0, \text{exp}}]^2$ proposed by Takahashi et al. (op cit.) was then minimised for values α_1 and α_2 for each particle size with equation 3 applied to the single granule interception and impaction mechanisms by the univariant search method described by Beveridge and Scheckter [33]. In this function, $\eta_{0, \text{exp}}$ denotes the clean bed single granule experimental efficiency value, $\eta_{\sigma i, \text{exp}}$ the experimental single granule value for the i th bed loading value and $\eta_{\sigma i, \text{calc}}$ the single granule total efficiency calculated from

$$\eta_{\sigma i, \text{calc}} = \eta_{0, \text{exp}} + \eta_{\text{imp, int}} \alpha_{1, i} \sigma \exp \alpha_{2, i} \quad (4)$$

The values in table 1 were obtained for the alumina dust with dolomite granules of 2,7 mm equivalent diameter and a filtration velocity of 0,45 m/s. As there is no clear correlation between the calculated α values and the variables of field strength and collector type, an average value for α_2 of 0,617 and the average of the above α_1 values for each particle size can be used in eq. 3 for design purposes.

Table 1: Experimental values for bed load parameters

The parameter in the first line of the table refers to the potential applied over the bed.

Particle size micrometer	Glass 6,7 kV/cm				Dolomite 5 kV/cm			
	α_1	α_2	Efficiency increase factor for $\sigma =$		α_1	α_2	Efficiency increase factor for $\sigma =$	
			0,00054	0,00108			0,00054	0,00108
0,3	$1,19 \cdot 10^6$	0,58	15151	22643	$1,81 \cdot 10^6$	0,66	12620	19941
0,5	$5,18 \cdot 10^5$	0,68	3108	4979	$2,1 \cdot 10^5$	0,57	2882	4279
1,5	880	0,69	5,90	8,90	945	0,63	9,26	13,78
3	12	0,56	1,18	1,26	9,7	0,57	1,13	1,20

It will be noted that a considerable increase in capture efficiency is caused by the already collected dust, especially for the small particle sizes. The factors obtained here also differ considerably from those published previously for monodisperse dust. They can however be used for dusts of other geometric mean average particle sizes by applying

$$[\eta/\eta_0]_2 = 1 + \{d_{p2}/d_{p1}\}^2 [\eta/\eta_0 - 1]_1 \quad (5)$$

with the subscripts 1 and 2 referring to operating conditions 1 and 2 respectively (Jung [22]). Similarly, a sensitivity analysis using calculations according to the correlations of Takahashi [op cit.] and Jung [op cit.] indicates that the value of α_1 will vary with the value of N_R (i. e. the ratio of particle size to granule size) to the power of approximately 2 over the particle size range from 0,3 to 4 micrometer and a proportionality to the Stokes number of the particles, and hence to bed velocity, to the power -1,437 at constant particle and granule sizes, and these relationships can be used in to calculate bed load parameters for other operating parameters than those under which the values in table 1 were obtained.

9. Results – Moving bed.

9.1 The influence of bed movement with the precharger

A moving 6 cm. thick bed, using 2,3 to 2,8 mm dolomite (Leva equivalent diameter 2,7 mm) was used in conjunction with the precharger described above. JIS fly ash was used as test dust. The effect of bed loading of this dust was calculated for by applying the methods of the previous section.

Bed movement was then allowed for by calculating a re-entrainment efficiency over the two layers of granules at the inlet and the outlet of the bed (adjacent to the retaining grids). In this configuration, the velocity of the two moving layers relative to adjacent layers (a static grid on one side and the fully moving bed on the other), and therefore the re-entrainment efficiency, is equal. The minimisation of the objective function (i. e. determining a value so that calculated efficiency taking re-entrainment into account is as close as possible to the measured experimental value) described earlier was again used to calculate values for the re-entrainment efficiency of each particle size for the varying operating conditions. Surprisingly, the re-entrainment efficiencies were found to be independent of the vertical bed velocity in the range 0,5 to 2,0 m/h. Results as a function of the other operating parameters are given in table 2.

There is a clear distinction in behaviour between the smaller particles up to 1,5 μm , for which the electrostatic mechanism dominates, the intermediate range for which mechanical and electrostatic mechanism are of the same order of magnitude, and the larger particles of 10 μm and larger for which the dominating mechanism is impaction.

Due to the fact that operating variables were tested only at two levels, it is not possible to obtain predictive models. Nevertheless, conclusions can be drawn about the relative influence of the parameters and the relationship between the re-entrainment efficiency and parameters which can be

calculated from the independent variables. Some heuristics for use of the empirical parameters for design at other than the experimental conditions can also be deduced.

9.2 For the smaller particles

For the particle sizes up to 1,5 μm , the re-entrainment efficiency is related to the calculated single granule electrostatic efficiency. The proportionality constant between re-entrainment efficiency and electrostatic efficiency is determined by the operating parameters as shown in Table 3.. The effect of the increase in impaction efficiency for larger particles at the higher filtration velocity causes a deviation from this relationship at larger particle sizes. The higher ratios in the columns corresponding to the lower filtration velocity are probably due to the fact that the deposited dust is less compacted.

Because re-entrainment efficiency results were obtained at only two values of bed potential, it is not possible to provide a predictive model for the efficiencies as a function of operating parameters. The empirical values found here must therefore be used for design; estimates at other than the above velocities and/or bed loads may however be made by interpolation using the above ratios. As an approximation, for a given set of operating parameters the same re-entrainment efficiency could be used for all particle sizes between 0,3 and 1,5 μm without introducing major error (see table 2). These results differ from those found where the precharger was not used, and this is an indication of improvement in efficiency obtained through the use of the pre-charger.

Table 3: Ratio of re-entrainment efficiency to electrostatic efficiency as function of operating parameters (both single granule values).

Particle size, μm	Bed potential 5 kV				Bed potential 10 kV			
	Precharger potential 5 kV		Precharger potential 8 kV		Precharger potential 5 kV		Precharger potential 8 kV	
	FV 0,24	FV 0,68	FV 0,24	FV 0,68	FV 0,24	FV 0,68	FV 0,24	FV 0,68
0,3	2,32	1,70	1,33	1,05	2,40	1,61	2,49	1,59
0,5	2,02	1,14	1,21	0,50	2,26	1,30	2,31	1,10
1,5	1,44	0,94	1,12	0,89	1,89	1,24	1,97	1,34

9.3 For the largest particles

For particles approaching 10 μm in size, impaction is the overwhelming capture mechanism and the electrostatic parameters have no effect on single granule re-entrainment efficiency. The high re-entrainment values in the bottom two rows of table 2 are caused by the very high unidirectional error in the measurement of particle penetration when the penetration approaches zero, and have no physical significance.

9.4 For the intermediate particles

In the size range between 1,5 and 10 μm , efficiency is influenced by both mechanical and electrostatic parameters. Attempts at correlating efficiency with operating parameters for particles in this size range were made using a variety of equations with two and three parameters. Amongst these were Freudlich, Langmuir and logistics-type equations as well as combinations of simpler mathematical forms. (Silva and Silva 2002) Because the number of experimental points for each set of operating variables is small, good correlation is easily obtained, especially using three parameters. No single form of equation does however fit data for the different experimental series equally well, indicating that the good correlation is mathematical in nature, rather than through the representation of common physical phenomena. It is therefore recommended that interpolation be used for the intermediate particle sizes until such time as more experimental data elucidate the relationship in this size range.

Table 2. Re-entrainment efficiencies independent of vertical bed velocity.

FV= filtration velocity in m/s; BV =vertical bed velocity in m/h

Bed thickness 6 cm; precharger wire-to-plate spacing 2,5 cm.

Particle size, μm	Bed potential 5 kV				Bed potential 10 kV			
	Precharger potential 5 kV		Precharger potential 8 kV		Precharger potential 5 kV		Precharger potential 8 kV	
	FV 0,24	FV 0,68	FV 0,24	FV 0,68	FV 0,24	FV 0,68	FV 0,24	FV 0,68
0,3	0,200	0,051	0,221	0,031	0,40	0,095	0,448	0,102
0,5	0,163	0,032	0,188	0,016	0,353	0,072	0,405	0,069
1,5	0,138	0,032	0,204	0,038	0,346	0,082	0,450	0,112
3,0	0,174	0,698	0,307	0,748	0,448	0,790	0,618	0,855
5,0	0,760	2,29	0,714	2,36	1,10	2,41	1,14	2,53

10. Conclusions

Parameters required for the design of continuously operated granular filtration beds with electrostatic augmentation were experimentally determined. These include the loading parameters, which determine the influence of previously deposited dust on filtration efficiency. Methods to “translate” loading parameters determined at one set of operating conditions to values applicable to other conditions are also proposed. Values for re-entrainment of dust due to bed movement were also determined under certain operating conditions. For small particles, up to 1,5 micron in size, the re-entrainment is linked to the electrostatic capture mechanism which is dominant for these particle sizes. For larger particles, where impaction is also significant, only interpolation between experimental values can at this stage be recommended. Impaction is the dominant mechanism for particles larger than 7 or 8 micron in size, and the impaction efficiency is so close to unity that re-entrainment is insignificant.

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