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Segregation of dry granular material in rotating drum: experimental study of the flowing zone thickness

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Abstract

We study experimentally the maximum thickness of the flowing zone in a rotating drum of diameter D half filled with glass beads of diameter d. Several drum diameters and beads sizes were studied, bringing a special attention to geometrically similar systems, i.e. of constant ratio D/d. The rotation speed ranges from 2 to 20 rpm, the minimum is chosen such that the system is in the continuous flow regime. The study of the flowing zone thickness versus the diameter of the beads and the diameter of the drum shows that the ratio D/d is the relevant parameter.

Keywords: Dry granular material; Rotating drum; Flowing zone thickness

1. Introduction

Many industrial processes implement operations of granular material mixing, granular material being cohesive (powders, flour,...) or noncohesive (sand, gravel, extruded polymers,...). Among these industries, we can cite food, cosmetic, drugs or ceramic industries, which aim to obtain a homogeneous product by mixing several ingredients. Industrial mixers are generally of free flowing type (or diffusive) where a closed volume revolves in a more or less complex trajectory, or a convective type, which have impeller such as paddle, ribbon or blade which movement produces the mixing of the powder.

When noncohesive powders are processed, segregation or demixing among the constituents during the operation can be observed. Particles migrate in different zones of the mixer according to their physical properties (size, density, shape,...). Segregation might also occur during operations following the mixing like emptying, transport, packaging,...

Several studies were carried out to understand and avoid segregation in industrial blenders. Some of these works have studied industrial mixers [1], but more frequently simplified systems like 2D and 3D rotating drums have been used. These rotating drums consist of a cylinder in axial rotation and filled with a binary mixture of particles. Three types of segregation may occur and appear consecutively in time [2]. The first to appear is the radial segregation: smaller (or denser) particles form a central core of segregation and are surrounded with larger (or denser) particles. This phenomenon is extremely rapid, one turn of the rotating drum is merely enough. After a much longer period, an axial segregation occurs and leads to the existence of several alternating bands perpendicular to the rotation axis and rich in large or small particles. Finally, if we wait long enough, we may observe two bands of fine particles at the ends of the drum connected each other by a thin core of segregated small particles [2]. The axial segregation occurs very slowly and only for long drums. The causes of this segregation are not very well understood. We will not study it here.

In rotating drums, several flowing regimes have been identified. From low to high velocity, the following regimes occur: slipping, slumping, rolling, cascade, cataract and centrifugation. In the rolling regime, two distinct zones are observed: an active zone where the material flows with a free surface, and a passive zone where the material rotates like a bulk with the rotating drum, the particles have no relative movement. The segregation phenomenon needs a relative movement between the particles, thus segregation will occur in the flowing zone. A good understanding of this active zone (thickness, angle of flow, geometry) is necessary if we want to predict quantitatively the kinetic and efficiency of segregation. Most of the studies carried out on segregation in rotating drums only consider the segregation in a global or systemic way. Only a few have focused on the flowing zone [3–6]. They study the variation of thickness of

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Table 1
The different ratios D/d studied experimentally are given with the corresponding size of the beads used and the dimensions (diameter D and width l) of the drum

D, l	d					
	2 mm	1–1.4 mm	1.19 mm	500–630 μm	560 μm	150–250 μm
D = 20 cm, l = 1 cm	100 (S1)	–	–	–	–	–
D = 20 cm, l = 2 cm	100 (S2)	166 (S9)	–	357 (S11)	–	1000 (S13)
D = 20 cm, l = 4 cm	100 (S3)	–	–	–	–	–
D = 20 cm, l = 6 cm	100 (S4)	–	–	–	–	–
D = 12 cm, l = 2.4 cm	–	100 (S5)	100 (S6)	–	214 (S10)	600 (S12)
D = 5.6 cm, l = 1.1 cm	–		–	100 (S7)	100 (S8)	–

The systems are numbered from S1 to S13. This notation is used further in this article.

the flowing zone versus rotation velocity or percentage of filling of the drum, for a given experimental system, and are concerned with the velocity profiles and the concentration of the species in the flowing zone. The shape of the limit between the active and the passive zone has also been studied and seems to be a parabola [7]. On the other hand, no results have been reported on the sensibility of the flowing zone versus the geometry of the drum. Nevertheless, a flowing zone thickness of 10 beads is largely admitted [8]. In this work, we will focus on the characteristics of this flowing zone.

2. Experimental set up

A simple and flexible experimental set up was designed. It consists of a ring of defined size held between two circular glass windows of diameter 30 cm. The system is held vertically on the axle driven by a motor. The central ring is partially filled with glass beads. The humidity is maintained constant between 50% and 60% in order to avoid problems connected with cohesion between the particles and static electricity [9]. Each experiment is recorded on a CCD digital camera at 25 fps.

We perform our study in the regime of continuous flow with a flat surface or a sigmoid surface. The variation of the flowing zone thickness in the rotating drum versus the size of the particles, the dimensions of the drum and its rotation speed w (ranging from 2 to 20 rpm) is measured. The speed is obtained using a tachometer with a precision of 0.01 rpm. Table 1 displays the different experiments performed.

The experiments are recorded with a low shuttering speed (1/3 to 1/12 s), that allows the recording of the particles trajectory. Particles move along arcs of circle of different radius in the passive zone, and flow parallel to the free surface in the active zone (see Fig. 1). All the trajectories are concentrically organized, and there is a stagnation point at the bottom of the free flowing zone. This stagnation point appears to be nonmoving on the pictures. The maximum thickness of the flowing zone h is estimated as the distance between this stagnation point and the surface of the free flowing zone. It is assumed that the trajectories of the lateral particles are little affected by the walls.

This measurement technique may seem rough or subjective. To check the reproducibility, two different experimentalists have performed the same measurements, and their results are in perfect agreement. All the points represented are obtained by averaging about 10 measurements, and the error bars correspond to an interval of confidence of 95%. This interval of confidence is a standard deviation divided by the number of measurements. Using this method, the error bars will be large if the points are scattered, also, if there is only a few measurements.

3. Results

Several combinations of rotating drum size and particles size were studied. Fig. 2 presents the thickness of the flowing zone, measured in cm, versus the rotation speed

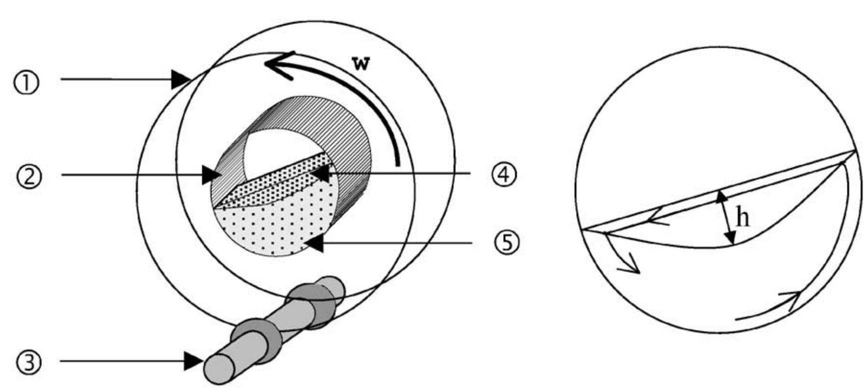

Fig. 1. Schematic view of the experimental device. ① Circular glass window of diameter 30 cm, ② central ring, ③ axle connected to the motor, ④ flowing zone, ⑤ static zone.

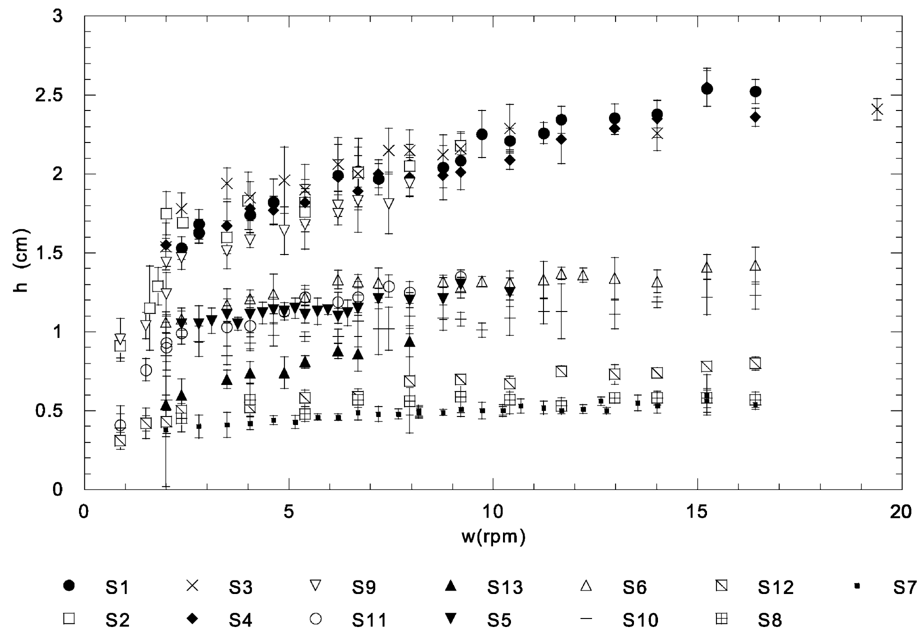

Fig. 2. Thickness of the flowing zone h versus the rotation speed w for several drum–beads couples.

of the drum for all these systems. The data are not organized in a clear way, even if tendencies might be observed: the thickness of the flowing zone increases when the angular velocity or the size of the drum increases.

The thickness of the flowing zone grows linearly with the angular speed of the rotating drum. This result has been observed by several authors [3]. The value of a 10-bead flowing zone is widely accepted. Nevertheless, if the flowing zone thickness was equal to 10 bead diameters, systems with different drum diameter but identical beads would have the same flowing zone thickness in cm. This is not the case. This shows clearly that the usual assumption that the flowing zone is equal to 10 beads layer is not correct. This result is developed Section 3.3 where data are normalized by the diameter of the particles.

The parameters that may affect the thickness of the flowing zone are:

- The size of the particles
- The size of the drum
- The thickness of the drum, i.e. the distance between the walls
- The size distribution of the particles
- The rotation speed of the drum

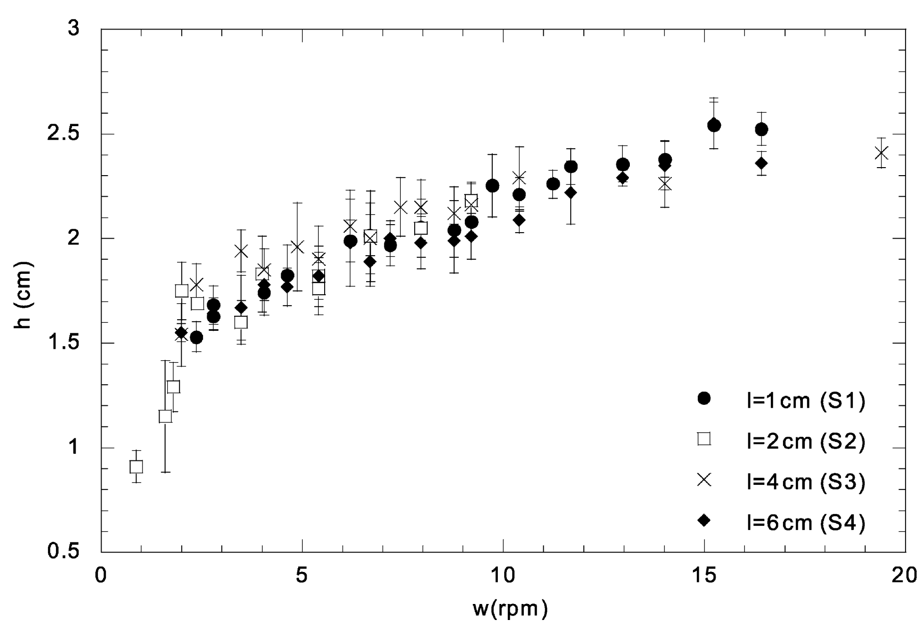

Fig. 3. Maximum thickness of the flowing zone versus distance between the lateral walls for 2-mm diameter beads in a rotating drum of diameter 20 cm.

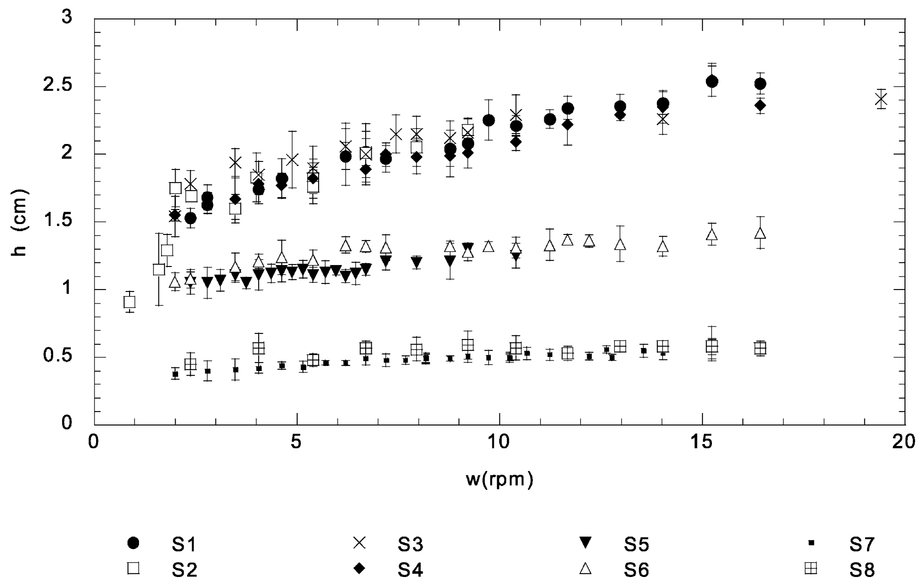

Fig. 4. Evolution of the thickness of the flowing zone (measured in cm) with the rotation speed of the drum for geometrically similar systems: $D/d = 100$.

About the size distribution of the beads, we have compared experiments performed with beads of 560 μm and beads of 500–630 μm (respectively with beads of 1.19 and 1–1.4 mm). These experiments have shown that the thickness of the flowing zone is not affected by the size distribution of the particles, while both avalanche and rest angles increase by 7° when the size distribution is large [10].

We will first focus on the effect of distance between the windows of the drum, and then on geometrically similar system, i.e. same beads diameter–drum diameter (D/d) ratio.

3.1. Effect of the lateral walls on the thickness of the flowing zone

The measurements of the thickness of the flowing zone are performed on a 20-cm diameter drum. The thickness of the drum can be changed ($l = 1$, 2, 4 and 6 cm). The drum is filled with 50% of 2-mm glass beads (Fig. 3).

It is observed in Fig. 3 that, in the range of widths tested, the thickness of the flowing zone is unaffected by the thickness l of the drum. The same thickness h is observed, even in a system of only five beads wide. To be sure to

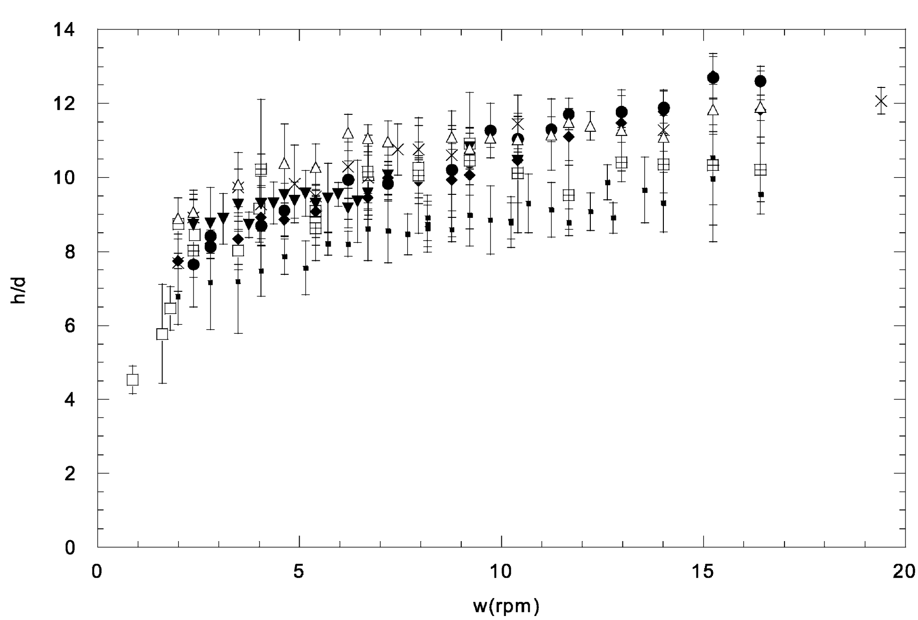

Fig. 5. Evolution of the thickness of the flowing zone normalized by the diameter of the beads (h/d) with the rotation speed of the drum. See Fig. 4 for symbols. $D/d = 100$.

avoid undesirable wall effects, we will only use systems of five or more beads wide.

3.2. Effect of the drum diameter on the thickness of the flowing zone: the geometrically similar systems

Among all experiments reported in Fig. 2, we focus on systems having a similar geometry, i.e. systems where the drum diameter is equal to 100 beads diameter. Fig. 4 presents the thickness of the flowing zone h in cm versus angular speed w for all geometrically similar system. If we normalize h with the beads diameter d (equivalent to measure h in number of beads), we see that all the points group in a master curve, suggesting that the flow in a rotating drum is geometrically similar (Fig. 5). One can also note that with a drum–beads diameter ratio of 100, the thickness of the flowing zone is about 10 beads size, but this is fortuitous.

3.3. The thickness of the flowing zone in beads diameter

With the geometrically similar systems, all the curves collapse in one master curve. Fig. 6 plots all the experiments with the thickness of the flowing zone expressed in beads diameter.

We clearly see that the curves of Fig. 2 organize with increasing value of the D/d ratio, and that the flowing zone reaches a thickness of 50 beads diameter for a size ratio of 1000. For a D/d ratio of 100, the thickness h of the flowing zone is merely unaffected by the rotation speed w, while for higher D/d ratio, h strongly depends on w. This result suggests the existence of two regimes depending on the ratio D/d: For low D/d ratio, the geometry of the system imposes the thickness of the flowing zone, and for large D/d ratio, the flow has a more "hydrodynamical" behavior. The transition between these two regimes seems to be continuous.

4. Conclusions

The study of the thickness of the flowing zone in rotating drum half filled with glass beads shows that this thickness may be very different from the commonly admitted 10 beads layer. The thickness of the flowing zone, when measured in beads diameter, increases with the D/d ratio. However, more than this, depending on the value of this D/d ratio, the thickness of the flowing zone will depend or not on the angular speed of the drum. For small D/d ratios, the geometry of the drum governs the way the system flows: the layer of flowing grains reaches a constant thickness. For large D/d ratios, the granular material flows on a thickness that is not limited by the geometry of the drum: h does not reach a constant value and continuously increases with w.

Thus, if we consider a system made of two types of beads with the same density but different sizes, for a given speed of rotation, one can expect to obtain a segregation time shorter in the case of a small D/d ratio than for a big size ratio. In that latter case, the thickness that the particle will have to cross to segregate in the flowing zone will be more

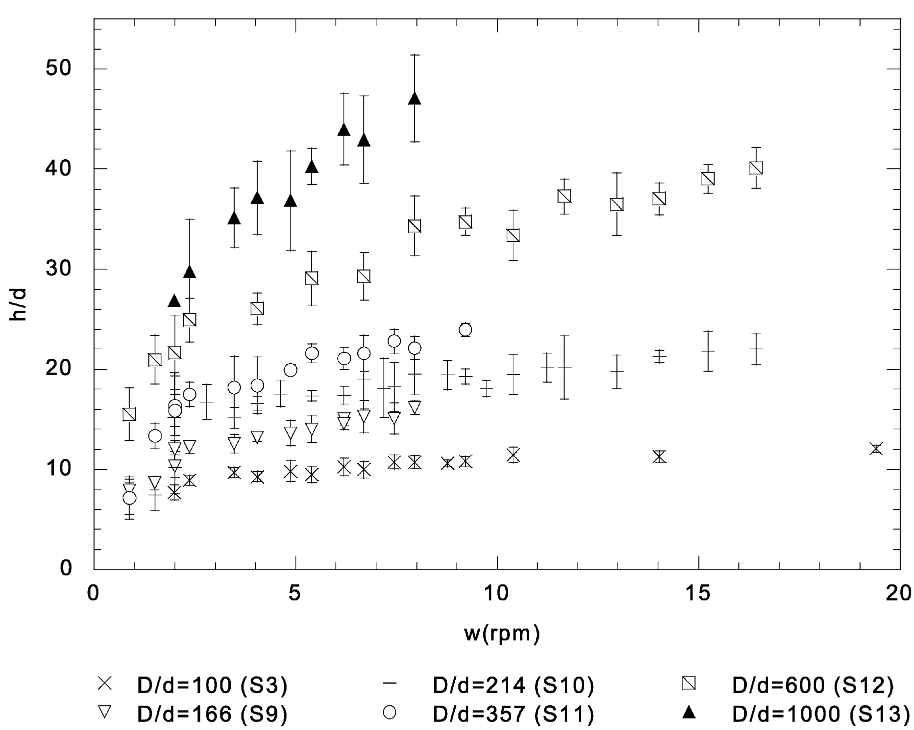

Fig. 6. Thickness of the flowing zone normalised by the diameter of the particles with D/d equal to 100, 166, 214, 357, 600 and 1000. All the experiments presented in Table 1 are not represented on the graph for clarity reasons.

important. The relation between segregation and thickness of the flowing zone in a rotating drum is now the next step of this study.

References

[1] M. Poux, P. Fayolle, J. Bertrand, D. Bridoux, J. Bousquet, Powder mixing: some practical rules applied to agitated systems, Powder Technol. 68 (1991) 213–234.
[2] M.B. Donald, B. Roseman, Mixing and demixing of solids particles: Part I. Mechanisms in a horizontal drum mixer, Br. Chem. Eng. 7 (no 10) (1962) 749–753.
[3] M. Nakagawa, S.A. Altobelli, A. Caprihan, E. Fukushima, Non invasive measurements of granular flows by magnetic resonance imaging, in: C. Thornton (Ed.), Powders and Grains, vol. 93. Balkema, Rotterdam, 1993.
[4] D.V. Khakhar, J.J. McCarthy, T. Shinbrot, J.M. Ottino, Transverse flow and mixing of granular materials in a rotating cylinder, Phys. Fluids 9 (1) (1997) 31–43.
[5] A.A. Boateng, P.V. Barr, Granular flow behaviour in the transverse plane of a partially filled cylinder, J. Fluid Mech. 330 (1997) 233–249.
[6] D.V. Khakhar, J.J. McCarthy, J.M. Ottino, Radial segregation of granular mixtures in rotating cylinders, Phys. Fluids 9 (12) (1997) 3600–3611.
[7] T. Shinbrot, A. Alexander, F.J. Muzzio, Spontaneous chaotic granular mixing, Lett. Nat. 397 (1999) 675–678.
[8] J. Rajchenbach, Continuous flow and avalanche of grains, in: H. Herrmann (Ed.), Physics of Dry Granular Matter, Kluwer Academic Publishing, Dordrecht, 1998, pp. 1–19.
[9] N. Fraysse, Humidity effects on the stability of a sandpile, Eur. Phys. J., B 11 (1999) 615–619.
[10] G. Félix, V. Falk, U. D'Ortona, in: Y. Kishino (Ed.), Proceedings of Powder and Grains 2001, Balkema, Sendai, 2001, pp. 475–478.