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Patterns of Solids Withdraw in the Discharge of an Aerated Hopper: Comparison with the Particle Velocity Field

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In this work the possibility to obtain uniform properties in stream of solids withdrawn from an hopper loaded with initially segregated particles by using aeration was verified. Experiments were carried out on a laboratory scale two-dimensional apparatus loaded with binary mixtures of solids of equal size perfectly segregated. The effect of the airflow rate was tested. The compositions of the solids stream exiting from the hopper and the modification of the solids segregation pattern during the discharge were measured. Results are discussed in the light of the solids velocity field.

1. Introduction

Significant size segregation phenomena can occur during operation of silo filling (see for example Enstad and Mosby, 1988). Loading of silos from the top, in fact, produces the formation of a conical heap. When the solids are loaded vertically from an axial position, a heap forms on the filling surface. In this case coarse solids tend to travel longer distances than fine particles and the result is a higher concentration of fines along the silo axis (i.e. Salter *et al.*, 2000). Completely different is the case of silo filling by using very high solids rates, particularly when these are pneumatically conveyed. In this case the presence of entrained air can produce circulating patterns in the empty portion of the silo, which determine a preferential deposition of fines in periphery (i.e. Arnold, 1991). Asymmetrical segregation patterns may take place when, during the silo filling, the velocity of the entering solids has a horizontal component (Williams, 1990a).

The effect of the segregation on the size distribution of the discharged solids depends on the solids flow regime during the hopper discharge. If the flow is of the funnel type, the motion occurs preferentially in the axial region of the hopper and the solids in this region are the first to leave the hopper. In this case any horizontal size segregation determines a variation of the size distribution over the time and the consequent indeterminacy of size distribution may determine a product loss of value. On the other hand, in mass flow hoppers, in any hopper section solids move almost uniformly towards the orifice and this determines a significant reduction in time variation of the size distribution of the discharged solids (Williams, 1990b). However, it must be noted that, although a partial solids re-mixing takes place, the radial segregation persists in the stream of solids leaving the hopper and may cause significant effects when a single hopper feeds more lines of solids withdrawal at different distances from the hopper axis.

Air injection (i.e. Ferrari and Bell 1998) is among the techniques used to promote the solids flow. It was verified that the hopper aeration could change the solids discharge regime and promote mass flow (i.e. Barletta *et al.* 2002), also at aeration rates much smaller than that for which fluidization of the discharging solids occurs and for which the maximum solids discharge rates are attained. Therefore, this technology might be used to reduce the effects of segregation in hopper discharge. The work presented in this paper is the first step in a larger project, which has the objective of verifying the possibility of using aeration to obtain a uniform withdrawal of segregated solids during the hopper discharge.

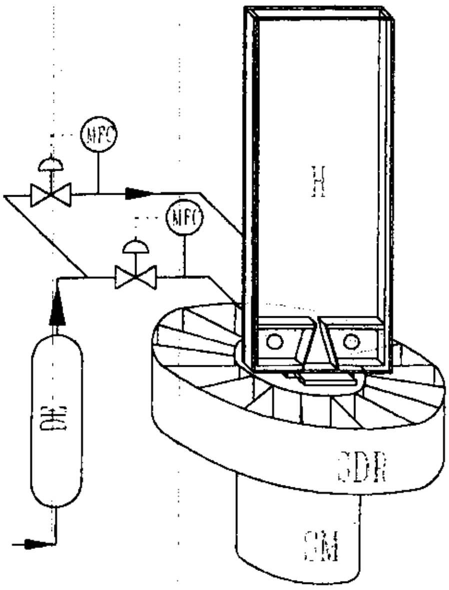


Figure 1. Experimental apparatus.

2. Experimental

2.1 Apparatus

A schematic view of the experimental set-up is shown in Figure 1. It mainly consists of a two-dimensional flat-bottomed hopper, H, in which air can be fed to two wind boxes at either side of the central outlet slot and through two porous polymer distributing plates. In order to have a symmetrical gas distribution, two electronic mass-flow controllers, MFC, independently control the airflow through the two distributing plates. The compressed air fed to the MFC's is desiccated in a refrigerated unit. The central outlet of the hopper can be closed by means of a sliding plate. The slot width is about 12 mm at the distributor level. It increases downwards to allow atmospheric pressure in the falling solids. The inside hopper dimensions are 180 mm for the width and 10 mm for the depth. The rear wall and side spacers are made of Perspex, whereas the front wall is made of tempered glass for improved visibility of the inventory. A load cell (not indicated in Figure 1) supporting a bin collecting the discharging powder is used to measure the solids discharge rate. Alternatively, a rotating drum, SDR, with 16 sector compartments moved by a stepper motor, SM, is used to separate the collected powder at fixed time intervals.

2.2 Materials

The solids used were fresh Fluid Cracking Catalyst (FCC) particles whose properties are reported in Table 1. Some of this material was dyed. Separate experiments were conducted to measure the solids discharge rate and the solids velocity

Table 1. Material properties

Material	d_p μm	80% range μm	ρ_p kg m^{-3}	U_{mf} m s^{-1}	ε_{mf} -	Geldart group
FCC	62	40-112	1960	0.0024	0.59	A

field. The measurement of the solids was carried out by evaluating the slope of the curve of the discharged mass of solids plotted as a function of time. Figure 2 shows the solids discharge rates as a function of the nominal aeration velocity $U_{fo}=Q_f/\Sigma_c$, with Σ_c the silo cross section. The effect of aeration on the solids discharge rate is similar to what found in the past and shows a region at the lower aeration rates in which aeration produces an increase of the solids discharge rate. A plateau value is reached at the aeration velocity of about 5.0 mm s^{-1} which correspond to the fluidization of the solids inventory (Donsì *et al.*, 1998) that, in the following we will call U_{mfo}. This rate corresponds to a nominal superficial velocity that is higher than the minimum for fluidization that is reported in Table 1. This, in fact, is obtained with an experiment in a traditional column or in a flat-bottomed hopper with a closed outlet and is not affected by the consistent deviation of the injected air towards the hopper outlet which characterizes the aerated discharge.

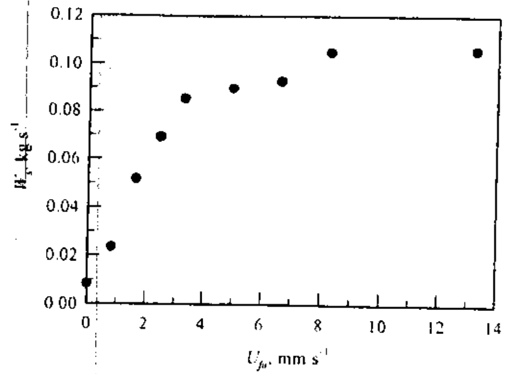


Figure 2. Solids discharge rates vs aeration velocity.

2.2 Methods

To measure the ability of aeration to produce a uniform withdrawal of segregated solids, the hopper was filled as in Figure 3 with the same amount of colored and uncolored powder in order to have two vertical bands of equal width of the darker powder at the hopper sides. This pattern reproduces an ideal segregation in the horizontal direction. The whole mass of FCC used is 600 g that is sufficient to obtain a static bed about 0.4 m high. The discharging powder is collected in the sector compartments of the rotating drum. Varying the aeration rate, the time interval between subsequent advancements of the rotating drum is regulated on the basis of the discharge times obtained with the solids discharge rate experiments in order the have the revolution period for the rotating drum as much similar to the solids discharge period. In any case the stepper motor was programmed to stop when the 16th compartment had reached the filling position. At the end of the discharge, the solids collected in each compartment is mixed and the fraction of colored solids is evaluated by means of a

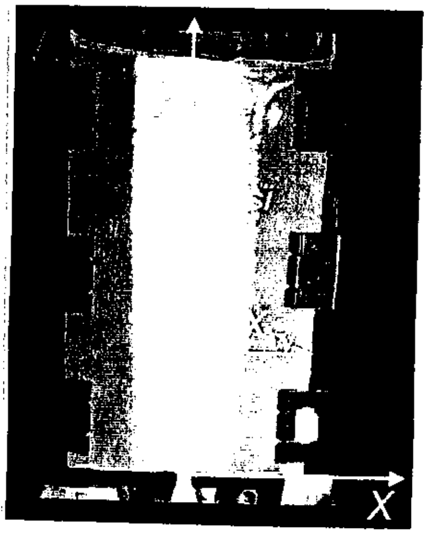
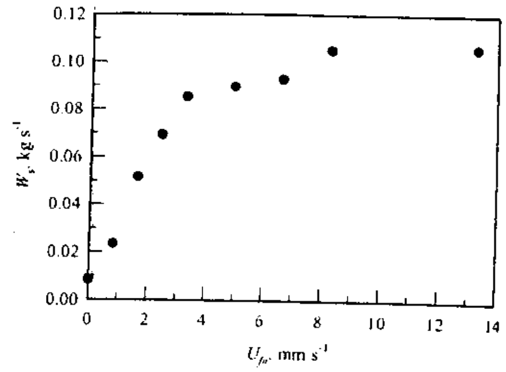


Figure 3. Picture of a hopper loaded with perfectly horizontally segregated black and white particles



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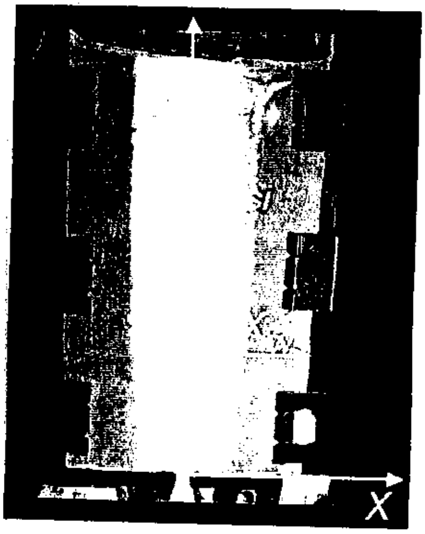

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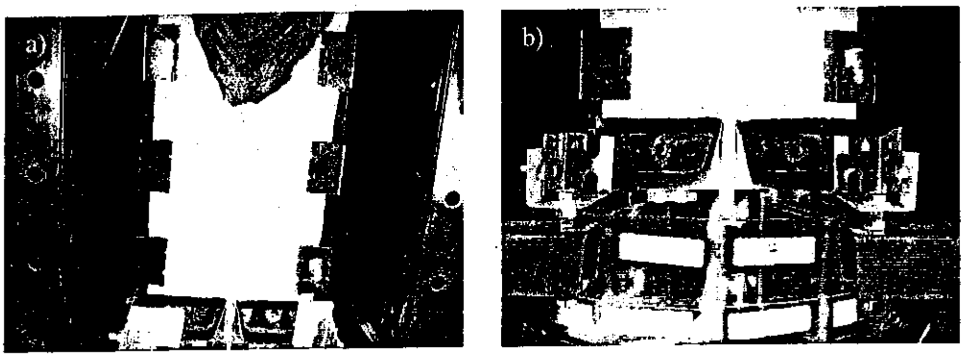

Figure 4. Discharge pattern a) without aeration, b) aerated at U_{fn}=6.62 mm s^{-1}.

photographic comparison with the samples of the initial uncolored and colored component, which had been previously calibrated. This procedure allowed obtaining 16 point time series. The measurements of the colored fraction found in each compartment w_i is validated with the help of the collected masses in each compartment, m_i, by comparing the overall mass of the same component, evaluated as $\Sigma w_i m_i$, with the loaded mass of the colored component. In all the experiments reported in the following, these two values do not differ of more that few points percent.

3. Results and discussion

Discharge experiments were carried out at different nominal aeration velocities U_{fn}, namely 0, 3.31, 4.97, 6.62 and 13.2 mm s^{-1}. An equal fraction of colored and uncolored particles was used. Figure 4 shows the discharge pattern observed at aeration rates of 0 and 6.62 mm s^{-1}. In this figure, the differences between the discharge pattern deriving from the funnel flow regime proper of the solids discharge without aeration and that deriving from the mass flow at high aeration rate appear clearly. Figure 5 shows the time series of the mass fraction of the dyed solids found in the drum compartments plotted as a function of the mean time of the period. In all time series it is possible to distinguish between three different regions. The first few points refer to the initial transient due to flow initiation. Then we find a more or less large set of data at a constant color fraction. Eventually, a final

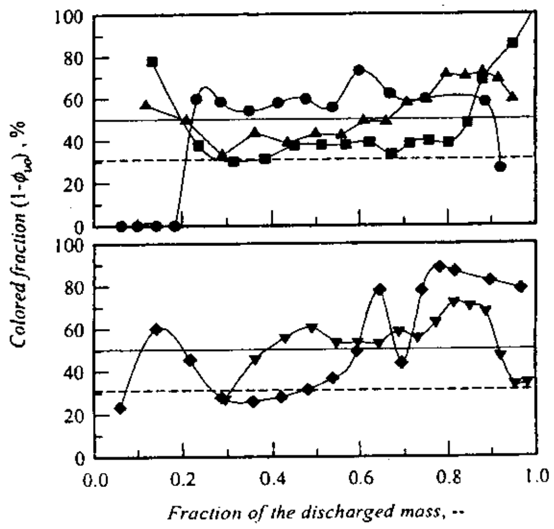

Figure 5. Fraction of colored solids discharged as a function of the discharged mass at different aeration rates: ●, U_{fn} = 0; ■, U_{fn} =3.31 mm s^{-1}; ▲, U_{fn} =4.97 mm s^{-1}; ▼, U_{fn} = 6.62 mm s^{-1}; ◆, U_{fn} = 13.2 mm s^{-1}.

transient accounting for the final phases of solids discharge is observed. Observation of these figures shows that a part from the first part of the discharged mass, the funnel flow discharge without aeration, produces a certain degree of mixing of the solids and does not perform too badly also in terms of material uniformity with time. This is due to the sloping action toward the center in the upper portion of the hopper which draws solids from the whole hopper section. The *last in first out* mechanism induced by funnel flow discharge, however, might not be acceptable in continuative operating modes with frequent and irregular loading and unloading operations of the silo. This may also depend on the kind of segregation pattern and on the funnel amplitude. The best performance in terms of time uniformity of the discharging solids is found at 4.97 mm s^{-1}, which is the closer value tested to the particle suspension during the discharge U_{mfn}. However, even the lower aeration rate tested 3.31 mm s^{-1} does not perform too badly. Velocities larger than U_{mfn} seem to produce more fluctuating results.

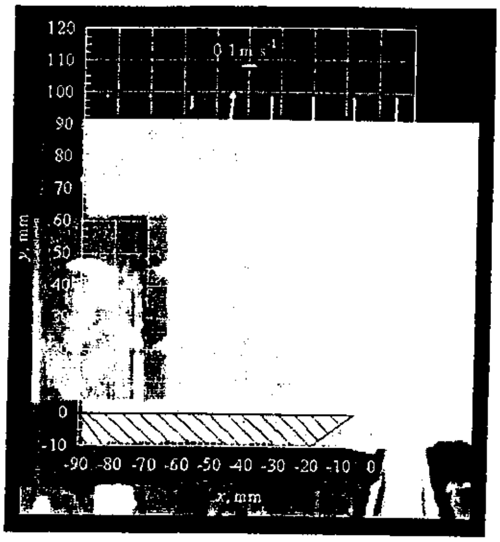

Figure 6. Measured map of the solids velocity and evaluation of the segregation interface during the discharge at 13 mm s^{-1}.

It is possible to compare the results on the solids discharge pattern with the solids velocity fields obtained in the same apparatus by Barletta *et al.* (2002). One example of these fields is superimposed in white on the picture in Figure 6. According to Figure 3 white particles are along the hopper axis and black particles are in the periphery. The position of the vertical separating boundary, x_s, in the initial condition depends on the relative proportion between the particles of the two colors and on the height above the hopper bottom. Keeping the same frame of reference used in Figures 3 and 6 and calling x_{si} the co-ordinate of the separating boundary in the initial condition, it is

$$x_{si} = x_w * \phi_{ui} \qquad (1)$$

where ϕ_{ui} is the fraction of white particles loaded in the hopper. At the highest level at which the velocity is measured, the horizontal components of the solids velocity during the flux are negligible and the boundary position during the discharge, x_s, does not change, at least in the first part of the discharge experiment, when the solids surface is far above that point. Therefore, in the first part of the discharge experiments, at the highest levels it is $x_s = x_{si}$. At lower levels towards the hopper bottom, the horizontal component of the solids velocity is finite and the separation boundary between the colors move towards the hopper axis. At any height, however, mass balances should apply and, assuming a pseudo stationary flow condition, the flux of solids at the exit of the hopper is equal to that evaluated at any height above the distributor. This equality refers not only to the whole mass but also to the single colored species and, therefore if we call, ϕ_{uo}, the fraction of white particles in the stream of solids at the outlet, it is:

$$\phi_{uo} = \int_0^{x_s} V_y(1-\varepsilon)dx \Big/ \int_0^{w} V_y(1-\varepsilon)dx \cong \sum_k V_{yk}\Delta x_k \Big/ \sum_j V_{yj}\Delta x_j \qquad (2)$$

where V_y is the vertical component of the solids velocity, the index k refers only to the points between the hopper axis and the separating boundary. Equation (2) can be used at the highest levels in Figures 6, where $x_s = x_{si}$, to evaluate ϕ_{uo} starting from the vertical velocity profiles. In Figure 5 hyphenated lines refer to results of the evaluation of the colored fraction a the outlet, $1-\phi_{uo}$, obtained with an aeration rate of U_{fn}=13.2x10^{-3} m s^{-1} and with ϕ_{ui}=0.5. The agreement with the measured solids fraction is good. In particular the present experiment produced a higher uniformity between the loaded solids and those withdrawn than predicted especially at aeration velocities near U_{mfn}. Equation (2) can also be used to evaluate x_s at all heights during the hopper discharge given the values of ϕ_{ui}= 0.5. These values of x_s were used to draw the boundary between the colors during the discharge at the same aeration rate as above plotted in Figure 6 with the line with dots. The comparison with the experimental profile seems satisfactory.

5. Conclusions

Experiments indicate that aeration can be used to promote uniformity in the discharge of originally segregated solids. The patterns of solids discharge at high aeration can be satisfactorily interpreted by means of mass balances applied to the maps of the solids velocity measured by Barletta *et al.* (2002). A better understanding of the phenomena and the application of experimental conditions more similar to real situations require further experiments by changing the relative size of the segregated fractions and the relative quantities.

6. Acknowledgements

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