Role of Bed Height and Amount of Dust on the Efficiency of Sound-Assisted Fluidized Bed Filter/Afterburner

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DOI 10.1002/aic.11951
Published online July 30, 2009 in Wiley InterScience (www.interscience.wiley.com).

A 40-mm sound-assisted fluidized bed filter/afterburner for hot gas clean-up has been characterized in terms of bed saturation time, total amount of collected particles, fraction of fine particles permanently adhered on the coarse bed particles, and efficiency of using a regeneration strategy based on mechanical (attrition) and/or chemical (combustion) action. Experiments have been carried out at ambient temperature as well as at 850°C, with and without application of sound and varying bed height and amount of dust in the gas flow. The controversial effect of the application of sound: not only enhancement of particles interactions but also increase of fines permanently adhering on bed coarse particles is presented and discussed. A simplified model has been developed to obtain rough predictions of bed height which maximize fine particles capture, bed saturation time, total amount of particles collected in the bed, fraction of fine particles loading present as adhered particles on bed particles.
 AIChE J, 55: 3066–3075, 2009
Keywords: fluidized bed filter, sound-assisted fluidization, dust removal, filtration efficiency

Introduction

Emission of fine particulates from combustion plants, fired both with fossil and waste-derived solid fuels, largely impacts the overall process performance and economics through the influence it exerts on combustion efficiency and environmental issues. Cyclones, fabric filters, electrostatic precipitators, or wet scrubbers are usually employed to control the emission of particulate in hot gas streams.[1–3] Granular bed filtration has also been indicated as a useful technique[4,5] and it has been proposed in four types: fluidized bed, intermittently moving bed, moving bed, and fixed bed.[5,6] In particular, fluidized bed filters are applied in the industry especially when simultaneous removal of pollutants are required,[7–11] e.g., for removal of organic compounds and particulate from flue gas of an incinerator. High temperature gas clean-up features the important property of combining mechanical filtration of fine particles with parallel afterburning of the residual solid carbon presents in the particulates. A possible application is the reduction of unburnt carbon in fine ash, as known, it profoundly affects the disposal and reuse of solid residues.[12,13] Fluidized bed, investigated in the past with reference to hot gas clean-up, has been recently indicated as operating more effectively when assisted by acoustic fields of suitable intensity and frequency.[14] Previous experiments, carried out under a relatively narrow range of

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operative conditions, have highlighted the increased captive properties of the bed and in turn the occurrence of a condition of bed saturation that requires a regeneration strategy of the filter.[14]

In the present study, a sound-assisted fluidized bed filter was completely characterized in terms of mean residence time of fine particles in the bed, bed saturation time, dust particles loading, fraction of fine particles loading permanently adhered on the coarse bed particles, and efficiency in using a regeneration strategy based on both mechanical (attrition) and/or chemical (combustion) action. Experiments have been carried out with a 40-mm ID sound-assisted fluidized bed filter/afterburner. Particle-laden gas streams obtained by dispersing carbonaceous ash, collected at a second-stage cyclone of a fluidized bed gasifier, in an air stream, are continuously fed to the filter/afterburner. Gas stream fine particles concentration in the range 0.015–0.052 g/l has been used. The experimental campaign was carried out at ambient temperature as well as at high temperature (up to 850°C) and with and without application of a 120 Hz and 140 dB acoustic field. One aspect coming out from experimental data is the possibility of a controversial effect of the application of sound. There is a beneficial effect related to the enhancement of fine vs. coarse particles interactions which results in an increase of the amount of fines captured by the bed before its saturation however the contemporary increasing of particle to particle interactions increases the amount of fines permanently adhering on the bed coarse particles. A systematic analysis of this effect is presented in the paper. A simplified descriptive model of a sound assisted fluidized bed filter is proposed. It might be a useful tool to predict the bed height which maximizes fine particles capture. The model, validated on the basis of experimental results, has been used through an inversion of information to estimate the adhesion probability factor, which is a key parameter of the model and whose value from literature is very uncertain.

Theory

The use of a sound-assisted fluidized bed filter to control the emission of particulate in gas streams is based on the concept that the application of sound to a fluidized bed filter can increase the captive properties of the bed.[14–17] The role played by sound application has been interpreted on the basis of a simple model presented elsewhere.[14] In the framework of this work, the model has been used to obtain rough predictions of the required bed height to maximize fine particles capture, bed saturation time, amount of particles collected in the bed. The model accounts for the action of sound to promote interactions between fine particles and the coarse bed particles as results of collisions due to a relative motion between particles of different size and density. A basic description of how the bed has been modeled is following reported.

According to Figure 1, the bed has been considered made up of parallelepiped cells each containing a single coarse particle centered in the cell, surrounded by gas in which several fine particles are uniformly dispersed. Hence the bed is characterized by a regular arrangement of coarse particles of size D which are not each other in contact and

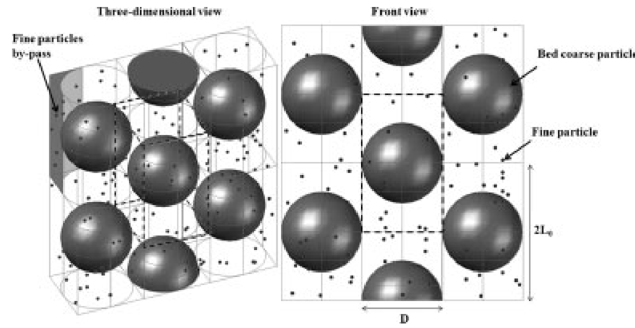

Figure 1. Schematic representation of the bed.

by a bed voidage corresponding to minimum fluidization conditions. Fine particles of size d, whose amount corresponds to dust concentration in gas stream, are homogeneously distributed in the voidage between bed particles. The application of sound results in a plane wave traveling through the bed along the vertical direction whose intensity is attenuated since the bed acts as an attenuator with a sound pressure drop which depends on the bed material and on the experimental conditions used. For the sake of simplicity, the profile of sound pressure along bed height has not been considered however only an average sound pressure level between the one at the top and the one at the bottom of the bed has been used in model calculations. Accordingly, coarse and fine particles, under the effect of sound application, move from their average positions with an oscillatory motion whose amplitude depends both on their size and mass and on the intensity and the frequency of the acoustic field. Considering particles used in the present study, namely 350 μm average size sand particles and 15 μm average size dust particles and the sound frequency of 120 Hz, coarse particles can be considered fixed in the space whereas fine particles oscillate with an amplitude which depends on the intensity of the acoustic field.[15] With reference to the cell in Figure 1, it is possible to calculate the intensity of the acoustic field that might make fine particles, located in the cell at the largest distance from the coarse particle, collide with the coarse particle itself. Those particles, located at the edges of the parallelepiped cell, have to travel a distance equal to L_0. The model assumes that collision between a fine particle and a coarse bed particle results in adhesion through an adhesion probability factor, e, which accounts on the possibility that a single collision act may result in adhesion. Besides, a cumulative probability, $\bar{e}$, related to manifold collision acts associated to different periods of oscillation exhibited by fine particles, is accounted in the model. Considering $\bar{e}$, the cumulative probability of n in series events of probability e, the probability that a fine particle adheres over n periods of oscillation is given by:

$$\bar{e} = 1 - (1 - e)^n \qquad (1)$$

On the basis of literature indications,[18] on the lack of particle adhesion probability induced by this type of collision mechanism, i.e., values of e smaller than 10^{-2} to 10^{-3}, Eq. 1 can be reasonably approximated by the expression:

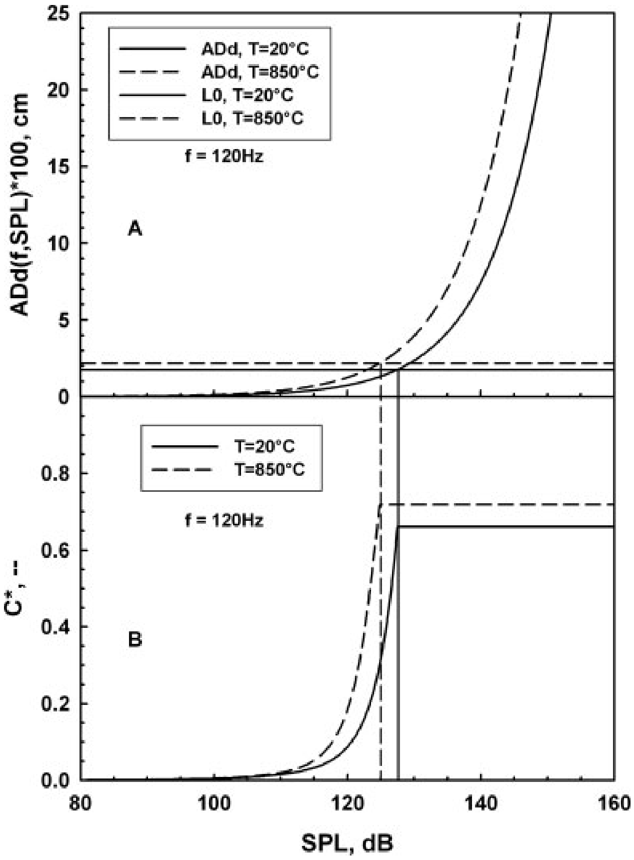

Figure 2. (A) Amplitude of the relative displacement ADd(f,SPL); (B) Maximum fraction of fine particles colliding on the bed coarse particles.

$$\bar{e} = 1 - \exp(-ne) \qquad (2)$$

It is worth to note that Eq. 2 is the equation commonly used to express the total efficiency of filtration of gasses passing through a filter made of n fibers.[19] In that case, the argument of the exponential named "coefficient of absorption through the filter," expresses the transition from the efficiency of the deposition on a fiber in the filter to the whole filter. This coefficient is given by the product of the single fiber collection efficiency, which depends on the properties of the particles and on the gas flow, times the number of fibers forming the filter, which depends on the filter geometry. In the present paper and partially different to a previous analysis,[14] the coefficient of absorption "ne" can be read as the probability that a fine particle will be collected by the coarse particles forming the bed during its residence time in the bed. In other words the fine particles traveling along bed height under the effect of application of an acoustic field will be subjected to different periods of oscillation and consequently they will undergo a number of similar situations occurring during particles cross over the bed.

Coming back to Figure 1 it must be noted that, once the geometry of the elementary cell is fixed, the maximum number of colliding particles may be smaller than the total number of fine particles in the cell due to the fact that some particles, as showed in the highlighted areas of Figure 1, may oscillate without colliding with the bed coarse particles, whatever the sound intensity is, because their distance from the coarse particle is never smaller than $(D + d)/2$. If C* is the ratio between the maximum number of fine particles which can collide with the coarse particle and the number of fine particles contained in the cell, the fraction F of particles which adheres onto the coarse particle surface over a time interval corresponding to n oscillatory cycles is:

$$F = C^*\bar{e} = C^*[1 - \exp(-ne)] \qquad (3)$$

Figure 2 reports the behavior of a sound assisted fluidized bed filter made by a bed of 350 μm in size sand particles, operated to remove a dust made of 15 μm char particles. The frequency of the acoustic field has been fixed at 120 Hz and the effect of the intensity of the acoustic field has been considered.[14]

Parameters used in model calculations are reported in Table 1. The figure gives the amplitude of the relative displacement Ad,D(f,SPL) vs. the intensity of the acoustic field (Figure 2A) and the maximum fraction of fine particles which collides with the coarse particle (Figure 2B). Figure 2A indicates that acoustic fields of intensity larger than 128 dB at room temperature and 125 dB at 850°C, are required to approach the maximum values of C^* that are 0.661 and 0.719 at room temperature and at 850°C, respectively (Figure 2B). The fact that the maximum fraction of colliding particles is smaller than 1, regardless of the intensity of the acoustic field, is a consequence of the existence of free-paths in the cell related to the way individual cells have been arranged into a fluidized bed. As expected the reduction of sound intensity results in a strong decrease of collision phenomena. Only 10% of fine particles collide at about 120 dB and 118 dB in comparison with 50% at about 126 dB and 123 dB at room temperature and at 850°C, respectively.

Figure 3 gives the filtration efficiency, in terms of fraction of fine particles collected by coarse particles as a function of the intensity of the acoustic field for a fixed frequency f = 120 Hz. An adhesion probability factor $e = 10^{-4}$, whatever the sound intensity is, has been considered. Curves are related to different duration of sound application. As expected, for a given SPL, increasing the time of sound application results in an increasing of the adhesion factor F

Table 1. Model Parameters

	Size, μm	Density, kg/m^3
Materials		
Fine particles	15	1300
Bed particles	350	2560
Model Parameters		
Temperature, °C	20	850
f, Hz	120	
SPL(at the top of the bed), dB	140	
Adhesion factor e	10^{-4}	
Distance L_0, μm	176	218
C^*	0.661	0.719
Bed voidage ε_{mf}	0.48	0.58
Air density, kg/m^3	1.2	0.314
Air kinematic viscosity, m^2/s	1.4×10^{-5}	1.57×10^{-4}

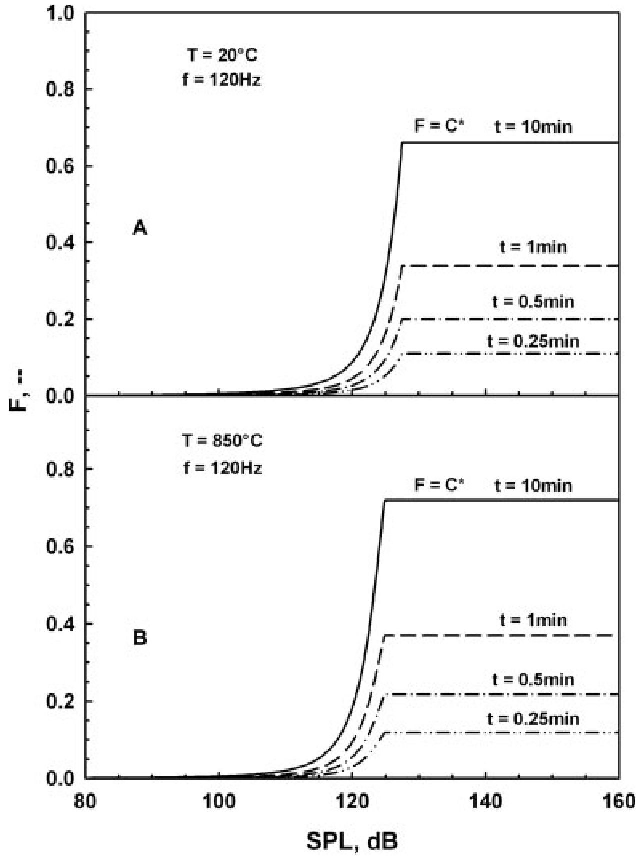

Figure 3. Efficiency of particle collection for f = 120Hz and e = 10−4: (A) T = 20°C, (B) T = 850°C.

up to C^*, which represents the condition that all the possible colliding particles adhere onto the aggregate.

Once fixed the probability factor e, the comparison between curves reported in Figure 3 and the corresponding curve reported in Figure 2B gives the residence time of fine particles in the bed required to maximize the filtration capability of the sound assisted fluidized bed filter.

Materials and Methods

The experimental apparatus used for filtration test at ambient temperature and high temperature consists of a 41-mm ID stainless steel sound-assisted fluidized bed reactor, Figure 4. A wind box (0.4 m height) operates as a gas pre-heater, and the fluidization column (1 m height) ends with a conical shape device followed by a capture device for fine particles escaping the bed consisting in a two-exit head collector. The gas distributor is made up of several stainless steel nets layered one on the other. The acoustic field has been applied to the fluidized column by using a signal generator, an amplifier and a loudspeaker to generate acoustic waves of the selected frequency and intensity. Carbonaceous ashes collected at a second-stage cyclone of a fluidized bed gasifier, whose properties are reported in Table 2, were dispersed in an air stream to simulate a particle-laden gas flow. Filtration tests have been carried out under steady state condition by feeding ash particles into a bed made of 90, 180, 270, and

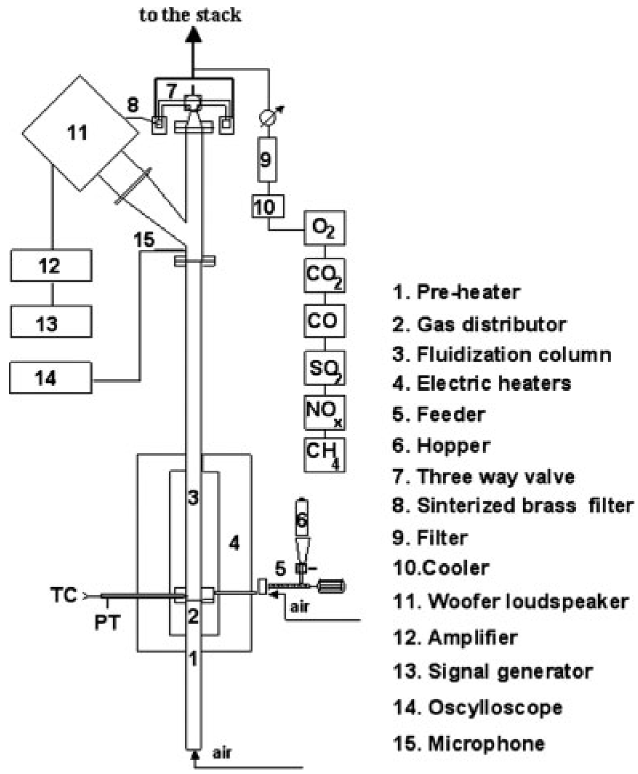

Figure 4. Experimental apparatus.

360 g of 300/400 μm quartzite. Injection of fine particles has been made by means of a mechanical/pneumatic system. Operative conditions are reported in Table 2.

Table 2. Properties of the Material Tested and Operating Conditions

Fuel: Ashes Derived From a Gasification Process			
Proximate Analysis (as received), % w/w		Ultimate Analysis (as fed), % w/w	
Moisture	3.4	Carbon	77.5
Volatile matter	1.8	Hydrogen	0.4
Fixed carbon	77.2	Nitrogen	0.8
Ash	17.6	Sulfur	0.1
		Chlorine	0.0
LHV, kJ/kg	26900	Oxygen	0.3
Density, kg/m^3	1300	Ash	17.6
d(3,2), μm	15	Moisture	3.4
Bed Inert Material: Quartzite			
Bed temperature, °C		20	850
Static bed height, cm		4.9; 9.7; 14.0; 19.4	9.72
Nominal size, μm		300–425	300–425
d(3,2), μm		350	350
Density, kg/m^3		2560	2560
U_{mf} (at bed temperature), m/s		0.11	0.046
Terminal velocity (at bed temperature), m/s		2.6	2.32
Operating Conditions			
U_g (at bed temperature), m/s		0.2	0.4
Fine particles feed rate, g/h		14–50	55

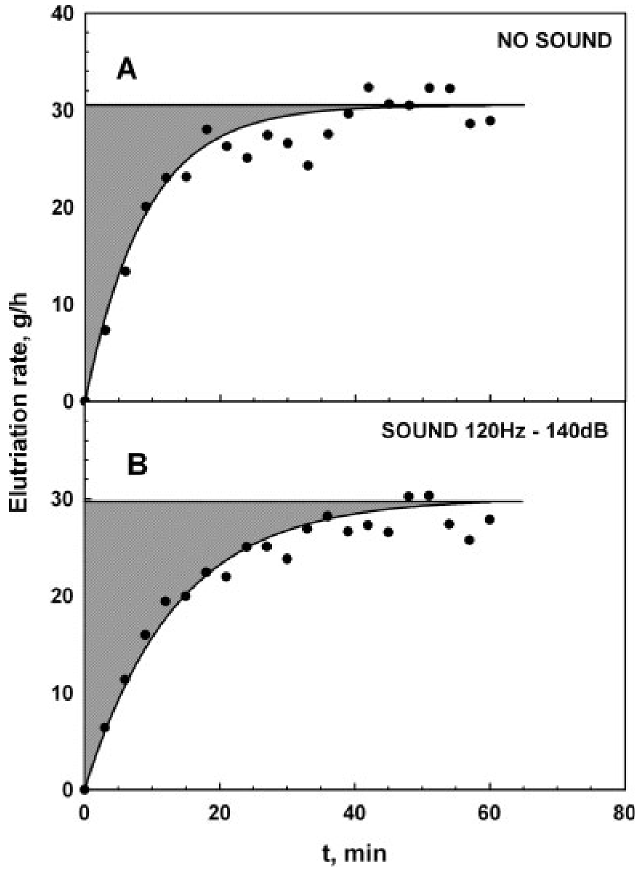

Figure 5. Effect of acoustic field application in filtration test carried out at $T = 20°C$, $C_f = 0.03$ g/l, $h_{mf} = 10.6$ cm, $U = 2U_{mf}$.

Experimental Results

Mechanical filtration

The amount of material escaping the bed as a function of time, obtained in experiments carried out at ambient temperature with a stationary feeding of fine particles, is reported in Figure 5. Curves, which are relative only to mechanical filtration, refer to experiments carried out without and with application of sound of 120 Hz and 140 dB. Analysis of the Figure 5A shows that, as expected, the fluidized bed, even if no acoustic field is applied, can operate as a filter for about 40 min under the operative condition tested. In fact after this time, namely bed saturation time, $t_{99\%}$, the amount of elutriated material becomes equal to the rate of fine particles feeding. The area between the horizontal line, relative to the rate of fine particles continuously fed to the reactor, and the E vs. t curve, is the amount of fine captured by the bed. Analysis of the Figure 5B shows that, the application of sound increases filtration performances in terms of increasing bed fine particles loading and the saturation time. An increase factor of about 1.4 for the bed fine particles loading and a bed saturation time increase from ~40 to ~60 min have been obtained.

Figures 6 and 7 report the saturation times, $t_{99\%}$, and the times required to collect the 50% of the total amount of fine particles, $t_{50\%}$, during mechanical filtration experiments carried out with beds of different heights, without and with application of an acoustic field of 140 dB and 120 Hz. A superficial gas velocity of $U_g = 0.2$ m/s, and fine particle feeding rate ranging from 14 to 50 g/h have been used. Analysis of the figures shows that, whatever the sound is or is not applied to the bed, both $t_{50\%}$ and $t_{99\%}$ decrease increasing the rate of ash feeding. This is due to the fact that once the bed height has been fixed, the increase of ash feeding rate saturates the bed quickly. On the other side, fixing the ash feeding rate, saturation times increase increasing bed height. The application of sound generally increases bed filtration performances but with a magnitude that depends on bed height. Sound attenuation in the bed is responsible of the relatively high attenuation of the beneficial effect of the acoustic field found with relatively deep beds. In fact, data obtained with bed height of 21 cm with and without application of sound are practically the same.

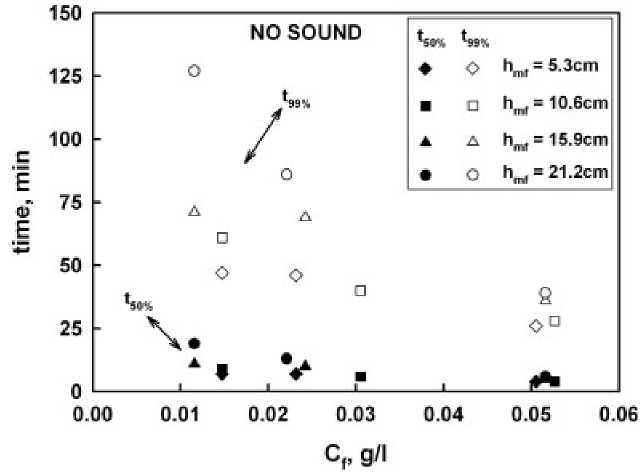

Figure 6. Behavior of saturation times of a fluidized bed filter parametric in a bed height without application of the acoustic field.

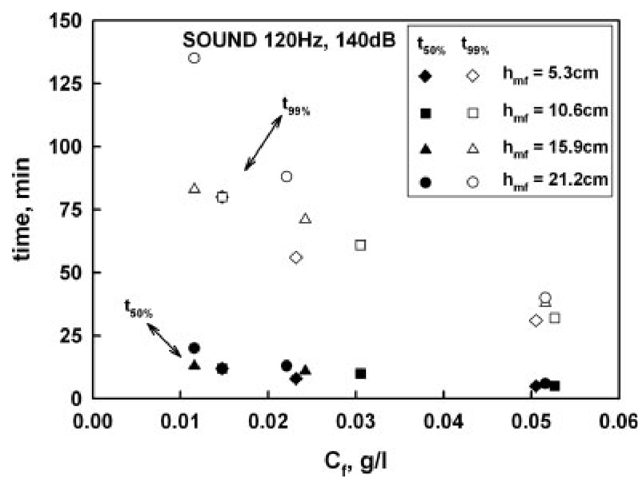

Figure 7. Behavior of saturation times of a fluidized bed filter parametric in a bed height with application of the acoustic field.

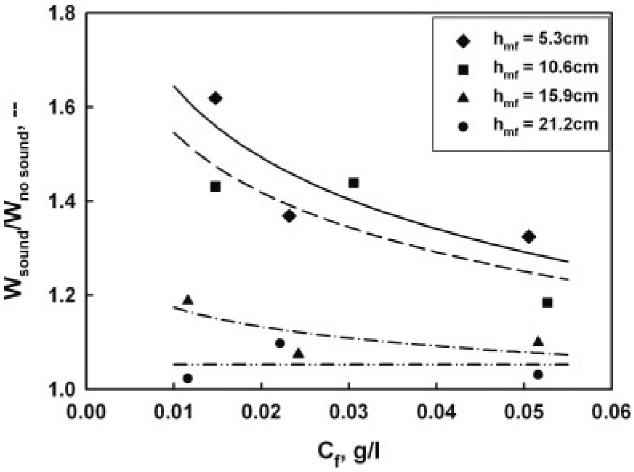

Figure 8. Ratio between the fine particles loadings into the bed at the saturation time obtained in mechanical filtration experiments with and without application of the acoustic field.

Figure 8 reports the ratio $W_{sound}/W_{no\ sound}$ between the fine particles loading into the bed at the saturation time during mechanical filtration experiments carried out with beds of different heights, obtained with and without application of an acoustic field of 140 dB and 120 Hz and with the same superficial gas velocity and fine particle feeding rate of data reported in Figures 6 and 7. W_{sound} and $W_{no\ sound}$ have been calculated by working out E vs. t curves. In experiments carried out without application of sound, the concentration of fine particles in the bed ranged between 2 and 3%. Data reported in Figure 8 show that the application of sound generally increases bed fine particles loading by a factor which depends on bed height. Again, as already considered when Figures 6 and 7 data have been discussed, the efficiency of fine particles capture operated by the bed as a result of sound application is strongly reduced by sound attenuation in the bed. In fact, $W_{sound}/W_{no\ sound} = 1.05$, obtained with bed height of 21 cm, indicates that the increase of captive properties of the bed is active only in a relatively small region near the top of the bed. As regards the generally decrease of the ratio $W_{sound}/W_{no\ sound}$ with C_f, it must be noted that even if there are uncertainties on the explanation of this dependence, this may be due to the effects related to the way adopted to disperse dust particles in gas flow. On this point, even if W_{sound} and $W_{no\ sound}$ increase separately with C_f, their ratio decreases.

Mechanical regeneration of fluidized bed filter

A regeneration strategy based on mechanical attrition of bed particles has been applied to remove fine particles present in the bed when the condition of bed saturation has been reached. The procedure used once approached the saturation time was: (i) to switch off the feed rate of fine particles, (ii) to increase the superficial gas velocity up to 0.4 m/s, which is two times larger than the one used during filtration tests, and (iii) to end the regeneration stage when the amount of fine particles escaping the bed becomes negligible.

Figure 9 reports the ratio W_p/W_{tot} between the amount of bed fine particles loading which remains permanently adhered on bed particles, W_p, after the regeneration stage and the bed fine particles loading at the saturation time, W_{tot}. Experiments of mechanical filtration have been carried out with beds of different heights, without (open symbols) and with (closed symbols) application of an acoustic field of 140 dB and 120 Hz and with the same superficial gas velocity and fine particle feeding rate of data reported in Figures 6 and 7. In particular W_p has been calculated as the difference between the fine particles loading into the bed at the saturation time and the one elutriated from the bed after the feed rate of fine particles has been switched off. Data relative to filtration experiments carried out without application of an acoustic field have been obtained with different bed heights but plotted with the same symbol because a negligible effect of this variable has been found. Analysis of data reported in Figure 9 shows that whatever the application of sound is there is a 40% of bed fine particles loading which remains on bed particles and prevents a full regeneration of the filter. Sound assisted filtration increases this fraction with a magnitude which depends on bed height up to 60% obtained operating the filter with the smaller bed height of 5.3 cm.

Data of W_{sound}, $W_{no\ sound}$, $W_{p\ sound}$, and $W_{p\ no\ sound}$ have been worked out to obtain a rough estimation of fraction of the external surface of bed particles, β, which is covered by fine particles after the approaching of the bed saturation time and after the regenerating action of the filter. For the sake of simplicity this fraction has been calculated assuming that all the fine particles present in the bed at the bed saturation time and after filter regeneration are adhered on bed particles and in addition a single monolayer of fine particles has been assumed. According to the definition:

$$\beta_{\text{tot, no sound}} = \frac{W_{\text{no sound}}}{W_{\text{bed}}} \cdot \frac{\rho_b}{\rho_f} \cdot \frac{D}{d} \quad \beta_{\text{tot, sound}} = \frac{W_{\text{sound}}}{W_{\text{bed}}} \cdot \frac{\rho_b}{\rho_f} \cdot \frac{D}{d} \tag{4}$$

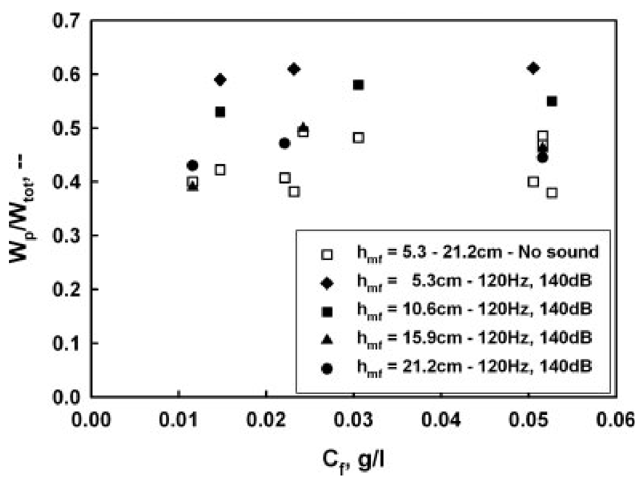

Figure 9. Fraction of fine particles loading which remain permanently adhered on bed particles with and without application of the acoustic field.

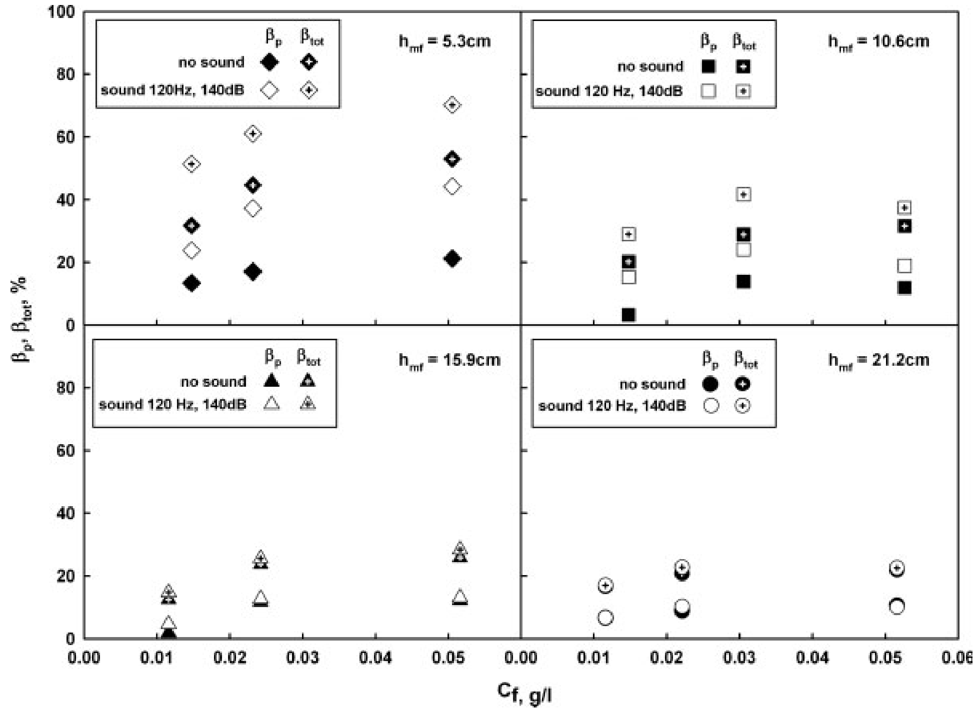

Figure 10. Fraction of the external surface of bed particles covered by fine particles when the bed saturation time is approached, β_{tot}, and after filter regeneration action, β_p.

$$\beta_{\text{p, no sound}} = \frac{W_{\text{p, no sound}}}{W_{\text{bed}}} \cdot \frac{\rho_b}{\rho_f} \cdot \frac{D}{d} \quad \beta_{\text{p, sound}} = \frac{W_{\text{p, sound}}}{W_{\text{bed}}} \cdot \frac{\rho_b}{\rho_f} \cdot \frac{D}{d} \tag{5}$$

Figure 10 reports $\beta_{\text{tot, no sound}}$, $\beta_{\text{tot, sound}}$, $\beta_{\text{p, no sound}}$, and $\beta_{\text{p, sound}}$ obtained in mechanical filtration experiments. Analysis of the data reported in Figure 10 shows that the percentage of bed particles covering at the saturation time obtained under fluidized conditions ranged between 20 and 50% and increased up to 70% under condition of sound assisted filtration. The higher value of bed particles covering has been obtained operating the filter with a bed 5.3 cm height, with the maximum concentration of fine particles in the gas flow and under sound assisted conditions. As expected, the increase of fine particles concentration in the gas flow increases the total amount of bed particles covering. Nevertheless, experiments carried out with different bed height have indicated that the enhancement of bed covering due to sound application decreases with increasing bed height and again this can be due to sound attenuation in beds of different heights.

The elutriation constant approach

The flux rate of fine particles from a bed of coarse particles is proved to be proportional to its weight fraction in the bed, all other factors remaining constant[20,21]:

$$-\frac{1}{A_t}\frac{dW_f}{dt} = k_f^* \cdot x_f = k_f^* \left(\frac{W_f}{W_{tot}}\right) \tag{6}$$

where k_f^* [kg/m^2/s] is called the elutriation rate constant. Another elutriation constant can be also defined as:

$$-\frac{dW_f}{dt} = k_{el} W_f \tag{7}$$

where k_{el} [1/s] is again called ''elutriation rate constant'' and has the meaning of the inverse of an average residence time of fines in the bed before their elutriation.

Comparing definitions we see that:

$$k_f^* = k_{el}\left(\frac{W_{tot}}{A_t}\right) = k_{el}\rho_b(1-\varepsilon_{mf})h_{mf} \tag{8}$$

According to the definition, k_f^* is the true elutriation rate constant accounting for the saturation carrying capacity of gas for a particular class of fine particles, while k_{el} varies according to bed properties and in particular is inversely with bed height.

The Figure 11 reports $1/k_{el}$ vs. h_{mf} obtained in experiments of mechanical filtration of gas carried out without sound application. For each bed height, an average value of k_{el} obtained in experiments with different fine particles concentrations feeding has been calculated. Analysis of the data reported in Figure 11 shows that as expected the residence time of fines in the bed varies linearly with bed height and under the experimental conditions tested it varies between 8 and 25 min. Data reported in Figure 11 have been worked out to calculate $k_f^* = 0.173$ kg/m^2/s.

The application of an acoustic field to a fluidized bed which has been indicated responsible of an increase of the

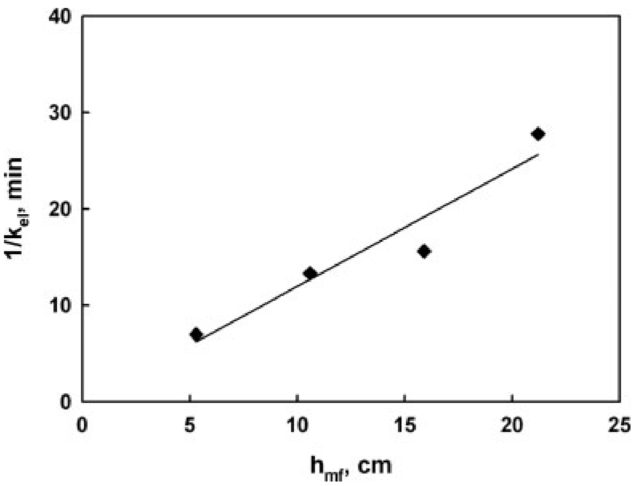

Figure 11. Residence time of fines in the bed.

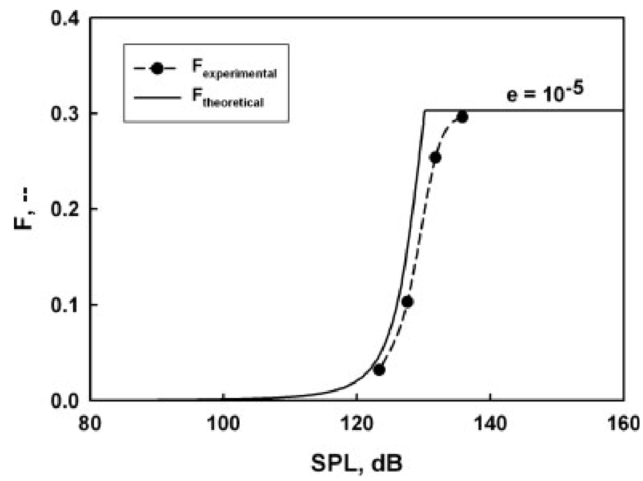

Figure 12. Experimental values of *F* obtained with beds of different heights (points) and theoretical value of *F* with an adhesion probability factor of 10^{-5} (line).

captive properties of the bed,[14] can be interpreted as a reduction of k_{el}, but not of k_f^* that represents the saturation carrying capacity of gas. In this framework, the role of sound can be accounted for in Eq. 8 adding a factor $(1 - F)$ with F, a number ranging from 0 to 1 that has the effect of reducing the elutriation rate constant k_{el} obtained without sound application, depending on the effective relevance of application of sound vibrations.

$$k_f^* = k'_{el}\rho_b(1-\varepsilon_{mf})h_{mf} = \frac{k_{el}\rho_b(1-\varepsilon_{mf})h_{mf}}{(1-F)} \quad (9)$$

Data obtained in sound assisted filtration experiments have been worked out to estimate $(1 - F)$. Tests were carried out by a continuous feeding, F_{fines}, of ash particles into a bed and collecting elutriated material until the bed saturation time when a steady state condition is approached. A material balance under unsteady conditions is:

$$\frac{dW_f(t)}{dt} = F_{fines} - E(t) = F_{fines} - k_{el}\cdot W_f(t) = F_{fines} - \frac{k_f^*\cdot(1-F)}{\rho_b(1-\varepsilon_{mf})h_{mf}}\cdot W_f(t) \quad (10)$$

At saturation time Eq. 10 becomes:

$$F_{fines} = \frac{k_f^*\cdot(1-F)}{\rho_b(1-\varepsilon_{mf})h_{mf}}\cdot W_f(t=t_{99\%}) \quad (11)$$

Figure 12 reports values of F obtained with beds of different heights which correspond to different average sound pressure level due to sound attenuation. The average sound pressure level of the different beds has been calculated as average value of those at the top of the bed, 140 dB fixed whatever the bed height is and those intensities calculated at the bottom of the bed, assuming a sound attenuation factor of 1 dB/cm (measured for similar bed material in a previous campaign of investigation[15]) and the actual bed height.

Experimental trend of F (dotted line) is similar to the curves of the filtration efficiency calculated by the model of fine particles oscillating under the effect of an acoustic field, as those reported in Figure 3. However, it is possible to note that experimental filtration efficiencies are relatively smaller than the maximum filtration efficiency calculated by the model assuming an adhesion probability factor $e = 10^{-4}$ and a sound application time $t = 10$ min. This time is enough to make possible that all colliding particles can adhere on coarse bed particles and as a consequence the maximum adhesion factor C^* is achieved. Considering that, according to Figure 11, the residence time of fine particles in the bed are generally larger than 10 min, the model has been used to estimate the value of the adhesion probability factor which better fits experimental data. In the Figure 12, this best fitting curve obtained with a probability factor of $e = 10^{-5}$ is represented by solid curve.

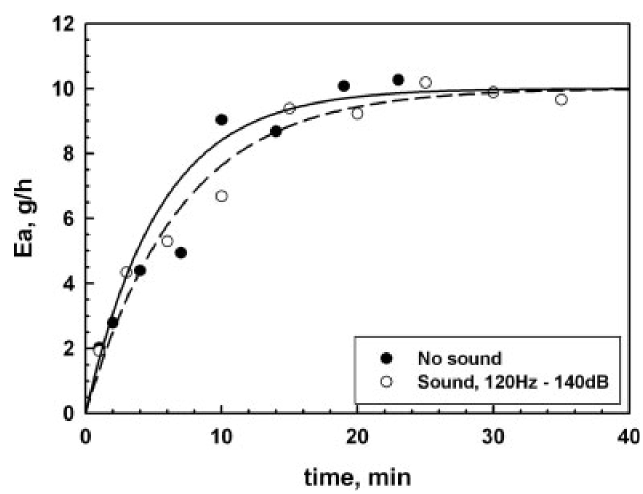

Figure 13. Effect of acoustic field application on the inorganic fraction in filtration test carried out at $T = 850°C$.

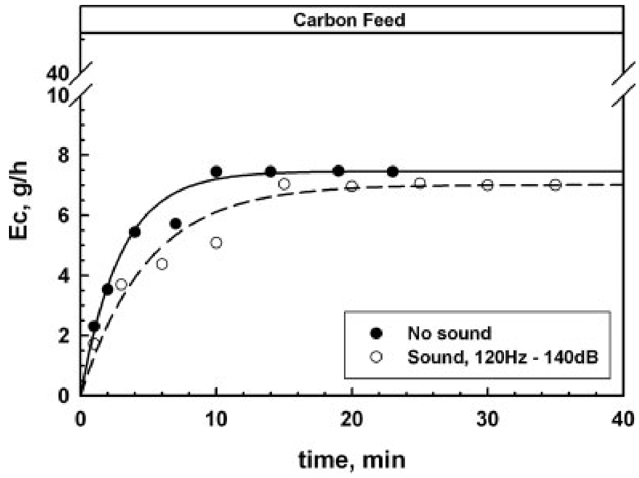

Figure 14. Effect of acoustic field application on the carbon fraction in filtration test carried out at T = 850°C.

Combustion-assisted filtration of carbonaceous fine particles

A limited number of filtration tests have been carried out at high temperature and under oxidizing condition. Figures 13 and 14 report the filtration behavior obtained with reference to the inorganic and carbon fractions respectively in experiments carried out at $T = 850°C$ without and with application of an acoustic field of 140 dB and 120 Hz with the bed operated at gas velocities of $U_g = 0.4$ m/s and with a fine particle feeding rates of ~55 g/h. The E_a vs. t curves are similar to the one reported in Figure 5, where only mechanical filtration was active. The application of sound increases filtration performances in terms of increasing both bed fines loading and the time required to reach a stationary condition, $E_a = 9.5$ g/h. Under the experimental conditions tested, an increase factor of about 1.3 has been obtained for both the bed ash loading and the ash residence time. The ash saturation time in the bed increases from ~23 to ~35 min.

Also, curves of carbon elutriation rate E_c vs. t reach a stationary condition which depends on sound application. However, in both the cases the stationary values of E_c are lower than 40 g/h, the carbon feeding rate used, owing to carbon reduction by combustion.

Conclusion

A study on the application of sound-assisted fluidization for gas clean-up has been carried out with a focus on bed saturation time, total amount of particles collected in the filter, fraction of fine particles permanently adhered on the coarse bed particles, and the efficiency of using a filter regeneration strategy. The application of an acoustic field of 140 dB of intensity and 120 Hz of frequency may result in an increase of the time of saturation of the filter, of the amount of particulate captured by the bed, of longer residence times of fines in the bed, under which condition of combustion-assisted filtration can increase carbon conversion. The beneficial feature of sound application is the enhancement of fine adhesion onto the coarse particle surface associated with the oscillatory motion of particles promoted by application of an opportune acoustic field. However, the enhancement of fine vs. coarse particles interactions results into an increase of the amount of fines captured by the bed before its saturation but at the same time the increased particle to particle interactions increases the amount of fines permanently adhering on the coarse particles of the bed and this has negative effect on the filtration regeneration strategy.

A 40-mm ID sound-assisted fluidized bed filter/afterburner has been developed and characterized in experiments carried out at ambient temperature and at 850°C. The experimental campaign has been carried out by varying the bed height in the range of 5–20cm and the amount of gas dust particles in the range of 14–55 g/h. Bed height has been varied accordingly to constrains detected by sound attenuation in deep beds whereas concentrations of dust are considered of practical interest.

The application of sound generally increases bed filtration performances but with a magnitude that depends on bed height. Sound attenuation in the bed is responsible of the relatively high attenuation of the beneficial effect of sound found with relatively deep beds. In fact, data obtained with bed height of 21 cm with and without application of sound are practically the same.

At ambient temperature, whatever the application of sound is, there is a 40% of bed fine particles loading which remains on bed particles and prevents a full regeneration of the filter. Sound-assisted filtration increases this fraction with a magnitude which depends on bed height up to 60% obtained operating the filter with the smaller bed height of 5.3 cm. Consequently, the percentage of bed particles covering at the saturation time obtained under fluidized conditions ranged between 20 and 50% and increased up to 70% under condition of sound assisted filtration.

Combustion-assisted filtration carried out at 850°C shows that a significant reduction of carbon can be achieved and application of sound vibration may further increase filtration capability of the bed with reference to both inorganic and carbon fractions.

A model of sound assisted fluidized bed filter previously proposed by the authors, which assumes that the efficiency of dust filtration through the bed is the product of a single dust collection efficiency of a single cell times the total number of cell forming the bed has been used to estimate the adhesion probability factor, e. This has been made through an inversion of information to estimate this parameter on the basis of experimental data, owing to the relatively high lack of literature information.

Acknowledgments

The authors are grateful to Dr. M. De Lorenzo for her support during the experimental campaign.

Notation

$A_{d,D}$ = maximum value of the relative displacement between the aggregate and the fine particle, cm
A_g = amplitude of the gas oscillation, cm

A_t = cross section of the bed, cm
C^* = fraction of colliding fine particles
C_f = fine particles concentration, g/l
D = fluidized bed coarse particles size, μm
d = fine particle size, μm
e = adhesion probability factor
$\overline{e}$ = cumulative adhesion probability
E = elutriation rate, g/h
E_a = ash elutriation rate, g/h
E_c = carbon elutriation rate, g/h
f = frequency of the acoustic wave Hz
F = fraction of fine particles adhering over a time interval corresponding to n oscillatory cycles
F_{fines} = fine particles feeding rate, g/h
h_b = bed height, cm
h_{mf} = bed height at the minimum fluidization velocity, cm
k_f^* = true elutriation rate constant accounting for the saturation carrying capacity of gas, kg/m^2/s
k_{el} = elutriation rate constant, 1/s
L_0 = distance between the center of a bed coarse particle and the edge of the parallelepiped cell, cm
n = number of cycles occurring in a fixed time interval
SPL = sound pressure level, dB
t = time, min
$t_{50\%}$ = Time required to collect the 50% of the total amount of fine particles collected, min
$t_{99\%}$ = saturation time, min
U_g = superficial gas velocity, m/s
U_{mf} = minimum fluidization velocity, m/s
W_f = weight of fine particles into the bed, g
W_{bed} = weight of the bed, g
$W_{no\ sound}$ = weight of fine particles into the bed at the saturation time without sound application, g
W_p = amount of bed fine particles loading which remain permanently adhered on bed particles, g
W_{sound} = weight of fine particles into the bed at the saturation time with sound application, g
W_{tot} = amount of bed fine particles loading at the saturation time, g
x_f = weight fraction of the fine particles into the bed

Greek letters

β = fraction of the external surface of bed particles covered by fine particles
$\beta_{tot,\ no\ sound}$ = fraction of the external surface of bed particles covered by fine particles when the bed saturation time is approached without sound application
$\beta_{tot,\ sound}$ = fraction of the external surface of bed particles covered by fine particles when the bed saturation time is approached with sound application
$\beta_{p,\ no\ sound}$ = fraction of the external surface of bed particles covered by fine particles after filter regeneration action without sound application
$\beta_{p,\ sound}$ = fraction of the external surface of bed particles covered by fine particles after filter regeneration action with sound application
ε_{mf} = bed voidage at the minimum fluidization velocity
ρ_b = bed particle density, g/cm^3
ρ_f = fine particle density, g/cm^3

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Manuscript received Jun. 12, 2008, and revision received Mar. 5, 2009.