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Effect of Aeration on the Discharge Behaviour of Powders

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Abstract

The effect of aeration on the discharge behaviour of free flowing and semi-cohesive powders was investigated in a flat-bottomed model bin. The following parameters were variables in the experiments: gas flow rate, solids head height in the bin and bin outlet diameter. Based on the results obtained thus far, aerated bins can be considered as suitable devices to promote the discharge of free flowing and semi-cohesive powders. Discharge rates of free flowing powders can be controlled (within limits) by varying the amount of aeration gas.

Nomenclature

A	orifice cross section area	[m^2]
D_o	orifice diameter	[m]
d_p	mean particle diameter	[m]
g	acceleration due to gravity	[m/s^2]
H	bed height	[m]
U_g	gas velocity	[m/s]
U_{mf}	minimum fluidization velocity	[m/s]
W_s	solid mass flow rate	[kg/s]
ρ_b	solid bulk density	[kg/m^3]
ρ_f	gas phase density	[kg/m^3]
ρ_p	particle density	[kg/m^3]

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1. Introduction

Powders are a raw material, intermediate, or final product in many industries, such as foods, pharmaceuticals, chemicals and mineral processing. The storage and discharge of these powders from bins, hoppers and silos is an important, but frequently overlooked, part of the production process. Reliable and controllable discharge of powders from storage is a necessary requirement for successful operation of most processes.

Relatively coarse materials, such as plastic pellets and certain grains, rarely present discharge problems. Reliable discharge by gravity is reasonably assured without significant investment in engineering or equipment. Finer materials, starting at about 1,000 micron mean particle size, frequently will not discharge reliably from silos without careful engineering and selection of discharging equipment and silo geometry. For these materials, cohesive arching (bridging) at the outlet can be a serious problem.

Jenike [1] developed material testing methods and bin design techniques that permit accurate design of bins for reliable gravity discharge. Unfortunately, for many cohesive materials, the final product of the Jenike tests and calculations is a bin with a steep-sided hopper section and a very large outlet. Such bins are costly to build and may require more vertical space (headroom) than is feasible in an industrial situation. The gravity flow rate from the large outlet may greatly exceed process requirements, requiring the selection of an appropriate bin discharging device or feeder.

Conversely, for some relatively impermeable bulk materials, the discharge rate from a silo designed per the Jenike methods can be severely limited by the counter-current flow of air back into the bin from the outlet. In these cases, either greatly oversized outlets or air injection systems are necessary in order to achieve the desired discharge rates. The volume of air necessary to increase the flow rate of impermeable materials can be calculated using complex two-phase flow equations [2].

Local injection of air near the outlet of a bin has also been used to initiate or maintain gravity flow [3,4,5] in silos that may not satisfy Jenike's criteria for gravity flow. Surprisingly, there has been very little research into the mechanics of why such systems operate or into the design guidelines for their use, although recent studies by Jochem and Schwedes are promising [6].

The design of such aerated bins is, at the moment, as empirical as the design of mechanical flow promoters. Even the minimum local air flow rate or velocity to induce solids flow cannot be established on the basis of deterministic equations.

The aim of this work is to investigate the effect of aeration on the discharge rate of powders of scientific and industrial interest and to elucidate the prevailing mechanism of flow promotion. For this purpose, a wide experimental program was established, and the effects of several design variables and operating conditions were investigated.

2. Experimental Arrangement

Experiments were performed in a 140 mm I.D. model bin with a flat bottom, as shown in Fig. 1. The aeration gas was air, introduced into the bottom of the bin through a porous plate. The porous plate, made of sintered stainless steel, provided a uniform distribution of the gas flow in the bed section, since the pressure drop across the plate was in the range between 9.8-49 mbar for the gas flow rates tested. The air flow rate was measured with rotameters. The cylindrical portion of the bin was made of clear plastic, 800 mm high, fitted with an ex-

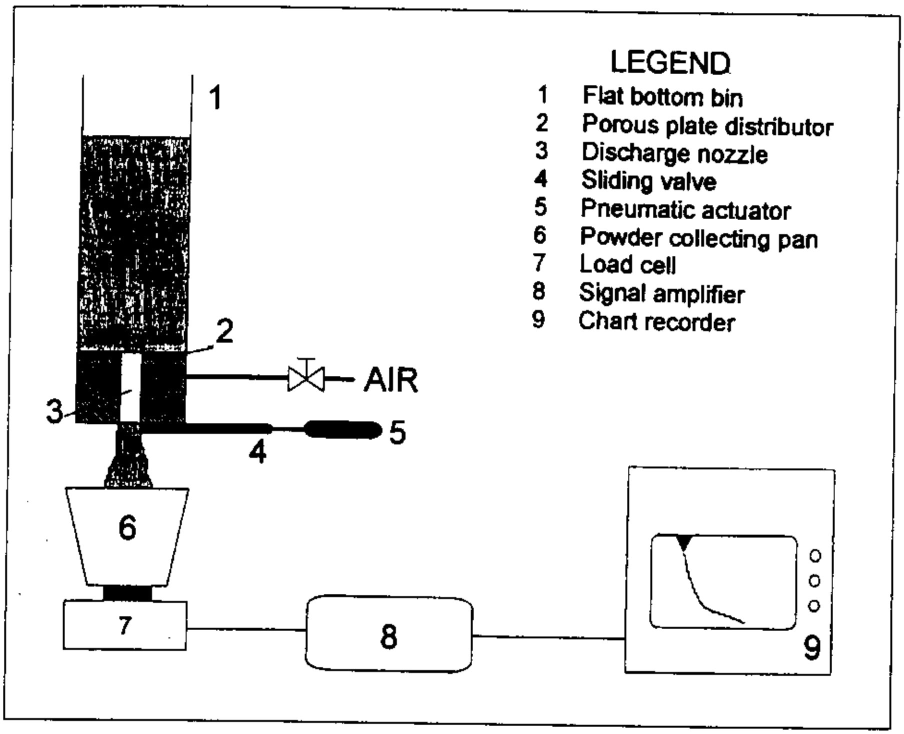


Fig. 1: Sketch of the experimental apparatus.

ternal rule to measure the bed height before, during and after discharge experiments.

The bin outlet (a brass tube) was centered on the bottom and surrounded by the porous aeration plate. Interchangeable tubes were used to vary the outlet diameter between 9 mm and 25 mm. Due to mechanical design constraints, there was a narrow annular region without aeration between the outer edge of the outlet and the inner edge of the aeration plate. The width of the annular region varies inversely with the diameter of the brass tubes, ranging from 1 mm with the 25 mm tube to 9 mm with the 9 mm tube.

The bottom of the brass discharge tube was closed with a pneumatically actuated slide gate valve. The valve did not obstruct the discharge tube in any way when it was open. The opening action of the valve was rather abrupt, and a small amount of vibration was transmitted to the model bin as a result.

Solids exiting the bin fell a short distance onto a pan which in turn was resting on a load cell. The output from the load cell was amplified and sent to a strip chart recorder. The mass flow rate exiting the bin was determined from examination of the strip charts in a time interval of 5 to 10 seconds.

A number of powders were used in the experiments, as shown in Table 1. GELDART's [7] classification system was used as a first approximation criterion to characterize the powders. This system attempts to predict the aeration/fluidization behavior of powders on the basis of their density and mean particle size. Under *Geldart's criteria*, the powders used in the experiments were either Class B (free flowing) or Class A (aeratable) or Class C (cohesive).

The fluidization characteristics for each of the powders was determined using a 50 mm I.D. glass column fitted with a differential manometer and an external rule to measure the bed height (expansion) as a function of gas velocity. Powders were considered to be fluidizable if the graph of pressure drop vs. gas velocity had a regular pattern and if the minimum fluidization velocity (U_{mf}) could be unambiguously determined.

For all the powders tested, experiments were performed with a quantity of material in the range between 5 to 11 kg, depending on the bulk density of the powder, in order to keep constant the initial height of the bed. The height of the bed was not kept constant during experiments, but this did not affect the solids discharge rate in the short time interval necessary for its evaluation.

The effect of the following variables on the solids discharge rate was investigated for each material:

- Gas velocity (U_g), as a multiple of the minimum fluidization velocity (U_{mf}), ranging from 0 to 2 times the U_{mf}.
- Bin opening diameter, ranging from 9 mm to 25 mm.
- Bed height, ranging from 1 to 6 times the bin diameter.

The effect of the latter variable was very weak, except for the lower extreme of the range. For this reason, the experimental data reported here refer to an average bed height of 500 mm.

In addition, the test materials were selected and prepared (screened) in such a way that the effect of the mean particle size and the particle density could be independently investigated.

3. Experimental Results

Powder discharge rates with a bin outlet tube diameter of 19 mm are shown in Figs. 2, 3, and 4 as a function of the gas flow rate.

Fig. 2 shows the results for glass beads "B", the alumina catalyst and the polymer powder, all of which are Class B (free flowing) per Geldart's criteria. For the glass beads, a continuous increase in discharge rate with increasing gas flow rate can be seen. For the polymer pow-

Table 1: Physical and transport properties of powders

Powder	Size Distribution [µm] 10%	Size Distribution [µm] 50%	Size Distribution [µm] 90%	U_{mf} [cm/s]	Bulk Density [g/cm^3]	Particle Density [g/cm^3]	Geldart's Group -
Glass Beads B	129	150	175	2.21	1.49	2.48	B
Glass Beads A	40	47	55	0.35	1.45	2.45	A
FCC A	62	84	120	0.51	1.01	1.96	A
FCC B	28	45	64	0.16	1.10	1.96	A
Alumina Catalyst	80	105	140	1.55	0.98	1.42	B
Polymer Powder	79	116	160	1.33	0.87	1.32	B
TPA	42	76	164	--	1.04	1.47	C
Corn Starch	9	19	39	--	0.72	0.75	C

der and the alumina, the discharge rate increases with gas flow until a steady-state value is reached. Beyond this point, additional gas flow is either ineffective or actually retards flow. The latter effect is probably caused by gas displacing solids in the discharge stream. The stream of solids exiting the bin was observed to be more highly aerated in these cases.

In Fig. 3, a similar behavior can be observed for the powders satisfying Geldart's type A "aeratable" criteria (Glass beads "A", FCC "A" and FCC "B"). All of the aeratable and free flowing powders (Figs. 2 and 3) will flow through the outlet of the bin without aeration.

A different behavior was observed for the two cohesive powders, TPA (Terephtalic Acid) and corn starch. As shown in Fig. 4, these materials do not flow at all in the absence of aeration, or they exhibit unstable flow, which stops when the bed height decreases. The introduction of aeration promotes powder flow. As with most of the other powders, a steady state value of discharge is reached with aeration, and further increases in the gas flow rate does not lead to a corresponding increase in the discharge rate.

Fig. 5 illustrates the solids discharge rate from a 13 mm outlet as a function of the ratio U_g/U_{mf} for all of the fluidizable powders. When compared to non-aerated discharge, the solid flow rate can be increased by up to 500% via aeration. Solid flow rates are increased even in cases where the aeration velocity is well below the minimum fluidization velocity for the material.

Fig. 6 depicts the influence of outlet diameter on the discharge mass flow rate for three powders, FCC "B", glass beads "A", and alumina catalyst. Aeration was provided to create a gas flow of 1.5 times the minimum fluidization velocity. The solids discharge rate increases with increasing outlet size for each of the materials, but there is an indication that the discharge rate for the alumina catalyst may reach an eventual limit. The FCC "B" material and glass beads "A" do not show such a limit.

The influence of particle size is presented in Fig. 7, which shows the solids mass flow rate of glass beads "A" and "B" from two different opening diameters (13 mm and 19 mm) as a function of the ratio U_g/U_{mf}. The glass beads were of identical chemical composition and shape. At all aeration rates (including zero), for both outlets, the "aeratable" glass beads "A" flowed at a higher mass flow rate than the "free flowing" glass beads "B" despite their slightly lower bulk density.

In Fig. 8 the effect of particle density is shown. It depicts the solids mass flow rate of glass beads "A" and FCC catalyst "B" from 13 mm and 19 mm diameter openings when aerated at up to twice the minimum fluidization velocity. Both powders are aeratable per Geldart's criteria and have approximately the same particle size. It can be observed that the denser powder flowed at a higher mass flow rate, although not in direct proportion to its density.

4. Discussion

The gravity discharge rate of free flowing powders and granular materials can be

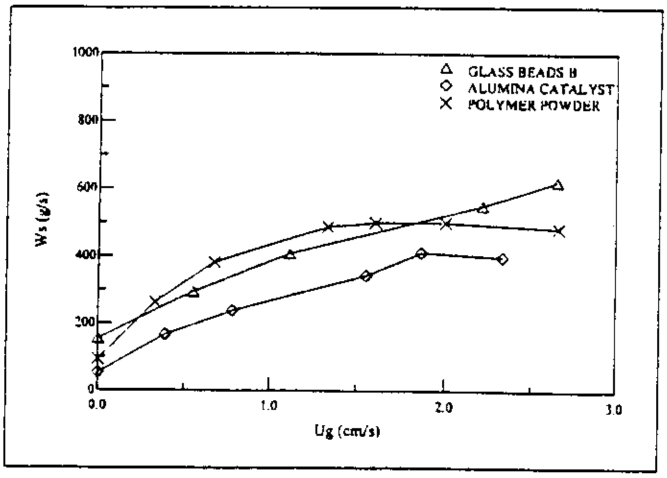


Fig. 2: Solid mass flow rate as a function of gas velocity.
Opening diameter D_o = 19 mm

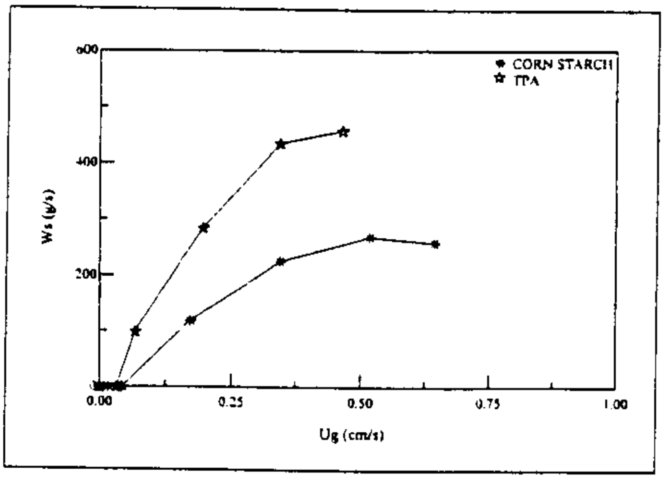


Fig. 4: Solid mass flow rate as a function of gas velocity.
Opening diameter D_o = 19 mm

Fig. 3: Solid mass flow rate as a function of gas velocity.
Opening diameter D_o = 19 mm

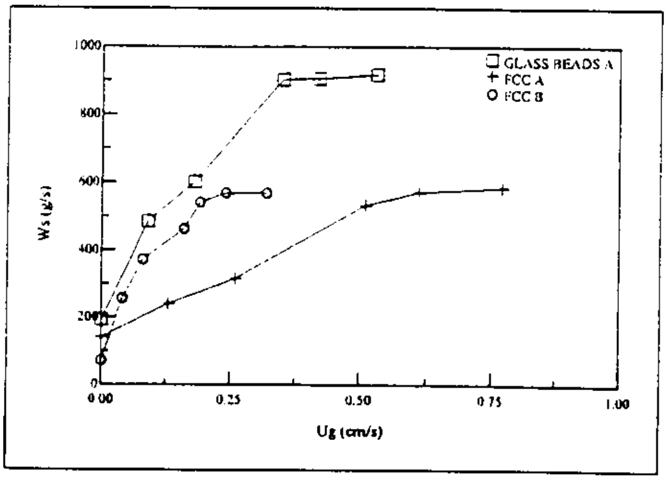
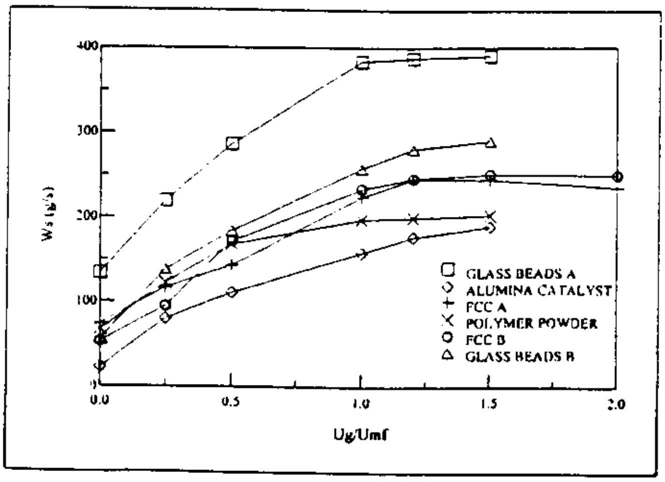


Fig. 5: Solid mass flow rate as a function of the ratio of gas velocity to minimum fluidization velocity. Opening diameter D_o = 13 mm



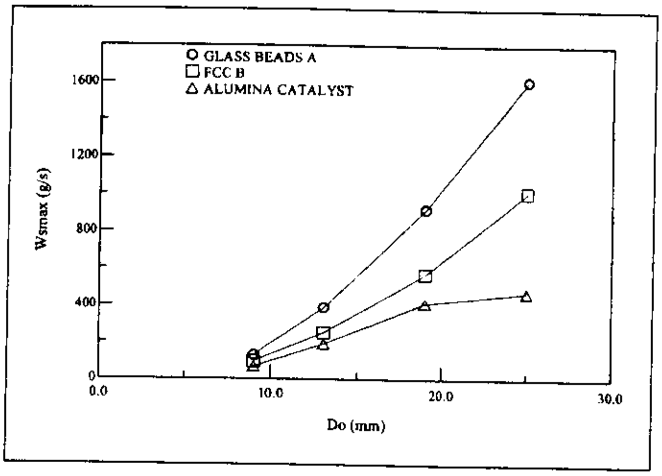


Fig. 6:
Maximum solid mass flow rate of Glass Beads A, FCC B and Alumina Catalyst as a function of the opening diameter.

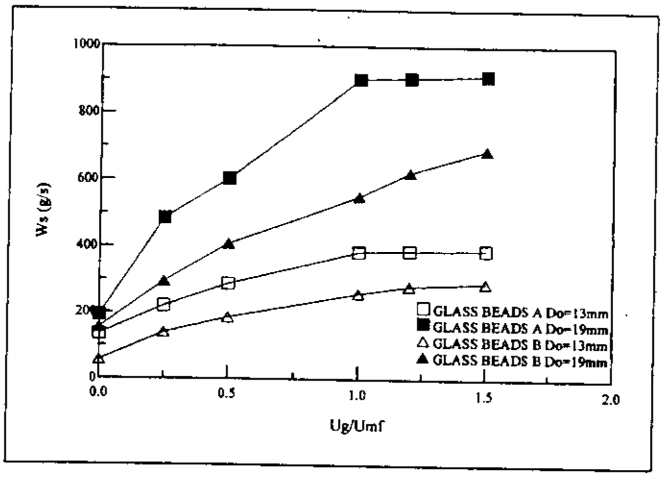


Fig. 7:
Solid mass flow rate of Glass Beads A and Glass Beads B from two different opening diameters as a function of the ratio of gas velocity to minimum fluidization velocity.

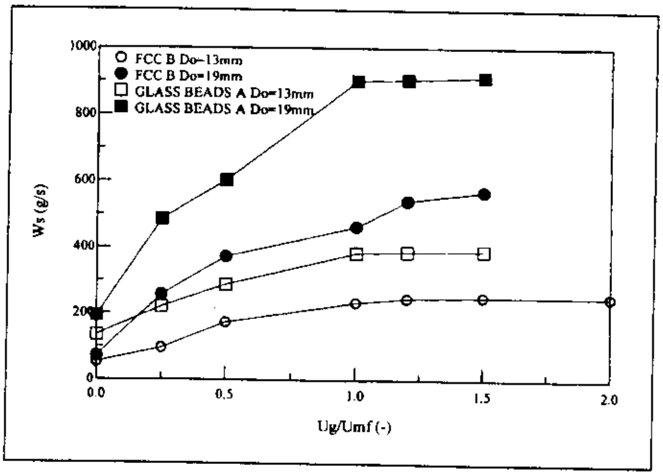


Fig. 8:
Solid mass flow rate of FCC B and Glass Beads A from two different opening diameters as a function of the ratio of gas velocity to minimum fluidization velocity.

predicted by empirical relations based on the *Bernoulli equation*. Using dimensional analysis, BEVERLOO ET AL. [8] proposed the following empirical correlation for solids discharge from a circular aperture:

$$W_s = C \cdot \rho_b \cdot g^{0.5} \cdot (D_o - k \cdot d_p)^{2.5} \quad (1)$$

where C is a constant factor usually set at a value of 0.58, k a particle shape factor, d_p the particle diameter, D_o the outlet diameter and ρ_b the loose bulk density.

For fine powders the *Beverloo correlation* tends to overestimate the solids flow rate even with modified values of the C and k parameters [9]. This is probably because it does not consider the impediments to flow caused by the counter-current flow of gas into the bin at the outlet. In addition, it fails to consider the possibility of cohesive arching at the outlet that would prevent flow entirely.

The reason that aeration has a positive effect on solid discharge rate is not clear at present. The most accepted hypothesis is that the increase of mass flow rate of powders somehow involves the interstitial pressure gradient at the base of the bed.

The effect of the pressure gradient within the material on the increase of the flow of granular materials was first studied by McDOUGALL AND KNOWLES [10], who also developed a correlation to evaluate the discharge rate from a bin. However, in this correlation, two parameters (K and ρ_{po}) must be experimentally determined. There is evidently a complex dependence on particle characteristics, i.e. size, size distribution and density, and on bin opening diameter and shape. This implies that experiments on the effect of aeration on the mass discharge rate are still necessary.

The hypothesis of McDOUGALL AND KNOWLES tends to fail when the flow of relatively fine materials, such as aeratable and semicohesive powders, is considered. In fact, the discharge of fine barely permeable materials can cause the development of significant vacuum pressure at the base of the silos. Experimental determination of the gas pressure at the base of the bin during discharge confirms this behavior for all powders tested [11]. Moreover, part of the gas supplied to the system via aeration flows downward through the bin outlet with the stream of solid. This was confirmed by analysis of a videotape, taken in our laboratory, of the solid stream flowing from the bin, which become looser (i.e. of lower bulk density) as the gas flow rate in the bin increases [12]. As a consequence, in our case the pressure gradient at the base of the bin can not be evaluated as suggested by McDOUGALL AND KNOWLES as $U_g \cdot k \cdot H$, with U_g the gas velocity, k the resistivity of the bed and H the bed height. Since some of the gas flows out of the outlet with the solids, the value of U_g is questionable. Similarly, the dilation of the solids in the region of the outlet makes determination of the resistivity (k) problematical.

Other hypotheses for the interpretation of the effect of aeration on the discharge of fine powders are the following:

- Fluidization of the powder, at least on a local scale, occurs and liquid-like flow develops.

Or,

- The momentum of the gas flow provides the energy input necessary to overcome inter-particle forces.

Under the first hypothesis, the motion of solid particles through the orifice can be treated as that of an inviscid continuum. The changes of the voidage fraction of the powder during discharge is neglected, thus the theory predicts that the mass flow rate is described by Bernoulli's equation for incompressible materials

[3,13,14]. The discharge rate can be predicted by an equation of the form:

$$W_s = C \cdot \rho_b \cdot A \cdot (2 \cdot g \cdot H)^{0.5} \quad (2)$$

with C a variable which assumes different values depending upon the size and shape of the discharge opening, ρ_b the bulk density of the powder at minimum fluidization conditions, A the cross section of the outlet, and H the bed height. Note that this equation differs from Eq. (1) by the inclusion of bed height. This is appropriate for the inviscid continuum assumption, and presumes that the entire bin achieves minimum fluidization conditions.

If the second hypothesis is correct, the effect of aeration is exerted only locally and a relationship similar to Eq. (1) should describe the phenomena. Moreover, the effect of aeration does not depend on fluidization velocity, but on gas momentum.

Our study (Fig. 5), and a previous report [15] demonstrate that the solids discharge rate is increased even with superficial gas velocities that are considerably lower than the minimum fluidization velocity. This supports the second hypothesis, that the effect of aeration is to overcome inter-particle forces. However, there was no observable step effect that would correspond to the gas momentum suddenly reaching a level sufficient to overcome inter-particle forces. It is possible that the gas flow rate, even at the lowest amount, was sufficient for this purpose on a local level and increasing gas flow merely increased the volume of powder affected. Full fluidization, if any, is the upper limit of the effect of increasing aeration on discharge rate.

In Fig. 9, the maximum discharge rates predicted by Eqs. (1) and (2) are compared to the actual rates observed for the various outlet sizes. The comparisons were made at zero aeration rate (shown with the hollow white symbols) as well as at the aeration rate that caused the highest discharge rate (shown with solid black symbols).

The Beverloo correlation (Eq. (1)) appears to underestimate the non-aerated flow rate from small openings and overestimate that from larger outlets. Aerated discharge results, which perhaps could be described by Eq. (2), showed large deviations from the theoretical prediction. Neither equation appears to be adequate to explain the observed behavior.

The results are further interpreted in Fig. 10, in which the discharge rates of FCC "B" are plotted as a function of outlet diameter for all the aeration rates tested. In this case, Eq. (2) appears to be effective in terms of describing the upper limit of mass flow rate but the Beverloo correlation again overestimates the discharge rate from larger outlets.

It is also interesting to note the step change in discharge rate corresponding to increasing aeration to a value of $U_g/U_{mf} = 1.0$ with the 25 mm outlet. With smaller outlets, the discharge rate appeared to vary more gradually with increasing aeration. This implies that there may be a scale effect in the experiments.

5. Conclusions

The experimental results confirm that aeration is a very effective technique in promoting the flow of a wide range of powders, including slightly cohesive materials. Even moderate gas flow rates (below minimum fluidization) have a definite effect on the discharge rate for the materials tested, including those categorized as "cohesive" by Geldart's criteria. For slightly cohesive powders, a no-flow situation converts to reliable flow by the addition of moderate gas flow rates.

The large number of experimental tests performed allows the following conclusions to be drawn or reaffirmed about the mechanisms of gravity flow in aerated conditions:

Aeration rates do not have to reach fluidization levels in order to be effective. Increasing aeration tends to increase discharge rates, but aeration rates in excess of the minimum necessary for fluidization may reduce discharge rates by displacing solids at the outlet.

The most likely mechanism for explaining the influence of aeration on discharge rates is the influence of the gas on the inter-particle forces. The gas may have three possible effects. First it may simply relieve the negative pressure created as the bulk solids dilate in the outlet region. Providing aeration eliminates the need for the air to enter the bed by traveling upwards from the outlet. Since this countercurrent air flow impedes the discharging particles, it is logical to conclude that the providing aeration will increase discharge rate. A second possible effect of the gas is to provide a mechanical force acting against the cohesive inter-particle forces in the vicinity of the outlet. The resistance (pressure drop) of the powders between the aeration source and the outlet is the source of the mechanical force, and increasing the gas flow increases the mechanical force and possibly the size of the region it acts on. The third possible role of the gas concerns inter-particle attractive

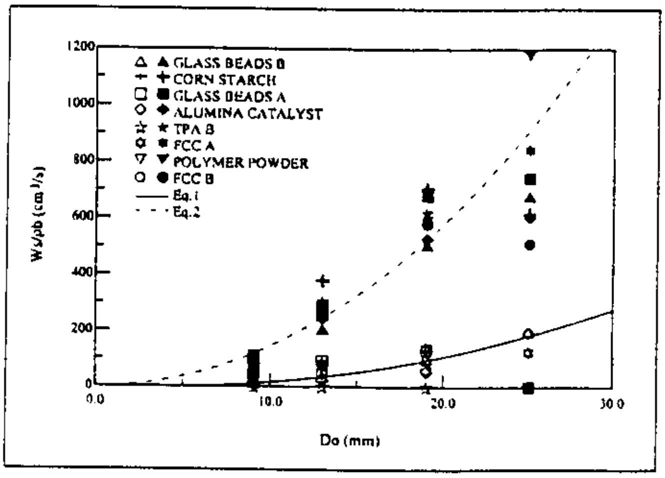


Fig. 9:
Maximum solid mass flow rate and solid mass flow rate at zero aeration rate as a function of the opening diameter in comparison with model predictions from Eqs. (1) and (2).

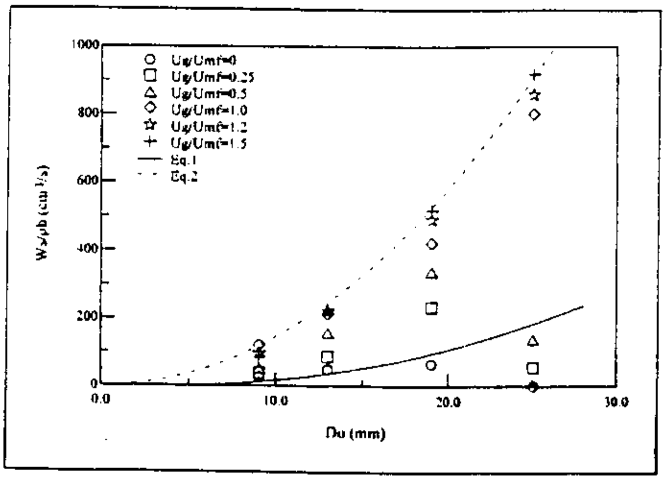


Fig. 10:
Solid mass flow rate of FCC B at different aeration rates as a function of the opening diameter in comparison with model predictions from Eqs. (1) and (2).

forces. Drag forces exerted by the gas phase overcome the inter-particle forces. This mechanism is likely to be most effective when the potential drag forces and the inter-particle forces are in the same range, as is the case for semi-cohesive powders.

It appears that the existing correlations for gravity flow and for discharge from fluidized beds both fail to accurately describe aerated flow from bins. Neither correlation quantifies the influence of aeration rates, and there are evidently particle or bulk material characteristics that they overlook.

Particle size affects the solid discharge rate. With aeration, the beds of finer aeratable powders expand as a consequence of the balancing between drag forces, exerted by gas phase, and inter-particle forces. The materials of larger mean particle size are free flowing and do not expand at all while undergoing aeration. The structure of the bed of aeratable materials becomes more loose, as a consequence of aeration, and the number of contact points between particles reduces. Thus, solid-solid friction is expected to be less pronounced for aerated aeratable powders than for free flowing ones.

The bulk density of the powder seems to play an important role. The effect of this parameter, which is strongly related to the porosity of the powder near the opening, needs to be investigated further.

The structure of beds of aeratable or slightly cohesive particles in presence of aeration is more complex due to the formation of cavities and aggregates stabilized by inter-particle forces. This could change the solid discharge rate from bins and hoppers in respect to beds of free flowing particles which exhibit a more homogeneous structure. This is one of the more interesting topics to be investigated to gain a deeper understanding of the flow mechanism.

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