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THE ONSET OF FLUIDIZATION OF FINE POWDERS IN ROTATING DRUMS

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Abstract. An estimation of the dominant stresses in powders with or without interstitial gas flow yields a semiqualitative criteria for the transition between flow regimes (plastic-fluidized, plastic-inertial, plastic-suspension, inertial-fluidized, inertial-suspension). It will be shown that, at ambient pressure, fine powders (particle diameter less than ~ 100 μm) experience a direct transition from plastic to fuidized regime, or from plastic to suspension. The inertial regime is absent in these fine powders. These ideas will be applied to understand the onset of fluidization in rotating drums. Previous measurements with xerographic toners (particle diameter around 10 μm) in rotating drums indicated that fluidized and plastic regimes coexist in the drum. The extent of the fluidized region grows when angular speed is increased. Here, we present measurements on the width of the horizontal surface of the fluidized zone as a function of rotation velocity, drum diameter and toner properties. We find that the results depend on the product of three fundamental parameters: (i) the ratio of the fluidized toner bulk density to the packed toner bulk density; (ii) the ratio of centrifugal acceleration to the acceleration of gravity and (iii) the ratio of gravitational potential energy per unit volume (or equivalently, kinetic energy per unit volume) to the powder tensile strength.

1. INTRODUCTION

Handling of powders require control of powder flowability. This is particularly important for industrial applications involving powder transportation and mixing. A key parameter in powder flow is particle radius. Flow behaviour of materials with particles of diameter larger than 30 μm is inertial. This means that transport of momentum by interparticle collisions is responsible for the transmission of stresses inside the material and that stresses show a cuadratic dependence on shear rate [1]. In the inertial regime the spacing between particles is greater than in the plastic regime, mobility of the particles is increased and mixing of different materials becomes possible. Problems arise when dealing with materials of particle diameter less than 30 μm. For this materials, attractive forces between particles become important and interaction with interstitial air plays a fundamental role. The result is that fine, cohesive powders experiment a direct transition between plastic and fluidized regime, with no inertial regime [2]. Thus, easy transportation and mixing of fine, cohesive powders requires fluidization of the material.

The behaviour of non-cohesive large grains in rotating drums has been often studied [3-5]. In industrial processes, such devices are mostly used used for drying, mixing and segregating grains. The drum is partially filled with the material and rotated horizontally. For low angular speed, the material experiments periodic avalanches whenever its inclination in the drum is larger than its angle of repose. As the angular speed is increased the frequency of the avalanches increases till no individual avalanches can be distinguished. Instead of them a superficial layer of a few grains in depth where the material moves continuously down the slope is formed. The rest of the material moves upwards as a rigid solid and feeds the layer. Further increase of the angular velocity makes the surface of the material adopt a

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Fig.1. Behaviour of a cohesive powder in a rotating drum for three different angular speeds: ω=10 rpm, ω=45 rpm, ω=100 rpm from left to right. The material is fluidized where the free surface is horizontal.

S shaped profile, which becomes more and more marked as the velocity is increased.

The behaviour of fine, cohesive powders in rotating drums in radically different. At low angular speeds the material also experiments periodic avalanches, but during the movement of the avalanching material, gas is entrained inside the powder and at least partial fluidization of the avalanching material becomes possible. It takes some time for the gas engulfed inside the powder to abandon it, so when an angular speed is reached such that the time between avalanches becomes comparable to the time needed to evacuate the gas, a permanent region of fluidized material appears. This region is recognizable because fluidized material behaves as a liquid so its surface remains horizontal. From this point, the increase of angular speed has the effect of:

a) increase the velocity of the powder respect to the gas in the drum (the so called slip velocity). The importance of the hydrodynamics interactions between gas and particles raises with increasing slip velocity [6], so a better fluidization of the powder will occur.
b) Bringing more quantity of material to the fluidized region per unit time.

Both effects favour the growth of the fluidized region with increasing angular speed which can be seen through the growth in length of the horizontal region of the material in the drum and the progressive decrease in the average dynamic angle of repose. Also, as fluidization is accompanied by expansion of the powder, the filling fraction of the material in the drum raises with angular speed, Fig.1.

2. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 2. We have used a computer controlled step motor with a velocity range from 0.001 to 50 rev/s with a resolution of 4000 steps/rev. A gear box reduces the motor speed by a factor of 12.5 and drives the movement of the drum. The gear box is joined to the motor by means of a elastic cardan and it is placed on an air table to isolate the gear box from any external vibration. A 25 frames/second video camera placed in front of the drum records the experiment. Drums of 42 mm, 50 mm and 90 mm diameter and 40 mm height were used in the experiment. One of the ends of the drums has a porous filter to let air in and out of the drum but retaining the particles. A typical run is as follows: The powder is initialized by fluidizing it at 180 rpm approximately. The powder is maintained at that speed until no further expansion is seen. Then the drum is stopped and the powder is let to collapse to obtain a reproducible initial state. Then angular velocity is slowly increased from 0 to 200 rpm. The width of the horizontal region formed by fluidized toner and the filling fraction of the toner in the drum are measured for each velocity from the record using an image processing program. At velocities were individual avalanches could be distinguished the width of the horizontal region and the filling fraction were measured immediately after an avalanche.The toners used in the experiment were taken from a series of toners sharing the base polymer, particle diameter (12.7 μm), density (ρ_p = 1065 Kg/m^3) and shape but blended with different concentration (from 0.02% to 0.4% by weight) of flow controlling additive. The concentration of additive controls toner cohesivity: the less the concentration of flow controlling additive, the more cohesive the toner.

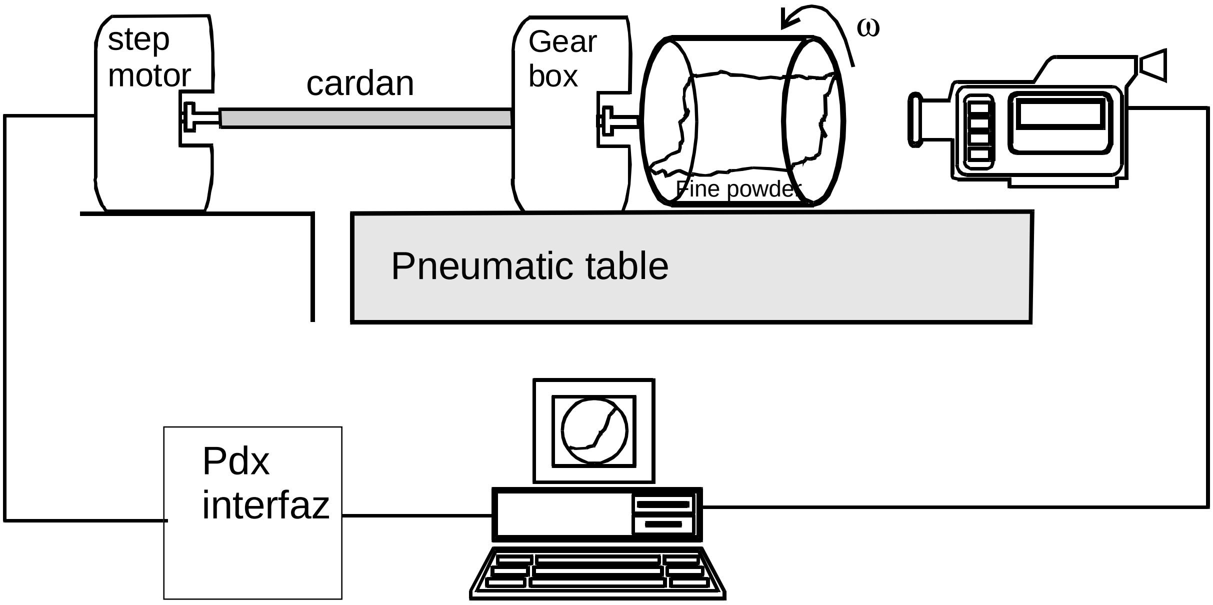

Fig.2. Experimental setup. The elastic cardan and the air table isolate the drum from external vibrations.

3. RESULTS

We consider that the material in the drum is divided in two regions: a plastic region that moves as a rigid solid with the drum and a fluidized region formed by material from the avalanches occurring in the plastic region which is fluidized during the process of avalanching. The growth of the horizontal surface and the expansion of the material in the drum reflects the growth of the fluidized region with angular speed. Fig. 3 presents the measured extension *d* of the horizontal region in the drum and the filling fraction φ of the material in the drum versus angular speed.

As a general trend, for a given angular speed and diameter of the drum, *d*/*D* decreases with powder cohesivity. On the other hand, for the same toner and angular speed, the value of *d*/*D* raises with the diameter of the drum. This result is expected, because a larger diameter implies larger linear velocities for the material in the drum and hence larger velocities of the toner respect to the air in the drum.

The filling fraction of the material increases slowly until the extension of the fluidized zone is of the order of the diameter of the drum (*d*/*D* ~ 1). Then the filling fraction raises much faster with angular speed. The expansion of the toner is greater for the

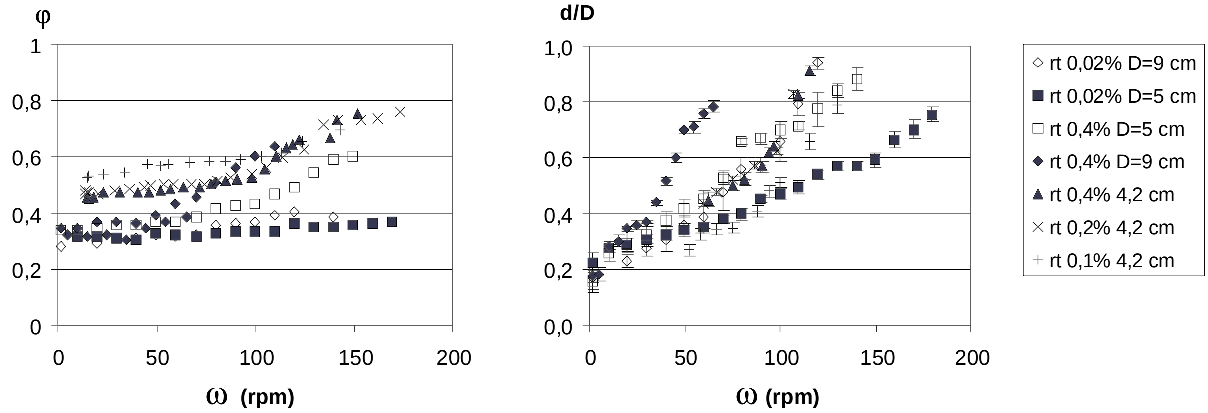

Fig.3. Width *d* of the horizontal free surface and filling fraction φ of the material in the drum versus angular speed for the xerographic toners studied.

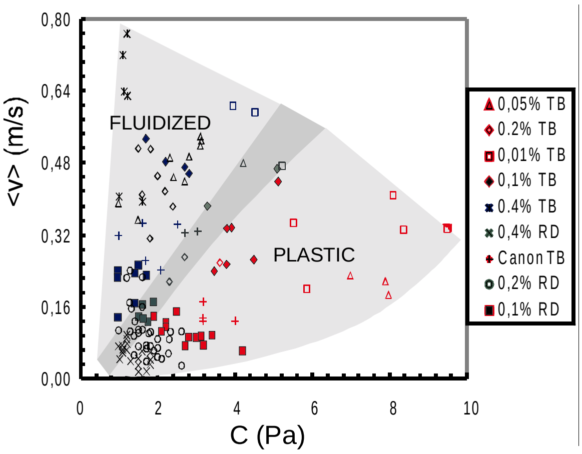

Fig.4. Plot of linear velocity of the material in an avalanche versus cohesion indicating when the material involved in the avalanche becomes fluidized.

less cohesive toners than for the more cohesive ones, which are difficult to fluidize [8]. As fluidization is accompanied with an increase in volume of the fluidized material, the increase in the filling fraction gives an idea of the extension of the fluidized region. The initial growth of d/D with angular speed while the filling fraction remains practically constant indicates that the fluidized region is a very shallow layer of fluidized material resting over the plastic region. Only when the extension of the fluidized region has grown to almost the diameter of the material, the depth of the fluidized region increases, with a noticeable increase in the filling fraction. The angular speed in which $d/D \cong 1$ can be taken as the speed for the onset of fluidization.

4. DISCUSSION

A physical model describing the progressive fluidization of a cohesive powder in the drum must take into account two steps:

a) the avalanches originated in the plastic region and the subsequent fluidization of the avalanching material;

and

b) the defluidization of the material in the fluidized region to return to the plastic region caused by the escape of gas from the fluidized region.

To study the fluidization of a fine powder in an avalanche we have realized a simple experiment in a tilted bed of rectangular shape. First, the material is initialized by fluidization. After shutting off the gas supply the material collapses under its own weight with a horizontal free surface. Once the material has collapsed, the bed is tilted slowly until an avalanche is triggered and a slice of powder slides down the slope formed by the rest of the material. If the material in the slice is fluidized during the avalanche, it will behave like a liquid and it comes to rest with a horizontal free surface. Recording the experiment with a TV camera makes possible to measure the velocity of the slice during the avalanche. As we know from other experiments the tensile strength of the materials used in this experiment [9], we know for each avalanche the tensile strength of the material in the slice and its velocity and we can make a plot like the one in Fig. 4. This figure shows that in order to become fluidized during an avalanche, the velocity of the slice must overcome a certain threshold which depends on the tensile strength of the material in the slice. The velocity of the slice depends on its gravitational potential energy before the avalanche. In the case of a rotating drum, the avalanching material has both a kinetic energy per unit volume $1/2\rho_0\omega^2 R^2$ due to its rotation with the drum, and gravitational potential energy per unit volume $\rho_0 gR\cos\alpha$, where α is the angle formed by the free surface of the material in the plastic region, that varies very slowly with angular speed. With this two magnitudes and the tensile strength σ_t we can construct two dimensionless numbers: the Froude number $\omega^2 R/g$ and $\rho_0 gR/\sigma_t$, the ratio of gravitational potential energy per unit volume of material to its tensile strength. We use the value of the tensile strength corresponding to the density of the material after initialization [9] as a measure of the cohesivity of the material.

Defluidization of a fluidized cohesive powder can be considered as a process in which a set of porosity fronts originated at the bottom of the material propagate towards the free surface with a velocity depending on the porosity ε_m of the front given by [6]

$$U_c = \frac{\rho_s g d_p^2}{60\mu}\varepsilon_m^2, \qquad (1)$$

where ρ_s is the density of the particles, d_p is the particle diameter, g is the gravity, and μ is the viscosity of the fluidizing gas. The porosity front propagating at the slowest velocity determines the time needed for defluidization of the material. In our case, the slowest propagating front has the porosity ε_p of the plastic region. As the plastic region is fed from defluidized material from the fluidized region and the material is initialized by fluidization and collapse, we assume that the porosity ε_p is close to the porosity of the material after initialization, irrespective on the angular speed at which the drum is rotating.

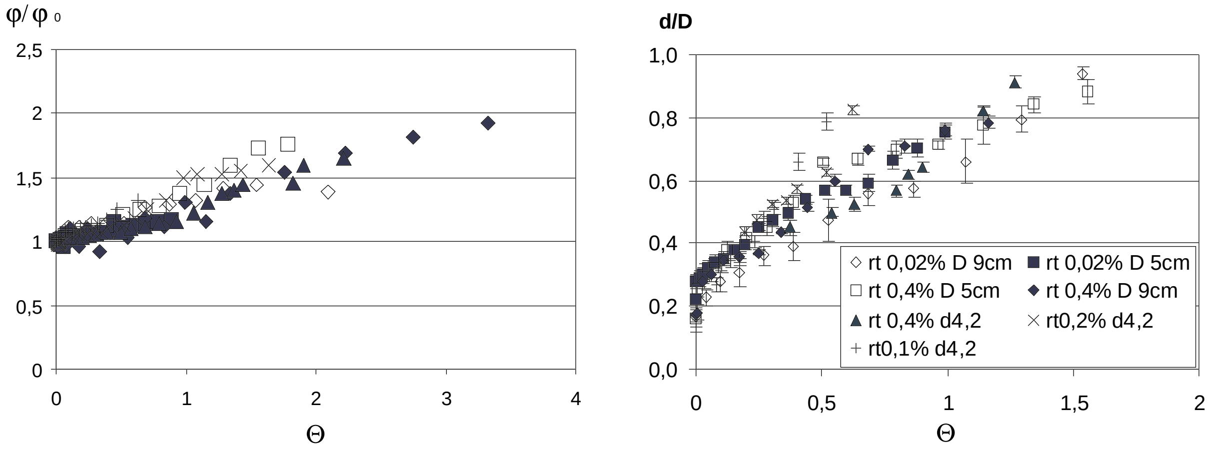

Fig. 5. Normalized values of the width of the horizontal free surface *d/D* and filling fraction φ/φ_0 versus the nondimensional parameter Θ.

The porosity of the toner after initialization is also a function of the tensile strength of the toner after initialization [9]. Therefore new magnitudes are not added to the problem and *d/D* and φ/φ_0 must be functions of the nondimensional groups ω^2R/g and $\rho_0 gR/\sigma_t$ only:

$$\frac{d}{D}=f\left(\left(\frac{\omega^2R}{g}\right)^{\alpha},\left(\frac{\rho_0 gR}{\sigma_t}\right)^{\beta}\right),$$

$$\frac{\varphi}{\varphi_0}=g\left(\left(\frac{\omega^2R}{g}\right)^{\alpha},\left(\frac{\rho_0 gR}{\sigma_t}\right)^{\beta}\right). \qquad (2)$$

The exponents α and β must be the same for *d/D* and φ/φ_0 because both are a measure of the extension of the fluidized region. Using that for $\omega\to 0$, $\varphi/\varphi_0\to 1$:

$$\frac{\varphi}{\varphi_0}=1+a_0\left(\frac{\omega^2R}{g}\right)^{\alpha}\left(\frac{\rho_0 gR}{\sigma_t}\right)^{\beta}+O(2). \qquad (3)$$

The exponents α and β are calculated so that the experimental points of φ/φ_0 fit to a universal law of the parameter $(\omega^2 R/g)^{\alpha}(\rho_0 gR/\sigma_t)^{\beta}$. The values obtained for α and β are

$$\alpha = 0.97 \pm 0.27;$$

$$\beta = 107 \pm 0.28. \qquad (4)$$

From the values obtained for $\alpha \cong 1$ and $\beta \cong 1$ the nondimensional parameters combine to give:

$$\frac{d}{D}=f\left(\frac{\rho_0\omega^2R^2}{\sigma_t}\right)=f(\Theta),$$

$$\frac{\varphi}{\varphi_0}=g\left(\frac{\rho_0\omega^2R^2}{\sigma_t}\right)=g(\Theta). \qquad (5)$$

Where Θ is the kinetic energy per unit volume of the powder divided by its tensile strength. The results of this fitting are depicted in Fig. 5.

It is observed from both figures that whereas φ/φ_0 increases linearly with Θ, *d/D* increases sublinearly with Θ. This is reasonable, because φ/φ_0 is a measure of the section of the fluidized region, and *d/D* is a measure of the linear dimensions of the fluidized region, so if φ/φ_0 is proportional to Θ then *d/D* must be proportional with $\Theta^{1/2}$.

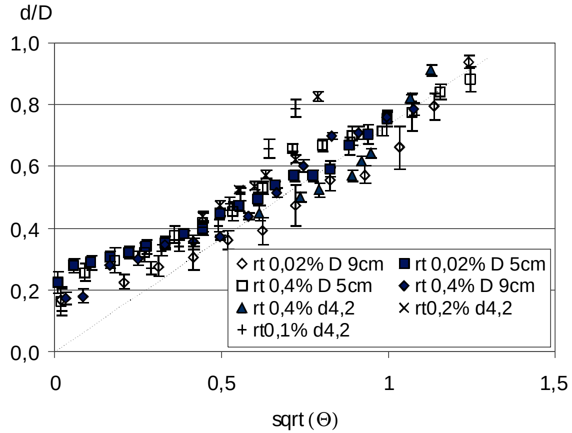

Fig. 6. Normalized values of the width of the horizontal free surface *d/D* against the square root of the nondimensional parameter Θ.

Fig. 6 displays *d/D* versus $\Theta^{1/2}$. It can be seen that *d/D*($\Theta^{1/2}$) deviates from a linear law for small values of Θ (that is, small values of the angular speed). The explanation is that for small values of the angular speed avalanches can be separated individually and the material that is fluidized in an avalanche has enough time to collapse in the interval between two consecutive avalanches so the fluidized region is not permanent and therefore increases at a slower rate with Θ.

5. CONCLUSIONS

The extent of the fluidized region in a rotating drum increases linearly with the ratio of kinetic energy per unit volume of material to the tensile strength of the material after initialization in the drum. For the set of fine powders of different cohesivities used in the experiment, the onset of fluidization, defined as the lowest angular speed at which the free surface of the material in the drum is horizontal occurs at a value of $\Theta = \rho_0\omega^2 R^2/\sigma_t \approx 9/4$. Generalization for other materials of different particle radius or in different ambient conditions (interstitial gas), requires a further study on the propagation of changes in porosity in a fluidized bed.

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