RECENT DEVELOPMENTS IN GRANULAR BED FILTERS

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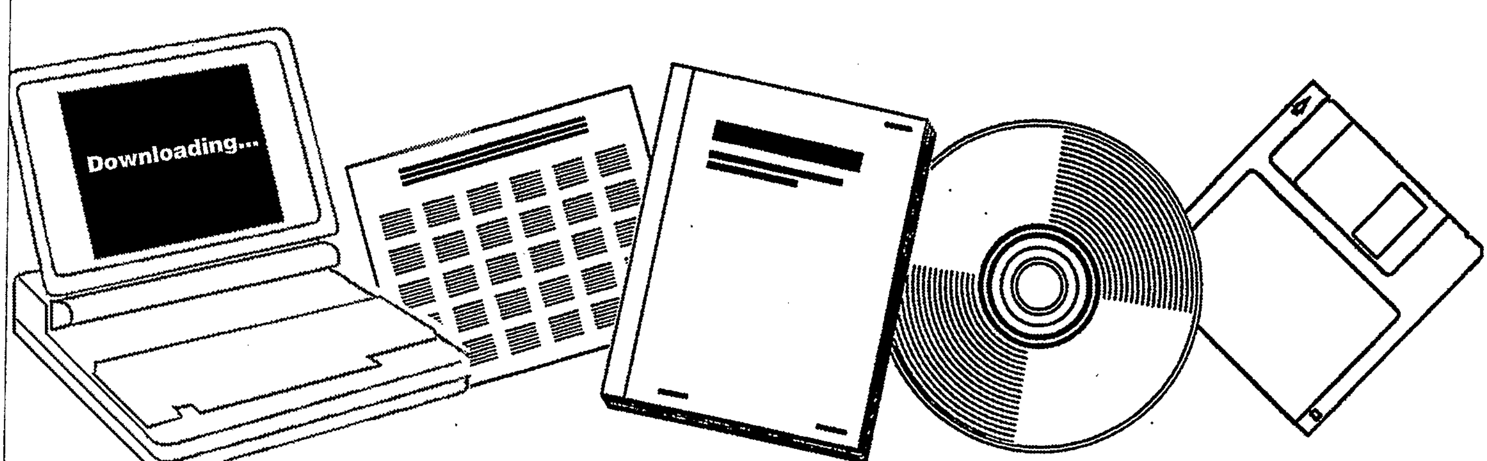

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by S. C. Saxena

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ABSTRACT

Granular-bed filters in various modes (fixed, fluidized, and moving) have been used for particulate and vapor filtration from gas streams for a long time. In recent years, their exploitation in coal conversion processes for removal of fine dust and traces of metal vapors has been pursued with good success. Exxon, Westinghouse, Combustion Power Company, General Electric, EFB, and Air Pollution Technology are engaged in developing such filters for the purification of hot and compressed flue gas from pressurized fluidized-bed combustors for power generation. In each mode of granular-bed filter operation, the particulate collection efficiency improves by the application of an external electric field and even further enhancement is possible if the dust particles are charged. A granular bed consisting of an admixture of magnetic and nomagnetic particles in a magnetic field is found to be a very attractive filter, and its complete promise and potential is under investigation. All these continuing recent efforts are reviewed and examined, and recommendations are made for future research in this particular area of coal combustion technology.

EXECUTIVE SUMMARY

The ultimate success of the coal-fired pressurized fluidized-bed combined-cycle combustion systems (PFBC/CC) for electric power generation depends on the availability of an economic filtration system which could remove efficiently micron and submicron range particles from the PFBC effluent gas stream before it is expanded into a turbine chamber for energy recovery. To accomplish this many filtration concepts are being developed and carefully tested from technical and economic viewpoints. All systems at least consist of two stages of filtration viz., primary and secondary. While single or multiple cyclones may constitute the primary stage, many filter choices and novel devices have been proposed for the secondary stage. The exploitation of granular-bed filters is one such alternative and is being currently investigated rather extensively. The purpose of the present report is to pool together all the ongoing efforts and examine their current status and relative merits and demerits.

Several variants of the granular-bed filters have been used for the filtration of dust-laden gas for PFBC/CC applications. Three possible alternatives which are being investigated are: fixed-bed, moving-bed, and fluidized-bed granular filters. The application of an external electric field is also shown to augment the particulate collection efficiency. Exxon and Westinghouse have experimented with Ducon filters and have modified them in the hope to obtain a trouble-free operation at high temperatures and pressures for large gas flow velocities. The latter is currently engaged in a program of research to evaluate the operation of such filters with a simulated PFBC gas stream. Enough test data, operational experience, and economic evaluation is not available at the present time to enable a final judgment and this will have to await the findings of Westinghouse.

The work of Combustion Power Company is certainly very encouraging on their countercurrent screenless moving-bed granular filters and it is fair to conclude that their results at ambient temperature and pressure and at higher temperatures and ambient pressure promise a great success for such filters. However, operation at high pressures and actual testing in conjunction with a PFBC system will only bring the status of such filters to a level where a definite technological decision can be made. EFB, Inc., have developed an electrostatically augmented moving-bed filter with inside out cross-gas flow which appears very promising. Again, enough test data with an operating PFBC gas effluent are not available at the present time to make a final judgment. Air Pollution Technology investigations with electrostatic dry plate scrubber at room temperature and pressure are encouraging; consequently, the construction of a bench-scale unit for operation at high temperatures and high pressures is in progress. Availability of these results and their critical assessment will provide the adequate basis for a fair evaluation of this technique. The work of Exxon with magnetically stabilized granular beds appears very novel and attractive. If it becomes possible to adopt this technique at high temperatures and pressures, then on the basis of present results at ambient temperature and pressure it appears that the field of filtration will be highly revolutionized.

The status of the theoretical understanding of granular-bed filters is, in general, in a primitive stage of development both as regards to pressure drop as well as filtration efficiency. There is a difference of opinion even regarding the state of filter during filtration process. Most investigators believe that a dust cake is formed on the surface of media granules. The dust collected on individual granules bridges the distance between them, and the controlling collection mechanism is barrier filtration. On the other hand some workers emphasize that no dust cake is formed in large-scale filters and the dust collection takes place on the individual particles rather directly. A semi-theoretical approach is more often used in which the data are expressed in terms of the dimensionless characteristic numbers which are supposed to control the collection process such as Stokes, interception, impaction, and Peclet numbers. The "unit-cell" approach has been developed and tested in many cases with fair success. Within the framework of well-defined approximations, this method attempts to calculate the collection efficiency rather rigorously. The methods in which allowance is also made for the dust particles already collected on the media granule while computing the changes in pressure drop and collection efficiency are in infancy. All calculations suffer from our inability to quantify the phenomenon of re-entrainment for which very little is understood at the present time. It is a major limiting factor in the mechanistic modeling of collection process in a granular-bed filter.

INTRODUCTION

The adoption of coal-fired, pressurized, fluidized-bed, combined-cycle combustion systems by utilities for electric power generation depends to a large extent on the development of an efficient and economic cleanup system. This conclusion is based on several recent studies where different alternative energy conversion technologies have been examined and evaluated. For instance, Cain, et al.[1], have investigated several coal conversion processes, such as fluid-bed combustion (atmospheric and pressurized), fuel cells, open cycle magnetohydrodynamics from the viewpoint of cost and environmental constraints.

They infer that the pressurized fluidized-bed coal combustion (PFBC) process coupled with somewhat relaxed particulate removal requirements from flue gases appears to be the most preferable one. Thus, it seems quite clear that the development of successful hot and compressed gas cleanup techniques, and of suitable materials for turbine blades' coating and cladding, threaten to become a bottleneck for the success of pressurized, fluidized-bed, combined-cycle plants in the direct use of coal for power generation.

A number of gas purification devices have been developed over the years and these include conventional cyclones and its several modified versions: rotary-flow cyclones, multicone units, cyclone-centrifuge, augmented cyclones; porous metal, fibrous, fabric, and ceramic membrane filters; fixed-bed, intermittently moving bed, continuously moving bed, and fluidized-bed granular filters; and electrostatic precipitators. Several other novel devices which have been proposed and developed to different degrees of prefection are: molten solid contactors, dry scrubber, acoustic agglomerator, cyclones, and granular bed filters with an external field (electric or magnetic). In veiw of the pressing practical interest in the flue gas cleanup technology in relation to PFBC applications, the United States Department of Energy has sponsored a number of projects to explore, test, and develop several of the promising techniques and an overview of this program is presented by Moore[2].

The purpose of this report is to discuss the most recent work which is being done in relation to granular bed filters. The granular bed filters have been used over a long period of time to remove particulate material from dust-laden gas streams and in four different modes: fixed bed, intermittently moving bed, continuously moving bed, and fluidized bed. In some efforts an external electric field is imposed on the granular bed filter and the dust particles are electrically charged to augment the collection efficiency and specially for submicron particles. In many others the triboelectrification of the dust particles is considered adequate for the process. More recently, the use of magnetic field is proposed and results obtained to date appear quite promising. The earlier work on granular bed filters is included in the two previous reports, Saxena[3], and Saxena and Swift[4]. Recent experimental and theoretical efforts in progress to understand the design details or practical limitations are detailed in the following.

Granular-Bed Filters

Combustion Power Company has been investigating a moving-bed granular filter (GBF) for application in pressurized, high-temperature energy conversion systems under the sponsorship of the U.S. Department of Energy[5]. The design details of the moving bed granular filter and the flow diagram of the test system are given by Guillory[6], and Geffken, et al.[5] The dirty gas to be cleaned is allowed to flow radially outward in cross-flow through an annulus of granular collecting media. The dirty media is pneumatically transported to a fluid bed located just above the filter housing and after being cleaned is cycled back into the filter. Guillory[6] has correlated the collection efficiency and pressure drop by the following simple relation on the basis of linear regression analysis of the test data:

$$1 - \eta = A_o \left[\frac{\Delta P}{U} \frac{L_i}{\dot{M}} \right]^{A_1}$$

Here η is the particulate collection efficiency, ΔP is the pressure drop across the granular bed, U is the superficial gas velocity, L_i is the inlet dust concentration, $\dot{M}$ is the media flow rate, and A_0 and A_1 are the empirical coefficients to be determined from linear regression of the experimental data.

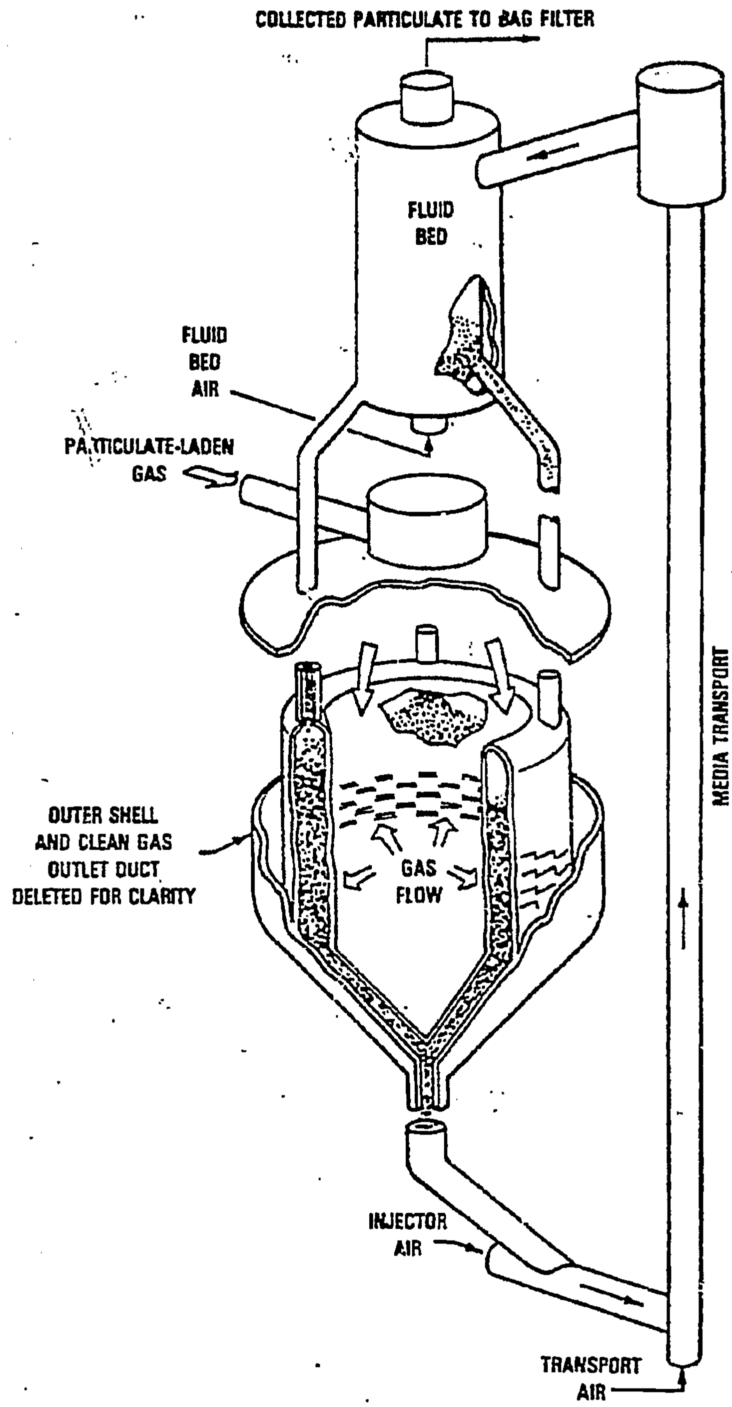
Wigton[7] and Geffken, et al.[5], have expressed the collection efficiency as an addition of four terms representing the particulate collection by impaction, interception, diffusion, and sedimentation mechanisms, viz,

$$\eta = \frac{1}{\varepsilon} N_{St}^3 + \frac{3}{2} \frac{d_p}{D_p} + \frac{4.36}{\varepsilon} (N_{Pe})^{-2/3} + \frac{0.384}{\varepsilon} (N_{Gr})^{3/4}$$

Gefken, et al.[5], have considered a simple empirical model for re-entrainment phenomenon with little theoretical basis. They[5] have also considered the collection efficiency and pressure drop relationship on dimensional considerations. Wade[8] has summarized the early experience of Combustion Power Company with moving granular bed filter including the design details, experimental data, and mathematical modeling. Moresco, et al.[9], have described the modified version of the moving granular bed filter with several improvements and report the results on the filtering of particulate matter from the exhaust gases of an atmospheric coal-fired, fluid-bed combustor. The results look encouraging inasmuch as particulate collection efficiencies of greater than 99 percent for particles greater than 3 μm have been found. The continuing work at the Combustion Power Company is described in a recent article by Moresco and Cooper[10].

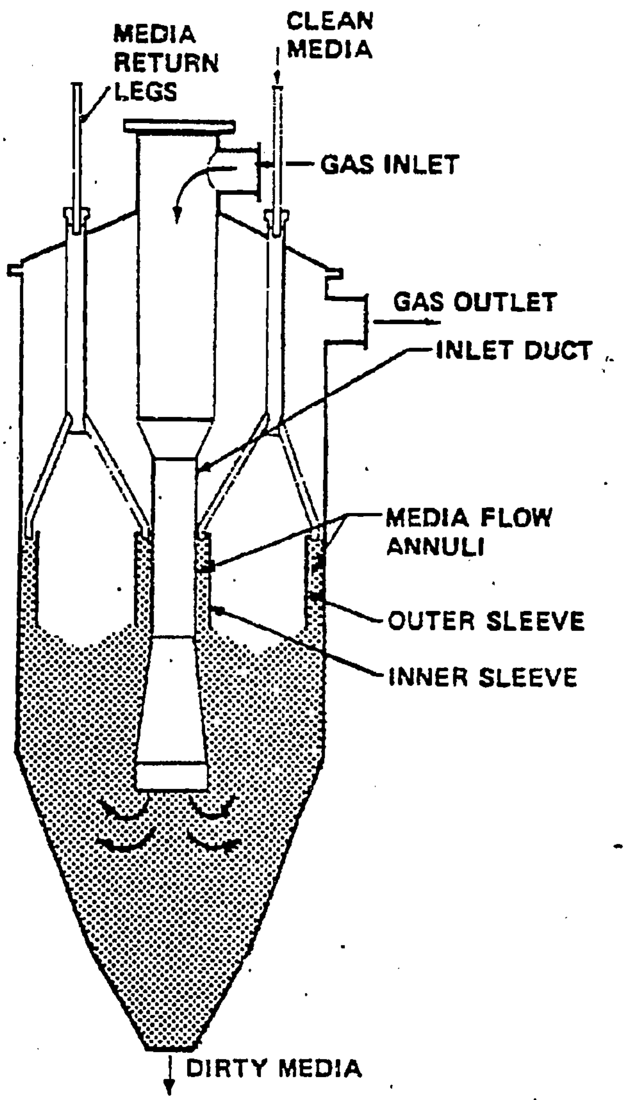
The Combustion Power Company has produced commercial cross-flow "screened" granular bed filters for high-temperature filtration of stack gas particulate and fugitive dust cleanup. The schematic of the screened cross-flow moving-bed granular filter is shown in Figure 1. The natural "pea gravel" is used as bed material in the commercial filters and special alumina in the high-temperature filters. Plugging problems were encountered in these screened filters both at low- and high-temperatures, due to the sticky nature of the particulate matter. The screens of the moving granular bed filter were blinded when the flue gas was filtered for particulate matter from an atmospheric fluidized-bed combustor burning Illinois No. 6 coal in dolomite. This screen blinding was attributed to the adhesive/cohesive nature of the coal ash and sulfated sorbent composite. This caused a steady increase in the pressure drop across the screened filter, and the test run had to be terminated. This lead them to develop a screenless, countercurrent flow design for the filter as shown in Figure 2. No plugging problem was encountered in the 1000-hour test run with this filter. Some details of this run are given below.

Illinois No. 6 coal was burned with dolomite in a fluidized bed at atmospheric pressure and 1143K. The feed air was preheated by in-line propane air heaters. Particle-laden combustion gases were passed through a recycle cyclone, a primary cyclone, a particle sampling duct, and thence, into the filter. The clean filtered gas exit at 1113K and was passed through a particle sampling duct before exiting into the atmosphere. Two mm high alumina refractory particles flow down countercurrently to the hot gas flow in the filter bed. Four test segments with continuous operation of the filter for 100-, 200-, 300-, and 400-hour periods for a total of 1000 hours have been successfully completed without any sign of deterioration. In all the tests the particle capture efficiency of the filter remained approximately 99 percent for filter pressure drop values ranging between 6.0 and 7.0 kPa and inlet gas flow velocity and particle loading of 0.18 m^3/s and 6.0 g/m^3 respectively at 1113K. The particle collection efficiency (by weight) is found to decrease from 99 percent for particles having an aerodynamic particle diameter ≥ 4 μm to about 93.2 ± 1.0 for particles of diameter about 0.3 μm.



CROSS-FLOW MOVING-BED GRANULAR FILTER
(COMBUSTION POWER COMPANY, INC.)

FIGURE 1 - GUILLORY[6]



HIGH TEMPERATURE SCREENLESS COUNTER-CURRENT MOVING-BED GRANULAR FILTER (COMBUSTION POWER COMPANY, INC.)

FIGURE 2 - MORESCO AND COOPER[10]

Moresco and Cooper[11] have recently reported on the low-temperature test runs conducted with this screenless granular bed filter. Titanium dioxide particulate was injected as it permitted to investigate the ability of the filter to collect micron and submicron particles. The mass median diameter of the particles was 2 μm. The measured dependent variables were the total filtration efficiency, fractional efficiency, and pressure drop. The ranges of the parameters varied during the runs in terms of Reynolds number (N_{Re}) and ($\dot{V}_p$ Z $N_{St}/\dot{V}_c$ D_p) were:

$$10^2 < N_{Re} < 10^4$$

$$10^{-5} < \frac{\dot{V}_p \, Z \, N_{St}}{\dot{V}_c \, D_p} < 10^{-1}$$

Here $\dot{V}_p$ and $\dot{V}_c$ are the volume flow rate of particulates and granular collector particles respectively, and Z is the filter bed depth. The experimental test results could be correlated by the following relation:

$$P = 3.5 \times 10^{-3} \frac{N_{Re}^{0.31}}{\left(\frac{\dot{V}_p \, Z \, N_{St}}{\dot{V}_c \, D_p}\right)^{0.26}}$$

Here, P is the penetration of the dust particles by mass.

Goren[12] performed a series of experiments at ambient temperatures and pressures for gas flow velocities and media particles of the same magnitude as employed by Combustion Power Company in their moving bed granular filter. The filter was formed by 2 mm diameter alumina spheres in a plexiglas tube of 4.39 cm internal diameter and supported over a coarse wire mesh screen and a standard plastic from a 47 mm Nuclepore filter. The bed height was varied from 3 cm to 19.3 cm. As test aerosol the solid monodisperse, electrically neutral potassium bipthalate particles, were used of five different geometric diameters viz., 0.51, 0.93, 1.56, 2.78, and 3.91 μm. The density of solid particles being 1.636 g/cm, the gas was dry air at room temperature and atmospheric pressure and its superficial velocity was varied from 1 to 100 cm/s. The individual bed particle efficiency, η_p, is calculated from the measured values of bed penetration, P, and the following formula:

$$\eta_p = - \frac{4 R_p \ln P}{3 (1 - \varepsilon) Z}$$

or

$$P = 1 - \eta = \exp \left[- \frac{3}{4} \frac{(1 - \varepsilon) Z}{R_p} \eta_p \right]$$

Here ε is the bed voidage or (1 - ε) is the solids fraction in the bed, Z is the bed height, R_p is bed particle radius, and η_p is the bed particle collection efficiency. A constant value of 0.4 was used for ε by Goren[12].

Goren[12] has reported the measured P values as a function of superficial gas flow velocity, U, for all the five sizes of bed particles. These data were then used to generate η_p and plots of η_p versus U are given for each particle size. For the largest particle (3.91 μm), η_p first decreases as U increases up to 9 cm/s, after that up to 35 cm/s as U increases η_p increases, and thereafter as U further increases η_p decreases again. These results can be qualitatively explained on the basis of different mechanisms which are responsible for the deposition of dust particles on bed particles. Gravitational settling is the predominant mode for large particle collection at low flow rates. As U increases the particle residence time decreases and less and less time is available for particle deposition on the bed particle. As a result, η_p decreases with U increasing. For sufficiently large values of U, the dust particles acquire sufficient inertia to bring the mechanism of inertial impaction into play and consequently η_p increases with U. However, for these hard nonsticky particles, an energetic collision with hard solid bed particles results in a rebound of the former. Thus, at some higher velocity the effect of dust particles bouncing off and be re-entrained in the gas flow overtakes their capture by the bed particles, and as a result, η_p starts decreasing again. Similar qualitative variation of η_p with U is found for dust particles of all sizes except as the size decreases, the transition velocities at which different mechanisms play significant roles are shifted to higher values. For small particles (0.51 μm) in Goren's work[12], the gas velocity was never too high to cause impaction as the dominant mode for dust capture, and hence, η_p decreases monotonically with U over the entire range of experimentation.

Another observation made by Goren[12] from his data brings out the importance of Brownian diffusion capture mechanism for smaller particles at low gas flow velocities. He found that η_p, for the smallest particles (0.51 μm), is larger than the next larger size particles (0.93 μm) at the same flow rate as long as the gas velocity is small. For such conditions, η_p will be larger, the smaller the particle size due to the larger contribution of the Brownian diffusion. Based on his data, Goren[12] derived quantitative expression for the particle collection efficiency in the regions where the predominant collection mechanisms are due to inertial impaction, gravitational settling, and Brownian diffusion. In these three regimes, the collection process is uniquely dependent upon the stokes, N_{St}; gravitation, N_{Gr}; and Peclet, N_{Pe}; numbers, respectively. The single particle collection efficiencies for the three regions will be represented by η^p_{II}, η^p_{GS} and η^p_{BD}, respectively. Goren[12] found that:

$$\eta^p_{II} = 1270\ (N_{St})^{9/4} ,$$

$$\eta^{p}_{GS} = 0.97\ (N_{Gr})^{3/4} ,$$

and

$$\eta^{p}_{BD} = 232\ (N_{Pe})^{-2/3} .$$

Further,

$$N_{St} = \frac{\rho_p\ d_p^2\ U\ C_s}{9\mu\ D_p} ,$$

$$N_{Gr} = \frac{\rho_p\ d_p^2\ g\ C_s}{18\ \mu U} ,$$

and

$$N_{Pe} \doteq \frac{3\pi\mu\ d_p\ D_p\ U}{C_s\ k_B T} .$$

Here ρ_p is the particle density, d_p is the diameter of the dust particle, C_s is the Cunningham empirical slip correction factor, μ is the gas viscosity, D_p is the bed particle diameter, g is the acceleration due to gravity, T is the temperature, and k_B is the Boltzmann constant.

The dependence of η^{p}_{II} on Stokes number is found to be very different than the nearly first power dependence reported in the literature which was established from the limited data then available. Experimental data for the range of operating variables of relevance to coal conversion processes are very essential to design granular bed filters for flue gas cleaning from coal combustors and gasifiers. Similarly the correlation for η^{p}_{GS} is strictly valid for gas flows vertically downwards through the filter. Horizontal or vertical gas flows might lead to somewhat different correlations. Similarly it is pointed out[12] that the exponent on N_{Pe} in the correlation for η^{p}_{BD} is in agreement with the theory of Brownian deposition from very low Reynolds number flows, but the coefficient 232 is larger than that derived from earlier workers in beds of smaller particles at lower flow rates.

In this perspective the work performed at Argonne National Laboratory by Swift, et al.[13], and Johnson, et al.[14], is of particular significance. The schematic of the test filter and filter loop are shown in Figures 3 and 4, respectively. One of the goals of their work was to evaluate the concept of using the spent sulfur absorbing sorbent from PFBC as a fixed-bed filtration media for the flue gas from the 15.2 cm diameter fluidized-bed combustor. Fresh or sulfated limestone or dolomite is used as a granular bed material. The flue gas passes downward through the granular bed filter, having an inside diameter of either 7.8 or 15 cm. Bed depths of 5-40 cm have been used. Preliminary experiments were performed at ambient conditions with no combustion to determine the degree to which the dust from limestone granular bed would contribute to dust loading in the effluent gas from the filter. In these tests the compressed air with gas velocities ranging from ~0.6 to ~2.4 m/s was passed downwards through granular filter beds of fresh or sulfated limestone of particle size ranges -14 + 30 mesh and -6 + 14 mesh. The test results revealed the appropriateness of using limestone sorbent materials in fixed granular bed filters.

Experiments were next performed employing the flue gas from the combustor which was operated at about 1123K and around 308 kPa. The flue gas temperature at the filter during a typical combustion experiment was only about 453K. The tests were, however, regarded as valuable in that these were performed using a gas containing particulate dust generated by an operating PFBC. These experiments were performed in particular to evaluate the effects of filter bed particle size, bed depth, and gas velocity on filtration efficiency. The filtration efficiency was found to increase with bed depth in the range examined. At the same gas velocity and bed depth, decreasing the mean particle size of the filter bed resulted in an increase in collection efficiency. The results of tests

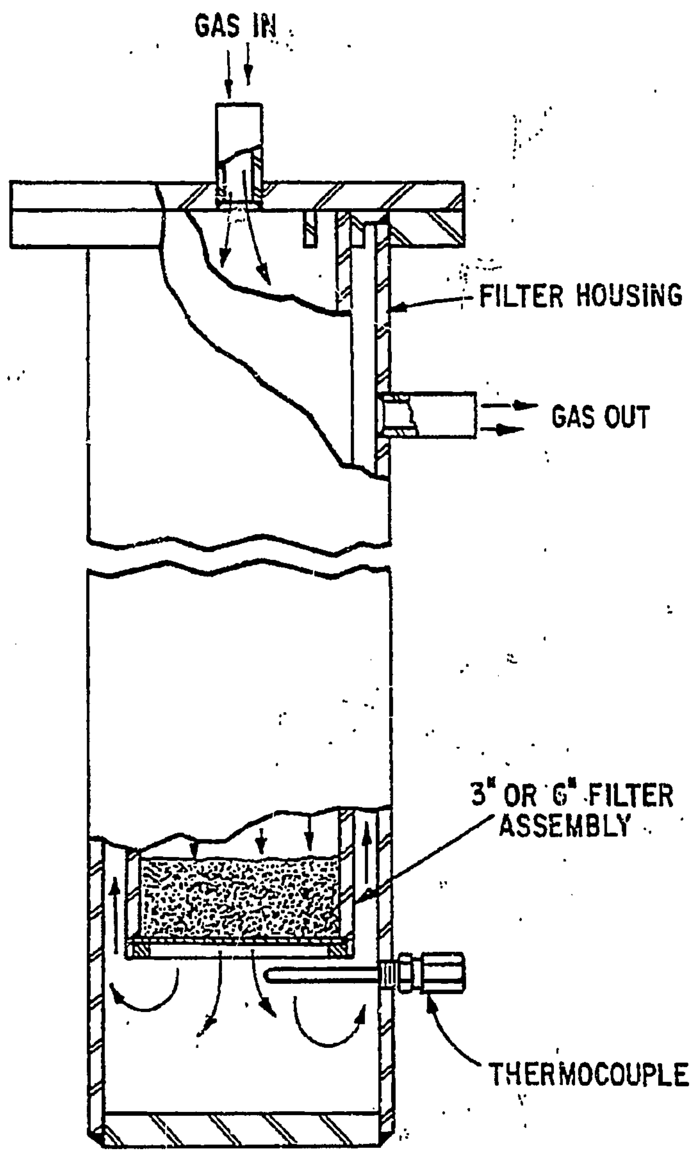


FIGURE 3 - ARGONNE NATIONAL LABORATORY
TEST FILTER, SWIFT ET AL.[13]

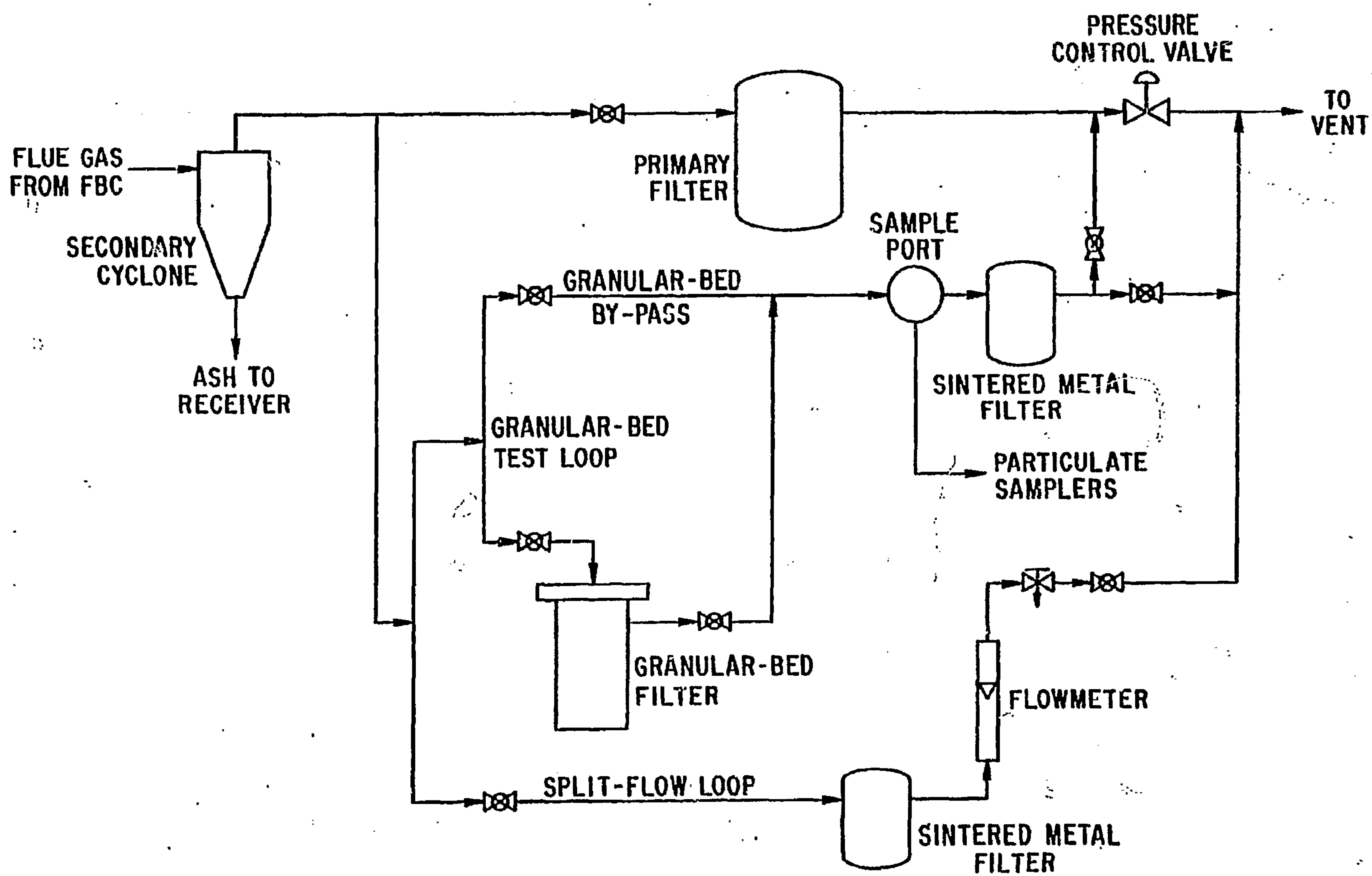


FIGURE 4 - ARGONNE NATIONAL LABORATORY FILTER LOOP SCHEMATIC, SWIFT ET AL.[13]

designed to determine the effect of gas velocity on filtration efficiency have been regarded as inconclusive by these workers[13]. However, they[13,14] comment on the basis of their results that either the principal mechanisms governing particle capture in the bed are other than inertial impaction or particle re-entrainment becomes a problem at high velocities.

Yung, et al.[15], proposed an analytical model for the collection efficiency of dust in a granular filter. It is assumed that most of the large particles present in the gas to be filtered are removed by the earlier filtering units such as primary and secondary cyclones, and as a result, the mass loading of particulates is reduced to the order of 1 gr per standard cubic foot. A granular bed is pictured as comprising of either stationary or slowly moving bed of individual relatively close-packed granules. It is assumed that in large-scale units, no filter cake will be formed either on the bed surface or within the bed. Consequently, the collection of dust particles takes place on clean granular bed particles. It is also claimed that the estimates of collection efficiencies thus obtained are conservative ones. The granular bed is visualized as collection of a number of impaction stages connected in series, the particle collection taking place by inertial impaction. The particle penetration, Pt_d, for the granular bed consisting of N impaction stages is given by the following relation in terms of the single stage collection efficiency, η_{II},

$$Pt_d = (1 - \eta_{II})^N ,$$

the subscript d signifies that the penetration refers to particles of diameter d_p. The inertial impaction collection efficiency, η_{II}, is assumed to be a function of the inertial impaction parameter or Stokes number, N_{St}, which is finally expressed in terms of the bed porosity, ε; bed particle diameter, D_p; and other quantities such that

$$N_{St} = \frac{3}{2}\,\frac{1-\varepsilon}{\varepsilon^2}\;\frac{\rho_p\, d_p^2 U\, C_s}{9\mu\, D_p}\,.$$

For a randomly packed bed

$$N = \frac{3}{2}\,\frac{Z}{D_p}\,,$$

where Z is the bed depth.

The explicit relationship between η_{II} and N_{St} is not developed but instead the particle penetration experimental data are analyzed on the basis of the above relations to evolve η_{II} as a function of N_{St}. Thus, the theory was not tested for its absolute ability to reproduce the experimental data but instead to examine its consistency over a range of operating variables. These equations did express the experimental data to a fair degree of accuracy and consistency. The overall collection efficiency, E, may be calculated from the knowledge of Pt_d and the particle size frequency distribution function on the basis of the following formula:

$$\eta = 1 - \int_0^\infty Pt_d\, f(d_p)\, d(d_p)$$

It is well known that the collection efficiency of the bed is dependent upon the amount of dust already captured by the bed. Most of the theoretical work is addressed to the dynamics of particle deposition on bed particles only during the initial stages of dust collection when it can be assumed that the bed particles are almost free of dust particles.

Recent works of the former category are due to Pendse and Tien[16], Gutfinger and Tardos[17], Tardos, et al.[18], and Thambimuthu, et al.[19] In the experiments of Goren[12], the filtration period was short enough that the dust deposition may be considered on a clean granular bed. In actual situations this is not the case and the dust loading in the bed controls both the particulate collection efficiency as well as the filter pressure drop. The theoretical work in this direction has just about began to emerge. Pendse, et al.[20], in a recent work have measured the increase in the hydrodynamic drag force under creeping flow conditions on a spherical particle as small spherical particles are attached to its surface. They[20] finally express the fractional increase in pressure drop for a granular bed filter which is partially clogged by dust particles as:

$$\frac{\Delta P_d}{\Delta P_c} = 1 + \frac{1}{F_{D_c}} \sum_{i=1}^{N} \Delta F_{D_i}$$

Here ΔP_d and ΔP_c are the pressure drops corresponding to the clogged and clean filter, respectively. F_{D_c} is the drag force acting on the clean collector, and ΔF_{D_i} is the drag force contribution due to the ith deposited particle on the collector which has a total of N particles deposited on its surface. The authors report a procedure for estimating ΔF_{D_i}, however, this involves the knowledge about the morphology of deposited particles. The position of each deposited particle on the bed particle is proposed to be established by the simulation model developed by Tien, et al.[21] and Wang, et al.[22] Extension of these ideas to predict the dynamic behavior of a granular bed filtration process as it becomes increasingly clogged is discussed by Pendse and Tien[23] under well-defined approximations. The granular bed is assumed to be represented by the constricted tube model proposed by Payatakes, et al.[24] and accordingly, it can be viewed as a number of unit bed elements (UBE) of specified thickness connected in series.

Each UBE consists of a number of unit collectors, constricted tube type unit cells, assumed to be identical in shape and size. The constricted tube model parameters such as number of constricted tubes per unit area, length of unit bed element, constriction diameter, height of the unit cell, and maximum diameter of the unit cell are related to the macroscopic properties of porous media. In the numerical simulation[22], additional approximations are made limiting the number of dust particles in the gas stream, particle trajectories are taken corresponding to extremely high- and low-particle inertia, and fluid streamlines are strictly appropriate only when the flow is laminar. Thus, though this work marks the beginning of a theoretical calculation in the right direction, it is far from being appropriate for application under conditions encountered in coal conversion technology.

At Exxon Nutkis, et al.[25], tested a Ducon-supplied granular bed filter in conjunction with their mini-plant pressurized fluidized-bed combustion system operating at temperatures up to 1253K and pressures up to 1000 kPa. At a typical fluidization velocity of about 6 ft/s, the flue gas rate is 650 scfm. The particulate loading in the flue gas entering the filter is about 2.3 g/m^3 or 1.0 gr/scf. The mass median particle diameter is 5 to 7 microns. The filter elements are installed in a pressure vessel lined with refractory and is 2.4 m in diameter and 3.4 m in height. The vessel has four flanges at the top and can hold up to four filter elements, each one contained within a shroud. The inlet dusty gas is piped and metered to each shroud at the top end through a flanged joint. The filtered gas also exits from the top of each shroud and fills the interior of the pressure vessel. The blowback air in the cleaning cycle enters in each of the filter elements at the top end and flows in the opposite direction through the granular bed to that in the filtration cycle. Particulates removed from the filter during filtration cycle impinge on the inside surface of the shroud and collect at the bottom in lockhoppers. The pressure vessel is heated to a temperature above the dew point of the combustor flue gas before starting filtration.

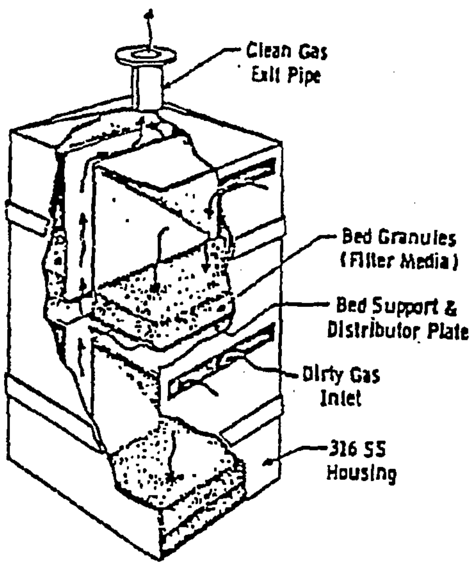
Initially, the tests were conducted with three filter elements bought from the Ducon company. Each element was 20 cm in diameter and 1.8 m long, and contained 12 beds of some granular material such as alumina, quartz, etc. The inlet screen size was 50 mesh and its function was to retain the filter media during the cleaning cycle while allowing the fine dust particles to pass through. A number of tests were then undertaken, but the pressure drops across the filter were excessive and all efforts to blowback were unsuccessful. Visual inspection of these filter elements revealed that a hard filter cake had formed on the inlet retaining screens. Very little particulate dust material was found in the filter medium. Further testing under different conditions was conducted, but the problem of screen plugging prevented any successful testing. Filter element design was, therefore, modified to remove the screens and by providing more freeboard to prevent entrainment of the filter media during blowback. A perforated plate fluidization grid was used to support the media which ensured good distribution of blowback air. Such modified filter elements were fabricated and two of the filter elements were installed, each containing five filter beds for testing. The freeboard height was 18 cm in each of the filter beds and was found adequate to prevent the entrainment of the filter media.

The successful operability of this modified filter has been demonstrated by a 24-hour test run. During this period, no significant increase in the baseline pressure drop across the filter occurred. Blowback was usually required every

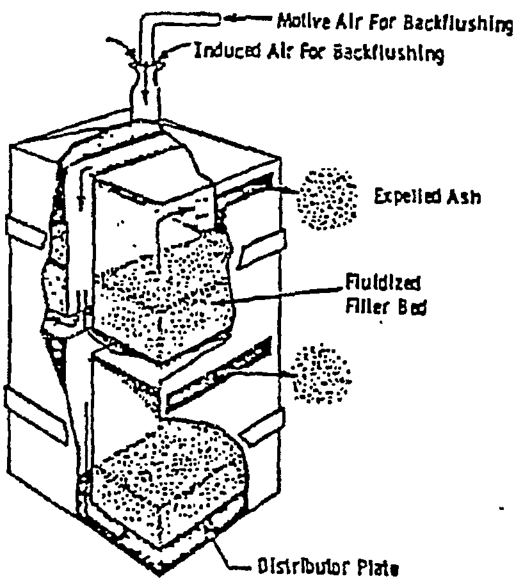
10-20 minutes during which time the filter pressure drop had increased by only 14 kPa above its baseline value. Blowback period ranged between 2 and 30 seconds, and the superficial gas velocity was verified between 0.15 to 0.75 m/s. Filtration velocities ranged between 20 m/s to 24 m/s. Filter media particles were 300 to 600 µm quartz particles, and 840 to 1400 µm alumina particles. The particulate collection efficiencies of 90 to 95 percent were found for the outlet particulate concentrations of about 0.1 g/m^3. The particulates in filtered gas had a mass median size of about 3 µm, with about 10 percent larger than 10 µm. It was also observed that the outlet loadings increased with time. Also, dust particles were found to retain in the filter bed (10 to 30 percent) and these were uniformly distributed throughout the filter bed. Several design problems have been recognized and many have been identified in ambient temperature tests in a transparent filter unit. With adequate refinements in filter design, experiments have been planned over longer periods of duration to establish this filtration technique.

Lippert, et al.[26], are also in the process of evaluating the concept of fixed-bed granular filtration under a PRDA contract from the DOE for PFBC applications. In Figure 5, is shown a single element consisting of four compartments which operate in parallel both in the filtration and cleaning (or blowback) cycles. Each compartment contains a shallow bed of granular particles supported on an appropriate distributor plate and serving as the filter media. In the filtration cycle, the dusty gas enters through a slot at the top of each compartment and percolates down through the filter bed. The cleaned gas from all compartment combines and exits out of the element through the clean glass plenum. In the cleaning cycle, the beds are cleaned by fluidizing them with a high-pressure air flowing in the reverse direction for a short time. Sufficient freeboard

GBF ELEMENT - FILTRATION MODE



GBF ELEMENT - CLEANING MODE



FIXED-BED GRANULAR FILTER (DUCON, INC.)

FIGURE 5 - LIPPERT ET AL.[26]

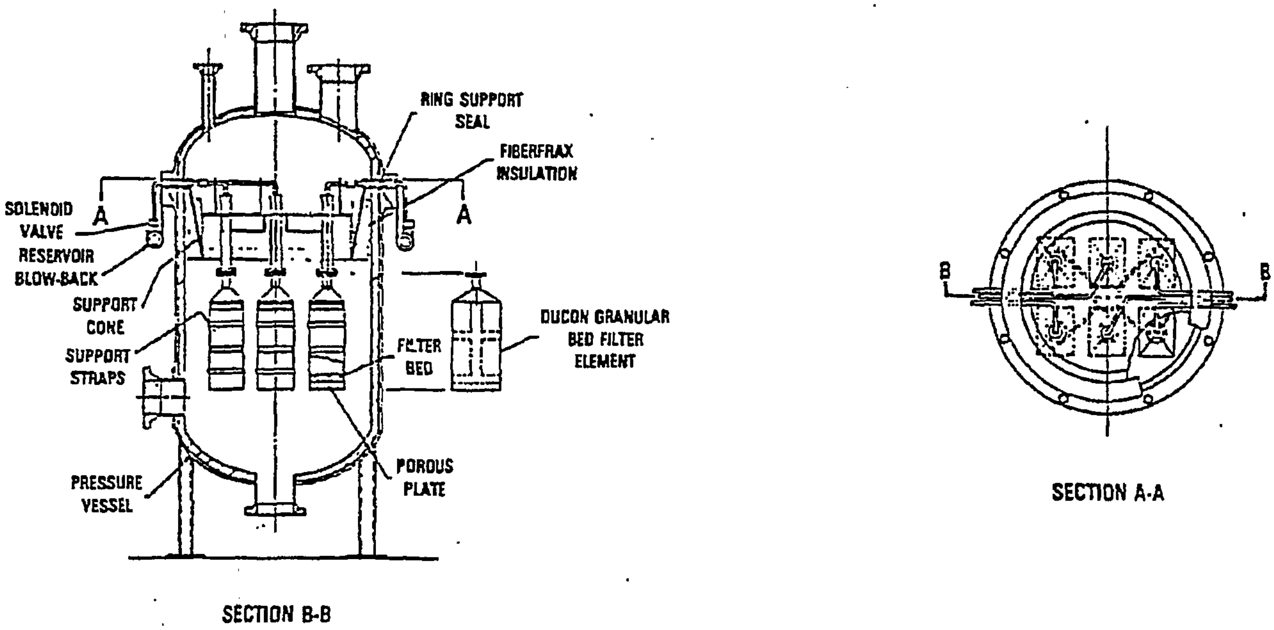
height is available in each bed compartment so that the media granules are not lost in this cleaning cycle while the dust particles are ejected from the bed. The selection of proper granule size, compartment design, backflush velocity and duration of the backflush cycle is necessary for steady-state bed fluidization. The backflush fluidization velocity must fall between the minimum fluidization velocity of the largest granules and the terminal velocity of the smallest bed granules. Other qualitative considerations have been given by these authors on the basis of their experience on cold flow model testing.

The parametric dependence of the operating variables and system geometry on particulate collection efficiency and filter pressure drop are reasonably well understood from the cold model and bench-scale test experiments, Saxena[3]. According to Lippert, et al.[26], in their filter bed, the high collection efficiency is not due to the clean bed conditions but to a state of filter where dust collected on individual media granules bridges the distance between them and the collection mechanism shifts to what is referred to as barrier filtration. Under such conditions, high filtration efficiency is achieved due to the formation of dust cake on the surface of filter granules. Indeed, the experimental work conducted by Ducon, Inc., and Westinghouse independently on small-scale, plexiglass models at low temperature and low pressure confirmed this. The Ducon tests were conducted with fly ash (90 percent < 95 μm, 50 percent <.10 μm, and 5 percent < 1μ m) and the formation of a surface cake was visually observed with collection efficiency of almost 100 percent. Similar results were found with carbon black. The filter face velocity was kept smaller than 80 ft/min which preserved the formation of surface cake. At higher velocities the breakthrough of the dust was observed. Westinghouse employed ground limestone dust (100 percent < 10 μm) and obtained a collection efficiency ranging between 99.7

and 99.9 percent in their low-temperature, low-pressure tests when the maximum system pressure drop ranged between 5 and 10 kPa during a test period of 12 hours. In their high-temperature (1100°F), low-pressure runs, the collection efficiency ranged between 96.0 to 99.9 percent for the gas velocity of 30 ft/min.

These authors[26] also examine the test runs of Exxon researchers and advance several possibilities that might have contributed to the limited success achieved in their work. A lot of concern is related to the backflush procedure and it is proposed that dust expelled from one element probably settled on to the other. It is pointed out that proper settlement of the dust in the containment vessel is an important aspect of filtration process. Further, it can get complicated if either the backflush velocity is excessively high or the bed is highly agitated. In both cases the agglomerated dust particles may get dispersed and the resulting particles will be of a size range which is hard to settle. These authors also feel that in most of the Exxon tests, the filter was pulsed on backflush and this might have caused a partial loss of bed media during the pulsed transient.

Based on their experience, the Westinghouse engineers have designed a six-element test unit contained inside a single pressure vessel as shown in Figure 6 for filtering hot gas containing fly ash or other dusts at high pressure. Each element contains four parallel operating compartments each having a bed of 15.2 cm x 30.5 cm x 3.8 cm deep and a surface area of 0.047 m^2. The six-element unit thus has a total surface area of 1.1 m^2. The bed has a media particle size range of 250 μm-650 μm, a freeboard height of 30.5 cm, and a backflush velocity of 52 cm/s. The operating filter face velocity is 25.4 cm/s and the capacity of the pilot unit is rated at 16.7 m^3/min. In the cleaning cycle, only one element will be operated on backflush at any given time.



GENERAL ARRANGEMENT OF SIX-ELEMENT GRANULAR BED FILTER PILOT UNIT (WESTINGHOUSE)

FIGURE 6 - LIPPERT ET AL.[26]

Kalinowski and Leith[27] report on their results obtained in a 20.3-cm diameter concurrent moving granular bed filter which they claim should be preferred over continuously moving cross-flow design. In their arrangement, the particle-laden gas passes downward through a descending bed of media granules while the clean granules are added continuously at the top of the bed. The least-squares regression fit of the mass penetration, P, data at two bed volumes yielded the following result:

$$P\ (\%) = 2.42 + 0.69 \times 10^{-4}\ KUZ$$

Here K is the intergranular dust deposit (1 to 5 percent by weight), U is the superficial velocity (100 to 200 mm/s), and Z is the bed depth (130 and 230 mm).

Gutfinger, et al.[28], employed a fluidized-bed, cross-flow filter to clean the exhaust gases coming out of a 2.5 H.P. "Peter" Diesel engine. The filter is operated in the steady-state mode so that the clean media granules are continuously introduced at the top and dirty granules are removed from the bottom. The particulate collection filter efficiency, η, is obtained from the single granule filter efficiency, η_p, by the following relation:

$$\eta = 1 - \exp\left[-1.5\ \eta_p\ \frac{1-\varepsilon}{\mu}\ \frac{Z}{2R_p}\right] .$$

Here Z is the total height of the filter, ε is the porosity of the filter bed, and R_p is the media granule radius. The mechanisms and theories involved in the determination of η_p are given and reviewed by these authors[28,29]. Gutfinger, et al.[30], have further discussed their result on moving-bed cross-flow filter in a recent publication and their main results are briefly discussed in the following.

They[30] performed experiments with the granular bed of coarse quartz sand of 1.6 mm average diameter in the fluidized mode with a bed thickness of 10 cm. Particulate efficiencies were measured of the fluidized-bed cross-flow filter as a function of dust particle diameter with the gas temperature as a parameter. The smoke coming out of the diesel engine was diluted with hot compressed air. The diesel smoke had a particle size distribution between 0.02-1 μm with a peak in the range 0.1-0.2 μm. The superficial gas velocity was 87 cm/s, and the measurements were conducted at the mean gas temperatures of 303, 468, and 478K. It was noted that in the particulate collection, all the three mechanisms of diffusion, inertia, and interception were participating. It is also observed that triboelectric effects are quite pronounced at room temperature with much less contribution at higher temperatures. The cross-flow moving bed filter mode is also examined at 300, 573, and 773K with a bed thickness of 15 cm. Experimental results in all cases are compared with the predictions of theory as given by the above relation where in computing the single particle efficiency the effects of inertia, interception, and diffusion are considered. In all cases the experimental results are greater than those obtained on the basis of theoretical calculations.

Yamamura and Terada[31] have extensively tested a moving bed filter in which the bed is about 50 cm of alumina balls of diameter 0.5, 1.0, and 2.0 mm. In one series of runs the gas velocity was maintained at 0.5 m/s and the inlet dust concentration at 1 g/m^3. It was noticed that the outlet dust concentration for each size bed decreased with the increase in the bed depth, the relation being linear on a semilogarithmic scale for bed depth greater than 10 cm. Further, for the same bed depth, the outlet dust concentration was found to be the largest for the smallest size bed particle and smallest for the largest bed particle (2 mm). Their experiments also revealed that the outlet dust concentration decreases as the gas velocity is decreased and also as the moving rate of the ball decreased. This increase in the outlet dust concentration with the increase in the moving rate of the balls slows down with the increase in the value of the velocity of the moving bed. The dust accumulation on the alumina balls per unit volume in the moving bed depends on the conditions of the moving bed and inlet gas. When the inlet dust concentration is high or the moving rate of the balls is low, accumulation is high. The experiments indicated that there is a maximum in the curve representing the particle collection efficiency versus average dust accumulation in the bed. The dust removal efficiency increases with the increase in the average dust accumulation, reaches a maximum value, and thereafter decreases as the average dust accumulation further increases in the bed. The authors emphasize the need to know such characteristics of the filter bed for an adequate design of a filter pilot plant.

The particulate collection efficiency exhibits a dramatic increase in its value when an electric field, E, of a few kV/cm (dc or ac) is applied across a bed of insulating or semi-insulating granules, Self, et al.[32] The enhancement is much more pronounced for particles of submicron size than for larger particles. The electrical effectiveness, γ, is defined in terms of the particle penetration, P, as

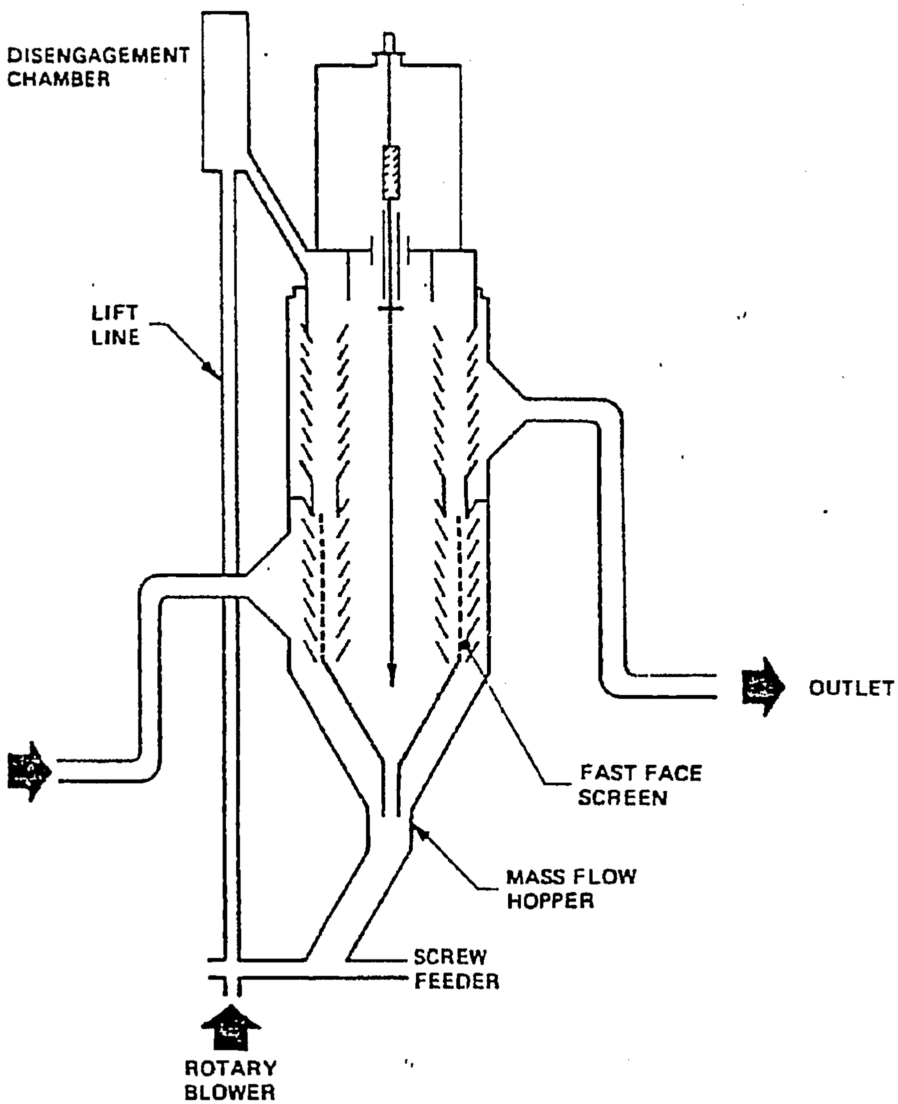
$$\gamma = \frac{P\ (E = 0) - P\ (E)}{P\ (E = 0)}$$

The experiments of Self, et al.[32], performed in an 8-inch fixed bed of ¼-inch alumina balls, contained in a 4-inch by 4-inch vertical duct of plexiglas, showed that γ increases with the applied electrical field and asymptotically approaches to a value of about 75 percent at E of about 5 kV/cm. A metal screen located in the central section of the bed served as a high-voltage electrode and similar metal-grounded screens were placed at the top and bottom ends of the bed. The dust particle diameter effect is expressed by an electrical factor of improvement, F, which is defined as:

$$F = \frac{P\ (E = 0)}{P\ (E)}$$

For submicron particles, F ranges between three to five, whereas F is about one for particles greater than 3 μm in diameter. They also report that γ is a weakly increasing function of grain loading, and it decreases as the gas velocity is increased. Their experiments did not distinguish between the effect of ac or dc voltages on collection efficiency. They also point out to the importance of electrical charge on the dust particle in enhancing the particle collection efficiency. It is concluded[32] that a large enhancement in collection efficiency for submicron range particles is possible by the application of a strong electric field and the increase is significant if the dust particles are charged.

Presser and Alexander[33] have reported their continuing effort on an electrically augmented moving granular bed filter, Figure 7. This design premiums on the experience of commercial technology of Electrified Filter Bed (EFB), which has been successfully used in specific situations. For instance[34], at an asphalt roofing plant, such filters operated with an efficiency of greater than 98 percent for particles less than 2 μm in diameter. In this design[33], the problem of front face plugging which involves the blinding of the incident filter face has been resolved by reducing the louver area to the minimum essential for retaining the bed granules because the dust deposits are formed at the lips of the louvers. The elimination of the exposed louver surfaces (overhanging portion of the louver) left no bare metal surfaces for structures to build on from dust particles which actually caused the plugging problem to start with. The filter is a cylindrical unit (60 cm outer diameter; 40 cm inner diameter; bed depth,



CROSS-FLOW MOVING-BED ELECTROSTATIC GRANULAR FILTER (EFB, INC.)

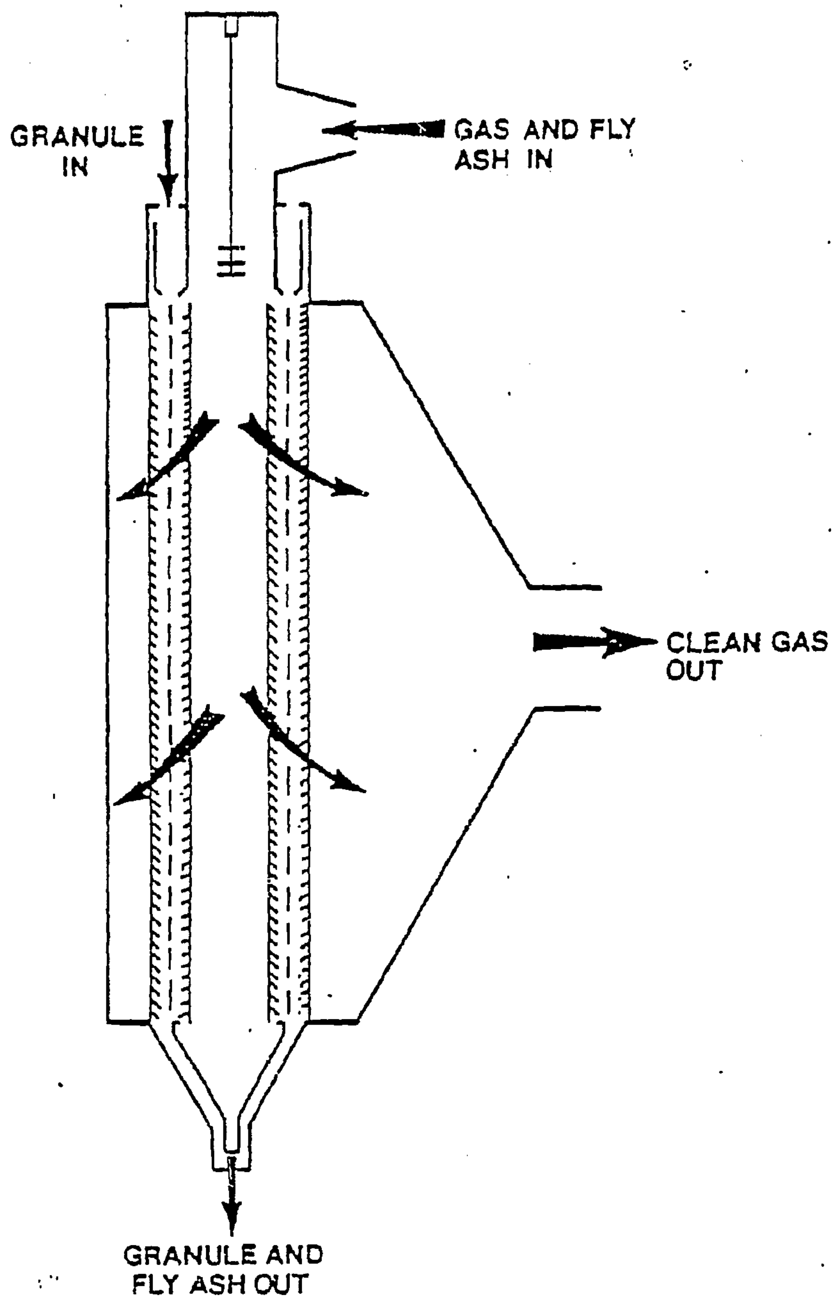
FIGURE 7 - PRESSER AND ALEXANDER[33]

10 cm; and bed particles, 2 mm in diameter) in which two filter stages are vertically arranged. The dust-laden gas passes first through the lower stage where most of the filtration occurs. The partially cleaned gas then rises up in the central hollow region where its dust particles are charged by the corona discharge from the high-voltage electrode installed along the axis of the filter. This gas next exits through the upper stage of the filter where the media granules are electrically polarized by an applied electric field to efficiently remove the dust particles. It is claimed that the problem of re-entrainment of collected dust is automatically solved in this design. Any dust re-entrained from the lower stage is recaptured in the upper stage. The granules move downward through the beds with a slow speed which can be controlled by the screw feeder as shown in the figure. The granule-dust mixture is separated, and the clean granules are recycled to the filter bed. In order to avoid bed freezing in the front region of the lower bed, a coarse mesh screen is installed at about ¼ of the bed overall depth away from the front louvers. Bed granules in this region are moved downward at a faster rate than in the remaining bed. This arrangement avoids bed freezing by removing the greater accumulations of dust faster from the bed. At the present time a successful 84-hour test run at room temperature and pressure in a 800-cfm pilot unit with Burgess No. 10 dust simulating the HTHP fly ash has been completed. Work is now in progress employing the effluent gas from a high-temperature (1550°F) fluidized-bed coal combustor.

More recent developments of this electrostatic granular bed filter are reported by Boericke, et al.[35] It is claimed that this two-stage design collects more dust per unit volume of the bed material than other designs. In some commercial designs, electrodes are inserted into the second stage to provide a voltage gradient across the bed granules. This arrangement is found to increase the collection efficiency of the particulates which are charged in the central section by the wire corona. It is pointed out[35] that in the PFB applications of this device, a high-voltage collecting field can no longer be used due to the finite electrical conductivity of the media particles and associated power loss. However, their present experience suggests that appreciable augmentation in the collection efficiency is possible due to the electrostatic attractive force between the charged dust particles and the bed conducting particles due to image charges which appear across the ground plane. From their limited cold flow test results, they[35] conclude that the particle penetration is a function of bed loading parameter which is defined as the ratio of rate of dust collection to the rate of media flow.

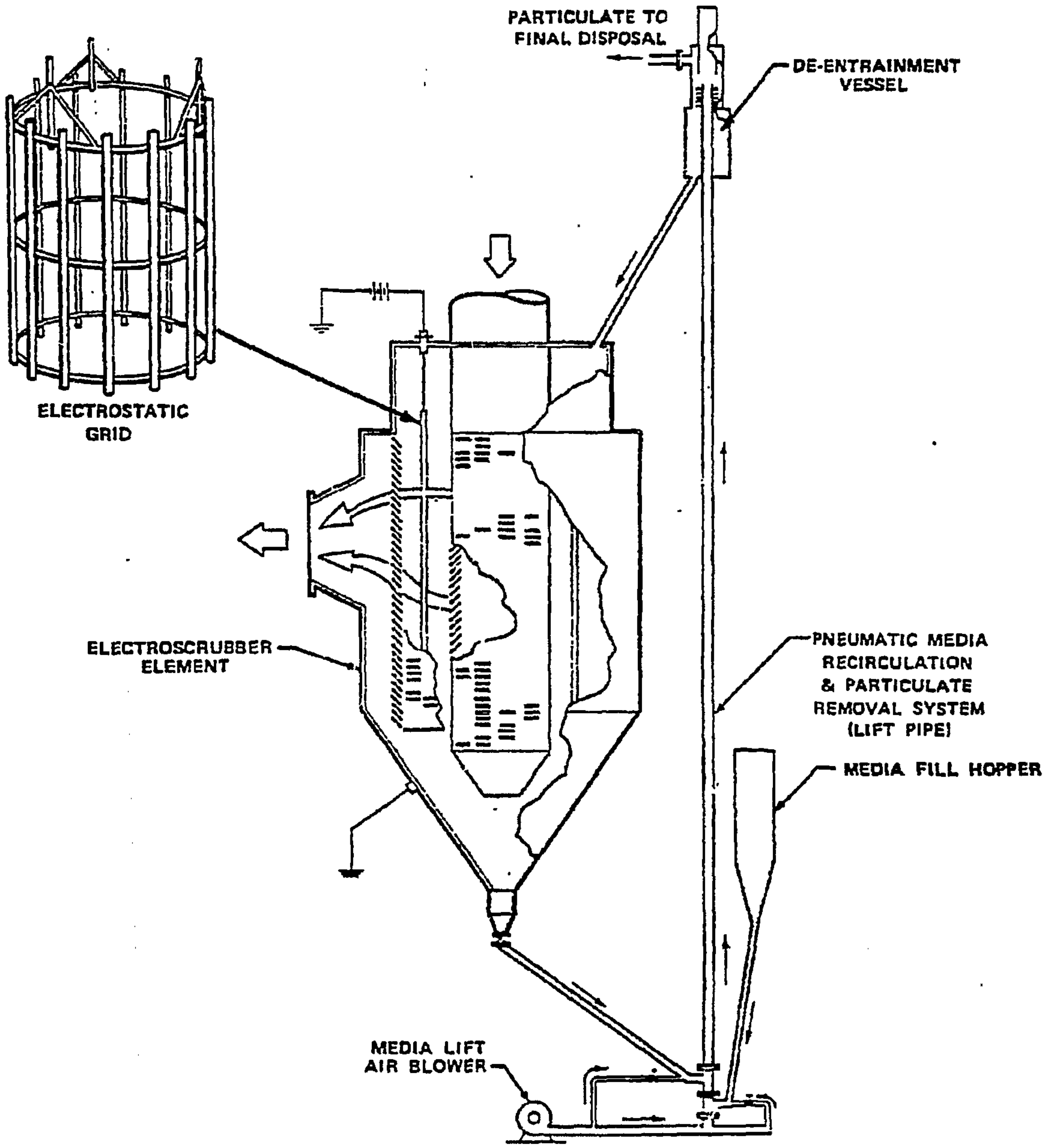
These workers[35] have also reported in brief their approach to model the dust collection process in such electrostatic granular bed filters. They are essentially working along the "unit cell" approach, outlined in one of the earlier papers from General Electric Company[36]. The granular bed is regarded as a homogeneous assemblage of identical cells, each cell consisting of an individual spherical particle surrounded by a concentric shell of gas whose radius is determined to duplicate the void fraction of the bed. By properly assigning the boundary conditions for the fluid flow corresponding to creeping (Stokes) flow at low Reynolds numbers or potential flow at high Reynolds numbers, particle trajectories have been computed for dilute noninteracting particle suspensions with appropriate initial conditions. Drag forces, particle inertia, and electrostatic forces have been considered in the calculations of the limiting trajectories and thence the collection efficiency. The total bed collection efficiency is next obtained by the integration of this result over the depth of the granular bed for the specified operating conditions and dust size. These workers realized that this unit cell approach underestimates the actual collection efficiency of a granular bed and one of the reasons for this is what is referred to as the "jetting effect." This is caused by the presence of particles in the bed which restrict the actual flow to a smaller region of the unit cell. Currently, analytical work is in progress to account for this jetting effect and also controlled experiments are being planned to validate the theoretical model. The experiments involve the measurements of collection efficiency with spherical particles of different sizes with monodisperse aerosols of different sizes and for a range of face velocities. These experiments are intended to establish a correlation for the jetting parameter as a function of particle Reynolds number. The experiments are also being conducted to understand the electrostatic augmentation by using conducting media and charged aerosols. Measurements will be made over a range of media particle sizes and gas residence times. An updated single-stage version of this two-stage design to handle large gas throughput for a given size of media granules chosen to optimize the dust collection process and without blowing them out of the bed is proposed as shown in Figure 8. The basic difference in this design from the earlier one of Figure 7, is in the direction of gas flow which is now inside out in contrast to being outside in. Also, the filter is now a single-stage unit.

Grace, et al.[37] at Combustion Power Company have developed an electroscrubber granular filter whose schematic is shown in Figure 9. It consists of a cylindrical vessel containing two concentric, cylindrical louvered screens. The annulus between the screens is filled with pea-size gravel media. An electrostatic grid in the form of a cage is located in this media. A high voltage is applied to this grid and the electric field generated between this conductor and the inner and outer screens enhances the particulate collection efficiency as the dusty gas passes through the media. The enhancement is due



UPDATED DESIGN OF CROSS-FLOW MOVING-BED ELECTROSTATIC GRANULAR FILTER (EFB, INC.)

FIGURE 8 - FROM REFERENCE 56



CROSS-FLOW-MOVING-BED ELECTROSCRUBBER GRANULAR FILTER
(COMBUSTION POWER COMPANY, INC.)

FIGURE 9 - GRACE ET AL.[37]

to the frictional charging (or tribocharging) of the particulates as the dirty gas flows through pipes and cyclones. Clean gas exits through the outer screen. The filter media moves continuously downward and is recycled into the filter after cleaning it. It was found that electrostatics increases the collection efficiency and for submicron particles, this enhancement is very pronounced from about 65 percent to 95 percent. As a result of this, the dependence of particle collection efficiency on particle diameter disappears and the curve becomes flat. Additional details and historical applications of Combustion Power Company's electroscrubber filter is given in a recent paper by Parquet[38].

The penetration of dust through such a filter where both mechanical and electrical effects are present is expressed as:

$$(1 - \bar{\eta})_{tot} = (1 - \eta)_{elec} \; (1 - \eta)_{mech}$$

Grace, et al.[37], have given the following expression for η_{elec} which involves the various system parameters:

$$\eta_{elec} = 1 - \exp \left[\frac{-2 \; (1 - \varepsilon) \; Z \; E \; q_p \; C_s}{\pi \; \mu \; D_p \; d_p \; U} \right]$$

Here, ε is the bed porosity, Z is the bed thickness, E is the average electric field strength, and q_p is the particle charge. It is evident from this relation that increasing the particulate charge and electric field strength increases the particle collection efficiency. The important mechanisms which lead to mechanical collection are impaction and diffusion and they[37] express these effects as

$$(1 - \bar{\eta}) = \left[1 - \left(\frac{N_{St}}{\varepsilon} \right)^{m} \right] \left[1 - \frac{4.36}{\varepsilon} N_{Pe}^{-2/3} \right]$$

where m is an empirically determined number whose value depends upon the Stokes number range. It appears that these results are not yet tested in detail on the basis of experimental data.

It has been known for some 30 years that electric charge acquired by the media particles of a granular bed as a result of frictional electrification (auto-electrification or triboelectrification) make them more appropriate for capturing dust particles. This effect is particularly pronounced if the bed granules are of dielectric material. In recent years, triboelectrification enhances the filtration efficiency has been explicitly demonstrated by Balasubramanian, et al.[39], for spout bed filters, and Tardos, et al.[40-42], for fluidized-bed filters. It was found[40] that the capture efficiency of a bed of plastic granules (40-50 mesh) exhibited a sudden appreciable increase as soon as the gas velocity exceeded the minimum fluidization velocity. In their next effort to demonstrate more conclusively that triboelectrification was responsible for the enhancement of the filter capture capabilities, they installed a spherical nickel probe in a 1 mm spherical particle Lucite bed of 30 cm thickness, filtering 0.23 and 0.48 μm neutral latex aerosols to measure the electrostatic potential. It was found that the probe potential increased with gas velocity beyond minimum fluidization and that the aerosol capture efficiency was maximum when the potential reached its maximum value. With a sand band, it was established that the potential of the nickel probe (2 mm in diameter) was uniquely dependent on the level of gas humidity for a fixed value of the fluidizing velocity beyond minimum fluidization. The potential decreasing with the increase in the relative humidity of the gas. Similar experiments were performed by Tardos and Pfeffer[42] with the refinement to include a modified Faraday cage so that the electrostatic charge generated on the granules could also be established. These experiments which were conducted with four different dielectric granules of average diameter, ranging from 0.45 to 3.1 mm, indicated that at lower gas humidities (10 to 30 percent) the particle caputre efficiency is almost constant with increase in gas velocity beyond minimum fluidization. It appears that the decrease in efficiency due to gas bypassing is counterbalanced by strong electrostatic forces, resulting from the electrification of the granules. For high values of relative humidity (40 to 60 percent) where the charge on the particles is relatively small and the electrostatic forces are weak, the collection efficiency decreases as the gas velocity is increased beyond minimum fluidization due to gas bypassing in the bubble phase.

Tardos and Pfeffer[55] have described a computational procedure to estimate the filtration efficiency of a granular bed of perfect insulators which have a very low and uniformly distributed surface charge. The general equation for calculation is the same as given above[28], except the single granule filter efficiency calculation is now more involved than in the case of uncharged neutral particles. In the evaluation of η_p inertial, gravitational and electrostatic forces have been considered. Hence the theoretical model provides a basis to calculate the trajectory of a small charged dust particle in a granular bed under the influence of these three types of forces. A number of approximations have been made in the numerical computations and these are explicitly mentioned in their work[55]. The theoretical overall collection efficiency of a single granule is obtained by adding to the value so obtained the efficiency value due to pure diffusion only for which an explicit expression is available involving the Peclet number. The theoretically calculated values are found to agree fairly well with the experimental data. They have also inferred from their analysis that the surface charge on the granules of the fluidized particles is dependent on gas velocity. It increases rapidly as the velocity goes beyond minimum fluidization velocity but then drops as the velocity is further increased. This drop is attributed to gas bubbles or to other fluid-mechanical factors in the bed.

At MIT Melcher and his coworkers[43-47] have been investigating electropacked (EP) and electrofluidized (EF) beds as devices for efficient particulate collection from particle laden gas streams. The bed has a central electrode to which an electric potential is applied relative to the bed wall and the gas entrained particles are already charged. Thus, by some such arrangement, the bed semi-insulating particles get exposed to an electric field. Zahedi and Melcher[44,46] expressed the particulate collection efficiency, η, of an electrofluidized bed as:

$$\eta = 1 - \exp \quad - \frac{3\pi c}{8} \frac{bE}{U} \frac{\ell_o}{R_p} \quad .$$

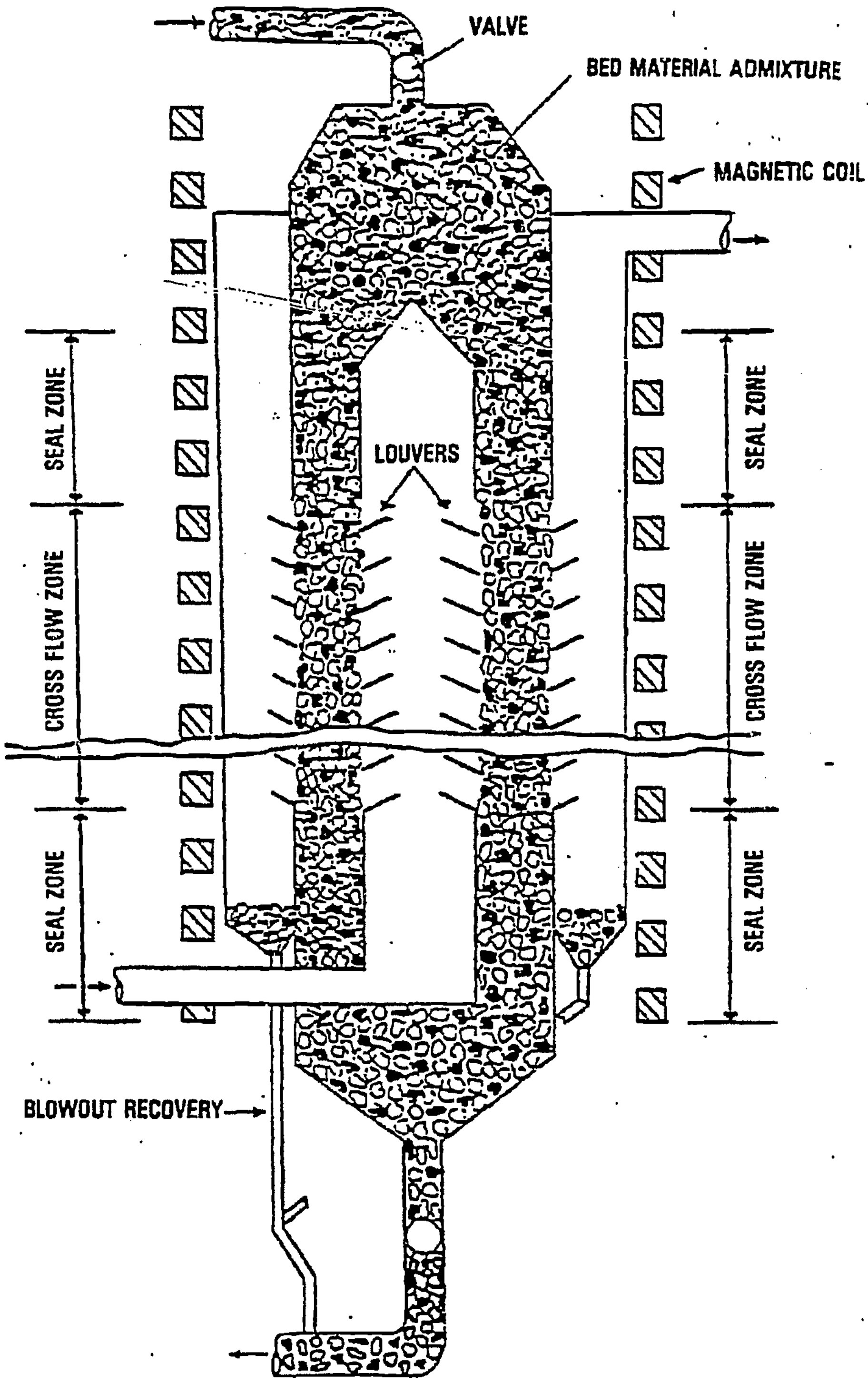
Here c is a constant, which is found[46] to vary between 0.8 and 1.2, b is the mobility of the particles to be collected, E is the microscopic field experienced by the individual bed particles and if the particle packing is not too close, it can be approximated with a fair degree of accuracy by the applied electric field strength, R_p is the bed granule radius, U is the superficial gas velocity and ℓ_o is the unfluidized-bed height.

In a recent report[45], the properties of such beds using sand and glass beads at ambient pressure but at temperatures up to a maximum of 1400°F have been investigated. At temperatures above 1100°F, the electrical power consumption in EPB is greater than 10 W/100 acfm, and EFB has been investigated as an alternative. Experiments revealed that for certain operating conditions where the particle electrical conductivity is low, the fluidized-bed current can be even larger than the packed-bed current. This was actually found for sand for bed voltage of 1KV, for temperatures in the range 300° to 700°F, and for fluidization velocities in the range 1.5 to 1.9 times the minimum fluidization velocity. At temperatures greater than 700°F, where the particle conductivity is high, the fluidization of bed reduces bed current by 25 to 50 percent. These results are strictly valid for a gently fluidized bed and with increase in gas velocity, different qualitative trends are possible. For glass beads the fluidized-bed currents always remain smaller than the packed-bed currents by about 25 percent. The experiments were conducted in the temperature range 200° to 800°F and the gas fluidization velocity ranged between 1.5 to 2.0 times the minimum fluidization velocity.

Two mechanisms for charge transfer are postulated[46]. In EPB situation the charge transfer occurs via particles which bridge the distance between the two electrodes. In EFB such a chain transfer can take place through the formation of such short time duration particle linkages. A second transfer mechanism in EFB exists and is due to the bubble induced particle convection. A particle while residing at the electrode surface acquires a limiting value of charge. The bubble sweeps this charged particle away and replaces it with a different bed particle. The charged particle while in the emulsion phase of the bed shares its charge with another particle on contact. It has been shown that the convective transfer mechanism dominates for particles of low-electrical conductivity but chain transfer dominates for high-particle conductivity.

Exxon Research and Engineering Company[48] pioneered a novel method for the collection of dust entrained in a gas stream by a cross-flow moving granular bed enclosed in an externally applied magnetic field, Figure 10. The bed material consisted of an admixture of ferro-magnetic (cobalt) and nonmagnetic (bauxite or alumina) particles. The experimental work of Golan and Matulevicius[48] revealed that the pressure drop across such a bed is considerably reduced and the solids blowout velocity is appreciably increased for otherwise identical conditions by the application of an external magnetic field. The increase in the value of the magnetic field affects these parameters favorably. In a 4-inch thick, magnetically stabilized bed particles of 900 μm diameter, the application of magnetic field could reduce the pressure drop by 50 percent at a fixed value of gas velocity, and for the same pressure drop the superficial gas velocity could be increased by a factor of two. This ability to reduce the pressure drop or increase the gas throughput of a magnetically stabilized bed (MSB) gives an edge to such granular beds over their normal operational procedure because of the associated economic implications. The other advantages claimed by Exxon researchers for such a MSB System are: high particulate capture efficiency, trace metal removal and ability to handle a wide variety of coals.

The application of a magnetic field to a granular bed influences the structure and orientation of its particles so that the bed voidage increases. Increase in the magnetic field increases the bed voidage. This characteristic can then readily explain the observed lower pressure drops and higher gas throughputs before any appreciable solids blowout occurs in a magnetically stabilized bed in relation to an unstabilized bed. The particulate collection capability of a small MSB from an air stream containing 1.7 grains/scf of fly ash at a superficial velocity of 3.1 ft/s was assessed as a function of time while the magnetic field was varied from 0 to 105 oersteds. The overall collection efficiency was found to decrease with time and the decrease during the first hour with no



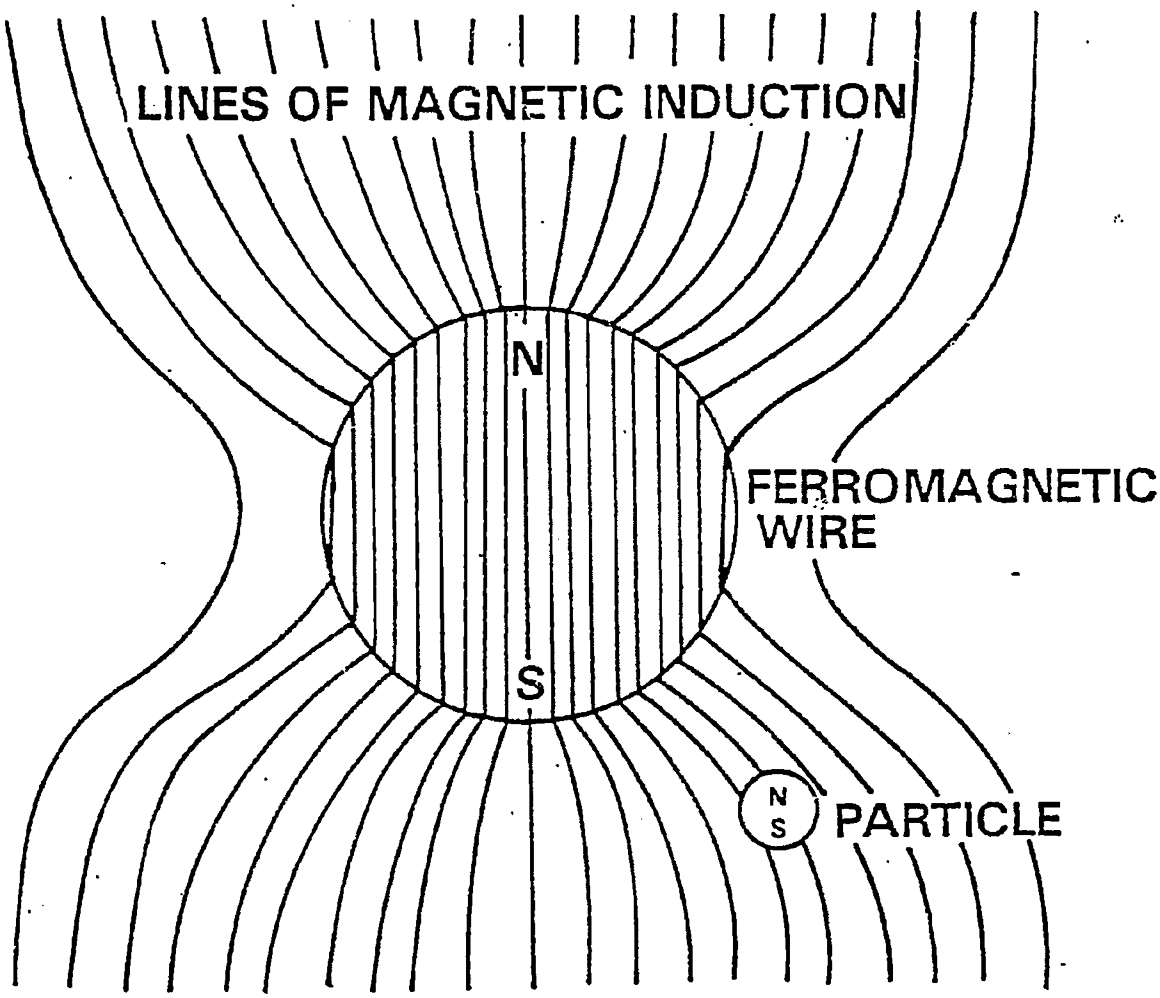
MAGNETICALLY STABILIZED GRANULAR BED FILTER (EXXON)

FIGURE 10 - GOLAN AND MATULEVICIUS[48]

field was appreciable but, as the magnetic field is applied, the rate of decrement decreased appreciably. For a magnetic field of 105 oersteds, the decrease in the overall collection efficiency was only small even after 1 hour. Thus, such MSB filters can be employed for a longer filtration cycle and also can handle much larger gas throughputs in comparison to unstabilized granular bed filters.

Golan and Matulevicius[48] have also demonstrated that MSB filters are much more efficient than other conventional filters such as sand filters, fabric filters, and electrostatic precipitators for particles in the size range 0.5 to 2 μm. The particle collection in MSB filters takes place by the combined effects of inertial impaction, direct interception, and Brownian diffusion. The reason for such high collection efficiencies of MSB filters is not well understood at the present time and the authors[48] attribute this to impaction due to higher bed velocities in MSB. Further, particle collection on already collected dust particle is possible in such filters without causing any plugging or excessive pressure drop problems due to the higher bed voidage values in MSB. Finally, it should be noted that the particulate collection in an MSB is independent of the magnetic properties of the dust particles and depends only on the magnetic properties of the bed particles and the magnitude of the magnetic field. This is in sharp contrast with the principle of dust collection of a magnetic material in the vicinity of a ferromagnetic wire placed in a magnetic field[49,50]. Here, the highly nonuniform magnetic field around the wire, Figure 11, attracts the magnetized dust particle and it is this attractive interaction between the two dipoles which brings about the collection of dust particle on the wire.

Exxon Researchers[48,51] under the DOE sponsorship have planned to investigate this novel filtration principle for the purpose of flue gas cleaning from an



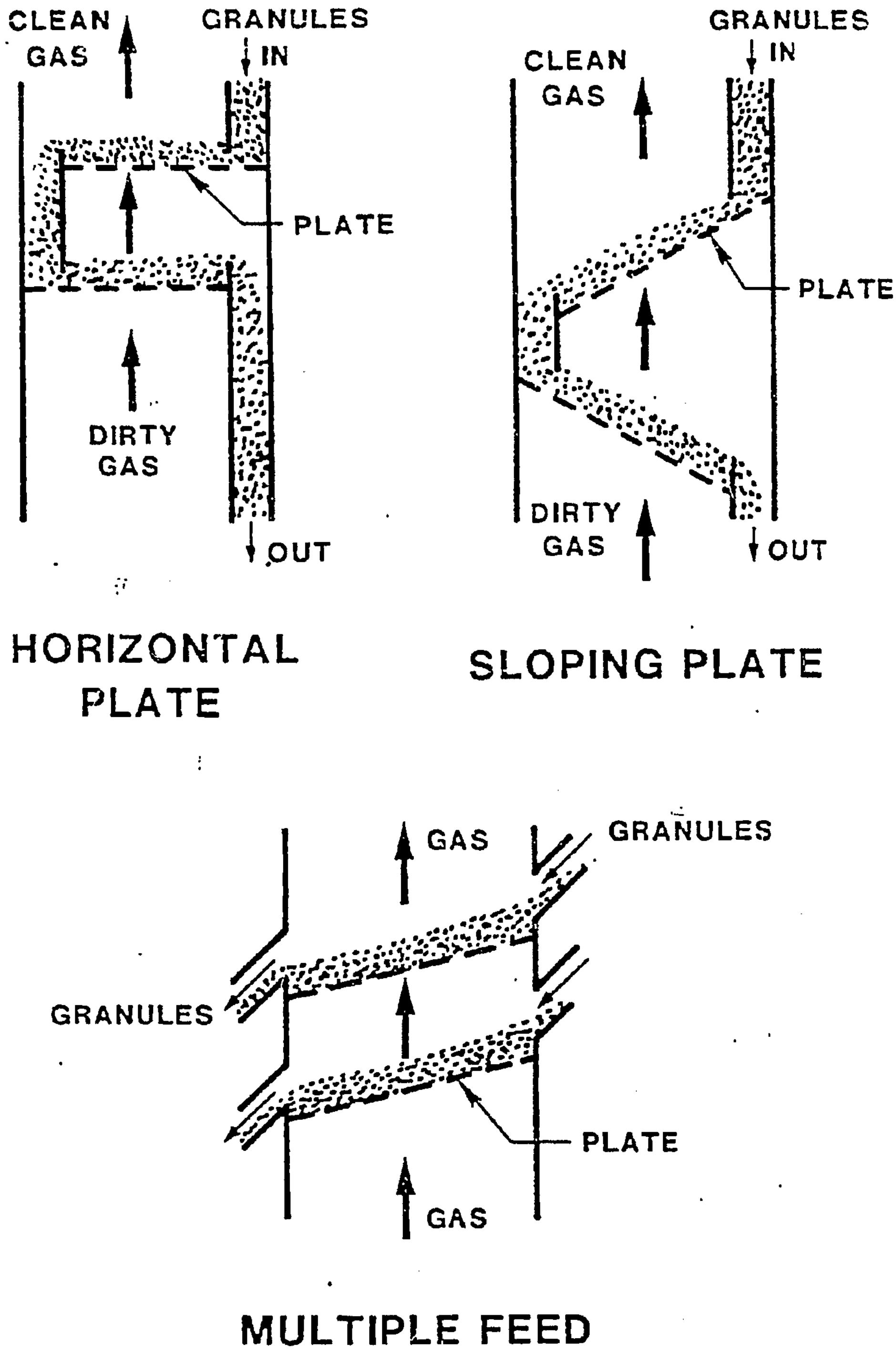
CONCEPTUAL ILLUSTRATION OF A HIGH GRADIENT MAGNETIC COLLECTOR (GOODING AND FELDER, 1981)

FIGURE 11 - GOODING AND FELDER[50]

actual PFBC at temperatures in the range 1500°-1700°F and pressures from 8 to 10 atmospheres. The particulate collection efficiency will be measured as a function of dust loading, filter media residence time, magnetic field strength, gas velocity, and ratio of magnetic to nonmagnetic material. An evaluation of the magnetic material is underway to establish the corrosion and erosion properties in the actual fluidized-bed flue gas environment. Continuous filtration process will be undertaken as also the economic evaluation.

Air Pollution Technology, Inc. (APT), have developed a dry plate scrubber (DPS) concept which they also refer to as particle collection by particles (P x P System) for dusty gas cleanup and which is being extended to the particulate removal from high-temperature and high-pressure gas streams. The early theoretical and experimental work is described by Calvert, Patterson, and Drehmel[52], and Calvert, et al.[53], and more recent results with plans for future work are given in a recent summary paper by Parker, et al.[54] Since the concept and the collection mechanism of the dust particles on the media granules is so similar to that of a moving granular bed filter, it is appropriate to discuss this device in this report on granular bed filters.

The dry plate scrubber uses one or more shallow beds of granular material which, as shown in Figure 12, could be horizontal or sloping and could have either single or multiple feeds. These dense mobile beds are supported over and moved across perforated plates while the dust-laden gas at high velocities emerges in the form of gas jets through these perforations and moves upwards through the solid collectors. The fine solid dust particles collect on the media granules by inertial impaction and direct interception. The dust deposition process can be augmented by the application of an electric field which also enhances the



DRY PLATE SCRUBBER CONCEPT
(AIR POLLUTION TECHNOLOGY, INC.)

FIGURE 12 - PARKER ET AL.[54]

adhesive force between the dust particles and the solid collectors. It is claimed[54] that the multiple stages of a DPS can be designed so as to preferentially collect the large particles on the lower stages and fine particles and vapors on the upper stages. The device is considered by APT to be specially appropriate for cleaning high-temperature (900°C), high-pressure (1000 kPa) effluent from a PFBC system. Single- and multiple-stage DPS units have been operated under controlled conditions to investigate the effect of various process design and operating parameters so as to evolve an appropriate bench-scale design for the evaluation of DPS operation at high temperatures and pressures. Some of these findings are reported in the following.

For preliminary tests and parametric investigations, monodisperse polystyrene latex (PSL) microspheres (0.50, 0.76, 1.1, or 2.0 μm in diameter) or polydisperse fly ash (0.5-10 μm) was used as dust. For room temperature uniform diameter glass beads (0.5 to 1.0 mm), and for high temperature slightly ellipsoidal zirconia beads (5.4 g/cm^3) and alumina spheres (3.6 g/cm^3) were used as bed materials. Glass beads were of diameter (0.48 and 1.00 mm) while the size range for the other two particles ranged between 0.42 to 0.85 mm. Experiments revealed that the deeper beds do not appreciably influence the collection efficiency with and without electrical augmentation, and it is proposed that shallow beds (about 1.5 cm) are preferable in view of the low-pressure drops. Investigations revealed that the collector media particles size sensitively controls the particulate collection efficiency. The smaller size particles (0.48 mm glass beads) were found to be more efficient for dust collection than large particles (1.0 mm). An average diameter of about 0.7 mm is proposed for media particles to obtain stable bed movement and flow from one stage to the other. In all these investigations superficial gas velocities were varied in the range 20-70 cm/s. The jet velocity is much higher in the range 15-40 m/s. Collector particles to gas flow ratio is about 0.1. The jet diameter is 1-2 mm and the percent open area of the perforations on the grid plate is 1.0 to 3.5 percent.

The electrostatic dry plate scrubber (EDPS) is also investigated in all the four possible operational modes viz, uncharged particles and neutral collectors (UP/NC), uncharged particles and polarized collectors (UP/PC), charged particles and neutral collectors (CP/NC), and charged particles and polarized collectors (CP/PC). The dust particles are charged with a corona discharge with an electric field strength of -5.4 kV/cm. The collector particles are exposed to an electric field strength of -4.5 kV/cm by introducing an electrode above the bed and maintaining it at a suitable negative potential with respect to the grounded body of the EDPS. The obvious advantage in EDPS is that only one electrode is in direct contact with the bed; and, therefore, the problem of electrical shortage at high temperatures does not arise. Both dielectric (glass, alumina, zirconia) and conductive (nickel) media collector particles have been used. In the case of conductive particles, the positive potential of the perforated distributor plates charges them positively by pulling away their electrons. While in the case of dielectric particles, these are polarized and local positive and negative charge regions will exist on their surfaces. Such a polarized collector system has an enhanced collection efficiency because of a stronger coulombic attraction between the dust and the media particles.

The single-stage laboratory experiments with 0.5 μm diameter PSL particles and dielectric particles revealed that the best collection efficiency is obtained when the dust particles are charged and the media particles are polarized (CP/PC). On the other hand, the worst results are obtained when the particles are uncharged and the collectors are not polarized (UP/NC). The collection efficiency improves as soon as either the dust particles are charged or the collector particles are polarized though the improvement is more in the former case (CP/NC) than in the latter case (UP/PC). Experiments have also been conducted with conductive nickel (0.38 mm) collectors. In this case also it is found that the electrostatics introduce a definitive improvement so that the collection efficiency for the (CP/PC) case is more than for the (UP/NC) case. The effect of electrostatics has also been studied in a three-stage unit where the alumina collectors were polarized in the third stage only by the application of a high-voltage electric field, the first two stages had no external field but the dust particles were charged. It was noticed that the collection efficiency in the first two stages did increase as a result of charging the particles in comparison to neutral DPS and specially for particles smaller than 2 μm. Further, most of the improvement in collection efficiency came in the third stage where the collectors were polarized. Zirconia beads appear very promising; and, on the basis of the preliminary investigations, these are preferable over alumina beads. Work in progress will provide the essential details for the adequate selection of the proper bed material.

The particulate efficiency of EDPS is found to range from 97.9 to 98.8 percent for particles smaller than 5 μm. The denser zirconia particles are found to stabilize the bed movement and also enable greater throughputs than the beds of alumina particles for the same amount of re-entrainment. The present work has demonstrated that DPS and EDPS are promising filtration techniques at room temperature and pressure. The bench-scale unit for operation at high temperatures and pressures is under construction for experimental work. This knowledge will be employed to design and conduct an economic evaluation of a subpilot-scale DPS unit.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In the above we have briefly reviewed the work performed, in progress, or planned to be undertaken in the near future on granular bed filters with a view to assess their reliability for adoption in PFBC/CC power systems. In the table we have shown the temperature and pressure ranges in which these filters have been operated. It should be noted that the effort of Exxon with Ducon filters and with its modified design comes closest to the test of a granular bed filter in actual operating conditions as will be encountered in an operating pressurized fluidized-bed coal combustor combined-cycle power system. The actual filter temperature was probably not as high as envisioned in combined-cycle systems. More testing and proper upgrading of the filter design as dictated by the operational experience is in order and indeed Westinghouse is currently engaged in such an endeavor. Argonne National Laboratory effort was also not ambitious enough and the test results of Westinghouse and their proper technical and economic assessment will bring to light the real potential of fixed-bed granular filters. Electrostatic augmentation enhances the particulate collection efficiency of granular bed filters and it will be worthwhile to assess this alternative once the Westinghouse investigations are available and found to be technically fusible and economically viable. We particularly emphasize this operational mode for it seriously influences the favorable collection of small particles, 2 μm and small. The work of Exxon with magnetically stabilized filters is very attractive and, if in their planned work at temperatures between 1500°-1700°F and pressures between 8-10 atmospheres as good success as they have obtained at ambient conditions is obtained, the entire art and practice of particulate filtration may have to undergo a revolutionary change.

TEMPERATURE AND PRESSURE RANGES EMPLOYED IN DIFFERENT GRANULAR BED FILTERS

Organization	Filter	Temperature	Pressure	Remarks
Combustion Power Company	"Screened" Moving Granular Bed Filter	1113K	1 atm	Illinois No. 6 Coal and Dolomite in AFBC at 1143K
Combustion Power Company	"Screenless" Moving Granular Bed Filter	Ambient	Ambient	Titanium Dioxide of 2 μm were Injected
Exxon	Ducon Supplied and its Modified Granular Bed Filter	< 1253K (not specified)	1000 kPa	Mini-Plant PFBC at 1253K and 1000 kPa, Filtration Velocities 20-24 m/s
Westinghouse	Ducon-Type Fixed-Bed Filter	1100°F	Ambient	Limestone Dust, 100 Percent < 10μm, Gas Velocity 30 ft/min
Argonne National Laboratory	Fixed-Bed Filter	453K	308 kPa	Combustor at 1123K and 308 kPa
EFB, Inc.	Electrically Augmented Moving Granular Bed Filter	Ambient	Ambient	84-Hour Test Run, 800 cfm Pilot Unit with Burgess No. 10 Dust
MIT	Electropacked and Electrofluidized Beds	< 1400°F	Ambient	--
Exxon	Magnetically Stabilized Bed	Ambient	Ambient	--
Air Pollution Technology	Dry Plate Scrubber and Electrostatic Dry Plate Scrubber	Ambient	Ambient	--

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The moving granular bed filters have been developed over years by Combustion Power Company and EFB, Inc. The "screenless" countercurrent moving bed filter of CPC has been preferred for applications in coal conversion processes. However, its operation in actual PFBC effluent gas environment is to be demonstrated as also of the electrically augmented inside out gas cross-flow moving bed filter of EFB. It is, thus, clear that though many technological problems associated with moving bed filters have been resolved, still the test experience in actual desired environment is missing, and this will have to be available for the proper assessment of this mode of granular bed filters.

Air Pollution Technology have been developing a filter which resembles to a large degree a moving bed filter. They have shown its performance at ambient temperature and pressure conditions and, based on these results, tests have been planned at high temperatures and high pressures. The actual adoption potential of this electrostatic dry plate scrubber will have to await the availability of these planned tests and their assessment.

In conclusion, we note that the art of granular bed filters have come to a stage that a tractable amount of experimental effort will bring out their true technological potential. It is gratifying that most of such work is in progress under PRDA contracts from the Department of Energy. The question of theoretical understanding of filtration mechanism in granular bed filters is an altogether different ball game. Differences of opinion exist even on the state of the filter during the filtration process and contradictory viewpoints are prevalent. In this background the questions of filter design and scale-up are handled rather empirically. Existing semi-empirical correlations have very little basis for any valid extrapolation. A well organized mathematical modeling effort will be in order and particularly directed to that variant of the granular bed filter which may turn out to be the most successful for adoption by the technology on the basis of ongoing experimental research and development programs.

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NOMENCLATURE

A_o	Empirical numerical coefficient
A_1	Empirical numerical coefficient
b	Mobility of the particles
c	A numerical constant
C_s	Cunningham slip correction factor
D	Mass diffusion coefficient
d_p	Dust particle diameter
D_p	Media particle diameter
E	Electrical field
F	Electrical improvement factor
F_{D_C}	Drag force acting on the clean collector particle
g	Acceleration due to gravity
K	Intergranular dust deposit by weight
k_B	Boltzmann constant
l_o	Unfluidized-bed height
L_i	Inlet gas dust concentration
m	Empirical numerical number
$\dot{M}$	Granular media flow rate
N	Number of impaction stages
N_{Gr}	Gravitation number $= U_t/U$
N_{Pe}	Peclet number $= D_pU/D$
N_{St}	Stokes number $= C_s d^2{}_p U \rho_p / 9 D_p \mu$
P	Dust particle penetration by mass

Pt_d	Penetration for particles of size d_p
q_p	Particle charge
R_p	Media particle radius
R_e	Reynolds number
T	Temperature
U	Superficial gas velocity
U_t	Terminal velocity
$\dot{V}_c$	Volume flow rate of granular media particles
$\dot{V}_p$	Volume flow rate of dust particles
Z	Filter bed depth

<u>Greek Letters</u>

γ	Electrical effectiveness
ΔF_{D_i}	Drag force contribution due to the ith deposited particle on the collector which has a total of N deposited particle on its surface
ΔP	Pressure drop across the filter
ΔP_c	Pressure drop across the clean filter
ΔP_d	Pressure drop across the clogged filter
ε	Filter bed voidage
η	Particle collection efficiency of the filter
$\bar{\eta}$	Average collection efficiency
η_{elec}	Collection efficiency due to electrical field
η_{II}	Inertial impaction collection efficiency
η_{mech}	Collection efficiency due to mechanical forces
η_p	Individual bed particle collection efficiency
μ	Gas viscosity
ρ_p	Particle density