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PARTICLE SEGREGATION IN BIDISPERSE NARROW BEDS FLUIDIZED AT DIFFERENT INCLINATIONS

Henrique Barbosa de Oliveira

Erick de Moraes Franklin

School of Mechanical Engineering, UNICAMP - University of Campinas, R. Mendeleyev, 200, Campinas-SP, Brazil

h217733@dac.unicamp.br

franklin@fem.unicamp.br

Fluidization is the suspension of solid particles by an upward fluid flow. Very-narrow fluidized beds are characterized by a close ratio between grain and duct diameters (less than 10) and are a new technology of increasing interest that can be used in chemical reactors and pharmaceutical processes. Over the last decade, most of the studies on very-narrow beds considered only vertically aligned beds, but introducing an inclination with respect to the gravity direction leads to interesting new behaviors, especially when using two types of grains (which better models real beds that are actually polydisperse). In this work, we investigate experimentally the growth of granular structures (such as granular plugs) and the motion of individual particles for very-narrow beds at various inclinations. In our experiments, the bed is filmed with a high speed camera and the images are processed to measure mean and fluctuation of grain velocities in both monodisperse and bidisperse beds, and we investigate how mixing and segregation of different species occur depending on the bed inclination and imposed flow. We observe differences in the segregation of solids for the angles tested because the layers of materials tend to align with the gravity direction, the two limits being fluidized beds in the vertical position and horizontal channels transporting grains; therefore, intermediate angles are expected to present a combination of the vertical and horizontal behaviors, leading to some degree of mixing. This is a relevant research area, as there is a great interest in understanding the mixing and segregation of polydisperse granular matter.

Keywords: *very-narrow fluidized beds, segregation, bidisperse beds, granular matter*

1. INTRODUCTION

Fluidization is the suspension of particles by a fluid (gas or liquid) flowing upwards, in which the grains weight is in balance with the drag. This phenomenon is characterized by the solids behaving, up to a certain degree, similarly to a fluid, which improves heat and mass exchange, disseminating the use of fluidized beds in many processes (Kunii and Levenspiel, 1991). That, in general, happens in large dimension beds, though recently there are new developments which require smaller equipments.

The study of small fluidized beds has advanced in the last few years specially for the applications not suited to regular beds. Such as the use in the research of burning efficiency of solid biofuels, with better control over the combustion parameters (Guo *et al.*, 2009), coating of solids in pharmaceutical and food industries, carbon capture with greater efficiency (Zhang *et al.*, 2021) and micro chemical reactors (Suryawanshi *et al.*, 2018). However, the smaller size and higher confinement of particles in the case of narrow beds lead to unusual behaviors compared to regular beds, which should be studied to improve their applications (Guo *et al.*, 2009). Another factor changing the behavior of fluidized beds is the presence of more than one type of particles, which leads to new behaviors that depend on initial condition, such as layer inversion or mixture of the solids (Cúñez and Franklin, 2020).

Most fluidized beds are vertically aligned, but an inclination relative to the gravity direction modifies the fluidization regime. Chaikittisilp *et al.* (2006) observed the circulation of the solids in the bed using Discrete element method (DEM) simulations. The formation of an air channel in the superior part of the tube and the particles remaining in a fixed condition is also described (O'Dea *et al.*, 1990; Li *et al.*, 2017) as the bed approach the horizontal position with the same flow velocity. Other notable effects are the reduction in the pressure drop (Li *et al.*, 2017) across the bed and reduction of the bed expansion (Del Pozo *et al.*, 1992) when compared to a vertical bed in the same operation regime. These studies performed experimental analyses and numerical simulations, a common approach in the field.

In this paper, we report experiments on bidisperse beds with different angles from the vertical positions. The mixing of the two types of particles was observed in some conditions and the mechanism for this behavior is explained.

2. METHODOLOGY

2.1 Experimental setup

The experiments were performed in an apparatus consisting of a narrow gas fluidized bed with inner diameter (D) of 3 mm that can pivot and be locked in pre-defined inclinations, as seen in Fig. 1. The beds were filmed with a high-speed camera to observe the individual motion of particles and the instabilities across the bed. Each experiment was initialized with the tube in the vertical position and the particles in a fluidized condition until steady separated layers were observed, after which the flow was stopped and the bed put in the desired configuration. We then reestablished the flow, and filmed the experiment for 30 s. To get a better understanding of bidisperse narrow gas fluidized beds, we changed the following parameters in the different cases:

1. Particles's material: glass ($\rho = 2500 \text{ kg}^3 \text{ m}^{-1}$) and zirconia ($\rho = 4100 \text{ kg}^3 \text{ m}^{-1}$) spheres with diameter of 0.5 mm;
2. Total particle's mass: 0.3 g to 1.2 g;
3. Flow entry velocity (U_e): 1.57 m s^{-1} to 2.16 m s^{-1} ;
4. Bed inclination: 0° to 60° .

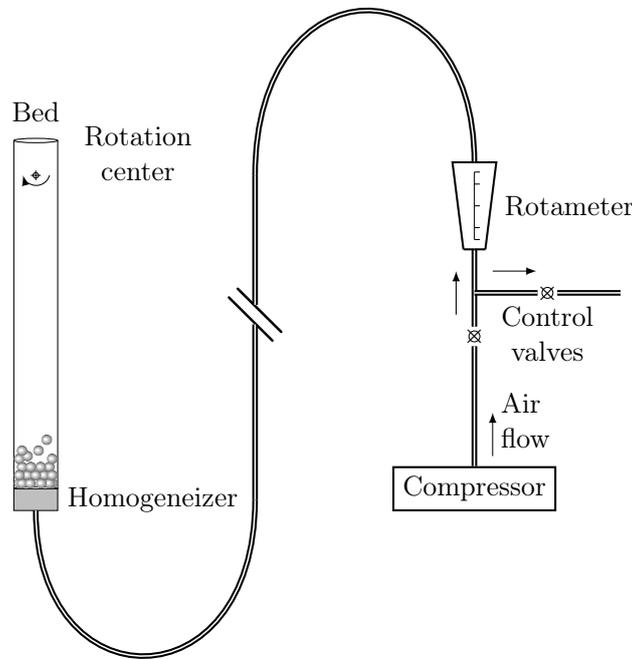


Figure 1. Experimental setup

The specific parameters used in monodisperse and bidisperse beds are listed in Tabs. 1 and 2, respectively. All experiments were performed with ambient temperature between 21°C and 23°C and relative humidity between 46% and 77%. The incipient fluidization velocity (U_{if}) was measured as the minimum velocity required to observe movement in the particles, this parameter is used to approximate the condition of minimum fluidization condition as a direct measure of the bed pressure drop was not possible.

The high-speed camera used to film the experiments has a sensor of complementary metal-oxide-semiconductor (CMOS) of size $2560 \text{ px} \times 1600 \text{ px}$, but in the recording a region of interest (ROI) of size $2560 \text{ px} \times 120 \text{ px}$ was used at 1000 Hz. The experiments were filmed with a lens of focal distance of 60 mm and aperture F2.8, the distance to the tube was changed to find the best field of view (FOV) for each run maximizing the number of pixels per particle diameter.

2.2 Image processing

The images were processed with a threshold filter to select bright pixels (particles in the image) and dark pixels (background). The bed height (H) was measured as the largest vertical position of a bright pixel in the tube, in the same

Table 1. Parameter variations in monodisperse beds

Material	Particle's mass [g]	Flow entry velocity (U_e/U_{if})	Inclination angle (φ) [deg]	Incipient fluidization velocity (U_{if}) [m/s]
Glass	0.3	2.5, 2.8, 3.1		0.63
	0.5	2.5, 2.8	0, 15, 30, 45, 60	0.63
	0.7	2.5, 2.8		0.63
Zirconia	0.9	1.2, 1.4		1.57
	1.2	1.0	0, 15, 30, 45, 60	1.73

Table 2. Parameter variations in bidisperse beds

Glass particle's mass [g]	Zirconia particle's mass [g]	Flow entry velocity (U_e/U_{if})	Inclination angle (φ) [deg]	Incipient fluidization velocity (U_{if}) [m/s]
0.2	0.4	2.5, 2.8, 3.1		0.63
	0.5	2.5, 2.8, 3.1	0, 15, 30, 45, 60	0.63
	0.7	2.0, 2.3		0.78
0.3	0.4	2.2, 2.5, 2.8		0.71
	0.5	2.0, 2.3	0, 15, 30, 45, 60	0.78
	0.7	2.0, 2.3		0.78

way, the scale of the images was determined comparing the width of the bed in pixels and the know inner diameter of the tube.

Individual grains were identified using a search for local maxima in the image and then filtered by size to eliminate false positives, the motion was determined minimizing the total distance traveled by the particles between consecutive frames using an Auction algorithm (Bertsekas, 1992) and a Kalman filter to compensate for frames when a particle was not identified. This tracking allowed the calculation of the particle velocities, an important quantity to understand the dynamics of fluidization.

When both types of solids were present in the bed, the identification was done by the average brightness of each particle, as the zirconia spheres appeared brighter than the glass ones in the pictures. The processing was done, and the relevant measurements stored to posterior analyze extracting the relevant parameters as explained in the next section.

2.3 Measurements of interest

The granular temperature (θ) is a measure of the agitation of particles, defined in Eq. 1, where $v_{k,i}$ is the k velocity component of the i particle and N is the total number of particles. To better capture the dynamic of the bed, it was divided in regions where the granular temperature was computed using an ensemble average (Eq. 1). This allowed to better represent the fluidization instabilities through the bed.

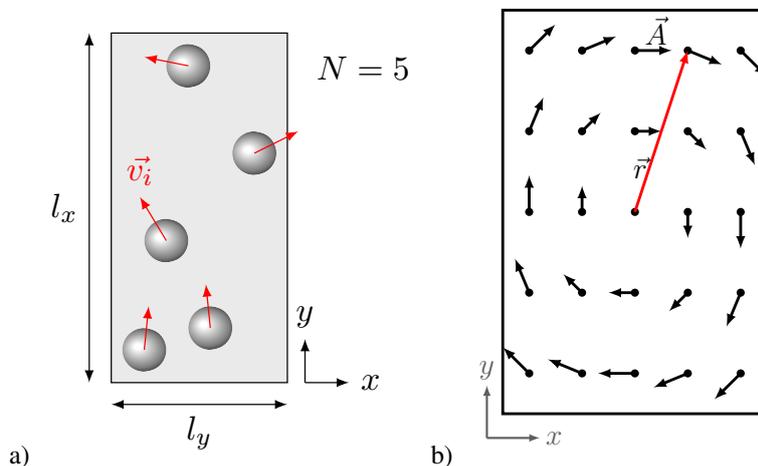


Figure 2. Area flux and granular temperature calculation (a) and bed moment diagram (b).

$$\theta = \frac{1}{N} \sum_{i=1}^N [v_{ki}^2 - \langle v_k \rangle^2], \quad \langle v_k \rangle = \frac{1}{N} \sum_{i=1}^N v_{ki}, \quad \text{with } k = x, y \quad (1)$$

A good measure to visualize circulation in fluidized beds is the volumetric flux of particles (Jiang *et al.*, 2018), it accounts for the flux of solids in terms of volume, calculated in cells through the bed with each particle's velocity. In this work, only the front of the tube is visible, therefore a modification is proposed to consider the flux in terms of area (\mathbf{A}), which represents better the available data from the experiment. In each grid cell the area flux was calculated as the sum of the particle's area multiplied by its velocity divided by the cell's side (l_k) perpendicular to each velocity component k as presented in Eq. 2. Figure 2 shows a cell model, in which the variation of velocities is related with θ and the mean velocity to \mathbf{A} .

$$A_k = \frac{1}{l_k} \sum_{i=1}^N [v_{ki} \pi r_i^2], \quad \text{with } k = x, y \quad (2)$$

Another measure to represent the circulation of solids in the fluidized bed is the moment of the bed (L), calculated as the cross product of the flux (\mathbf{A}) and the distance measured from the center of rotation (\mathbf{r}) show in Fig. 2, the formula is presented in Eq. 3.

$$L = \sum_{i=1}^N [\vec{r} \times \vec{A}] \cdot \hat{e}_z \quad (3)$$

To accurately represent the mixing of different particle types, the following mixing layer calculation was devised. A region was traced to surround every particle of the corresponding type, this frontier can be concave, but no internal angle can be larger than 270° to avoid jagged delimitations, as seen in the case (a) of figure 3. Particles of a different type inside the region are counted, case (b) of figure 3, and considered part of the mixing layer. The ratio between the number of particles in the mixing layer and the total number of particles visible is used to evaluate the mixing (M) of the bidisperse bed in Eq. 4.

$$M = \frac{P_{21} + P_{12}}{P_1 + P_2} \quad (4)$$

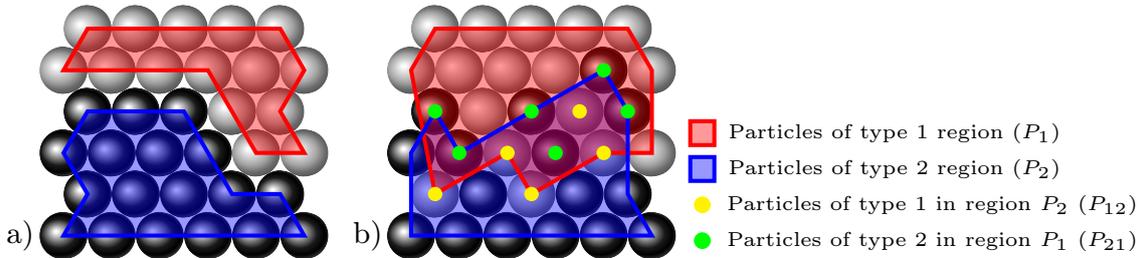


Figure 3. Measurement of particle mixing layer

3. RESULTS AND DISCUSSION

3.1 Experimental results

The snapshots of the experiment with monodisperse and bidisperse beds are presented in Figs. 4 and 5 respectively, it is possible to observe the mixing of the layers in the inclined bidisperse beds, which is an interesting result of a different behavior from monodisperse beds and vertical bidisperse beds. By observing the series of selected frames, one can visualize the evolution of the system and understand the motivation behind the parameters presented in the previous section as tools to look for underlying dynamics in the inclined narrow fluidized beds.

It can be seen in Figs. 4 and 5 that the narrow fluidized beds reach a regime where the instabilities saturate and the measured characteristics converge statistically, this was verified in every experiment. This behavior justifies using the mean values and standard deviation to represent the experimental results and look for patterns in the analyzed quantities, as presented more in depth in this section.

The measure of the bed height shows that the expansion reduces with the increase of the inclination angle until a certain angle, after this in some cases a non monotonically decreasing height is observed until the condition of a fixed bed is reached, as seen in Fig. 6. This agrees with the observations reported by Del Pozo *et al.* (1992) for the small angles

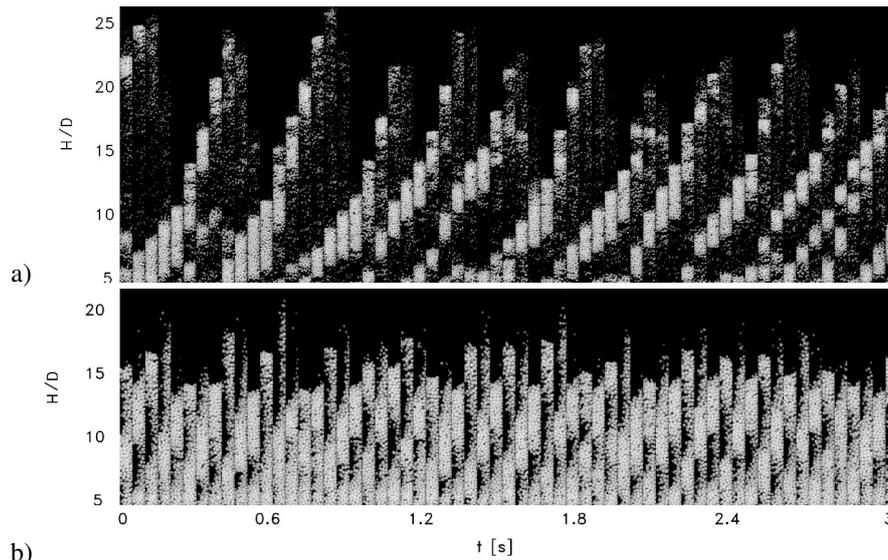


Figure 4. Snapshots of a monodisperse fluidized bed with glass particles, $m = 0.3$ g, $U_e = 2.8U_i$ and $\theta =$ (a) 0° , (b) 30° with a time interval of 50 ms between the photos.

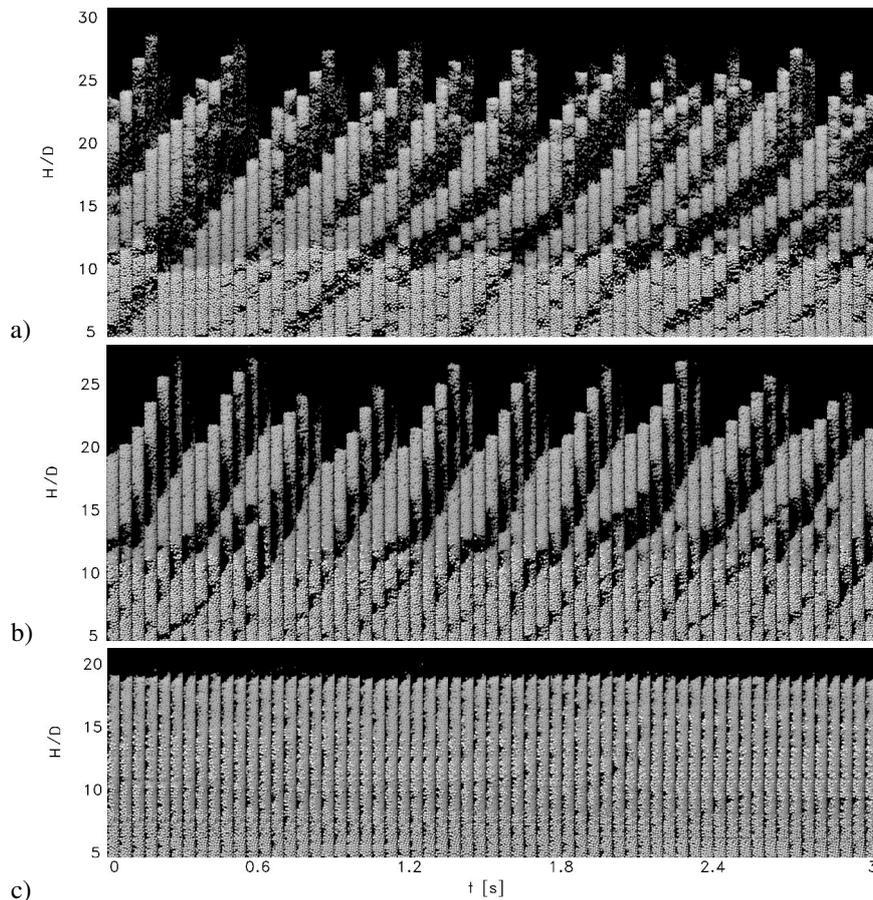


Figure 5. Snapshots of a bidisperse fluidized bed with $m_{glass} = 0.3$ g, $m_{zirc} = 0.5$ g, $U_e = 2.8U_i$ and $\theta =$ (a) 0° , (b) 15° , (c) 30° with a time interval of 50 ms

tested in the study. With the bidisperse beds tested, Fig. 7 shows a similar behavior, but fewer cases present monotonically decreasing bed height.

In both graphics of height per angle of inclination (Figs. 6 and 7) relatively high uncertainties are present when the bed presents instabilities in the form of plugs that lead to great oscillations in the bed expansion. Therefore, the cases with fixed beds can be identified by the small uncertainty in the graphic. The analysis of the bed expansion shows that the mass of particles is more relevant than the fluid velocity to determine the position of the observed local maximum,

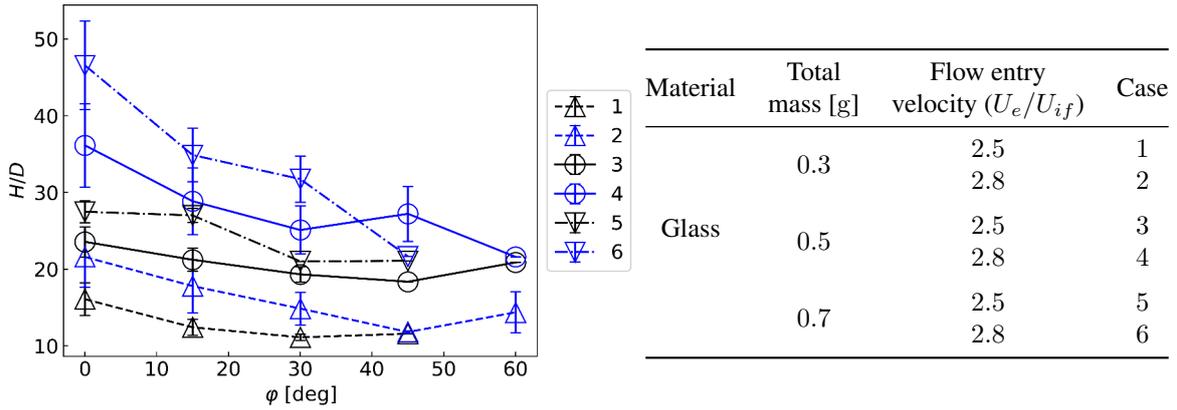


Figure 6. Average bed height with glass particles of the monodisperse case.

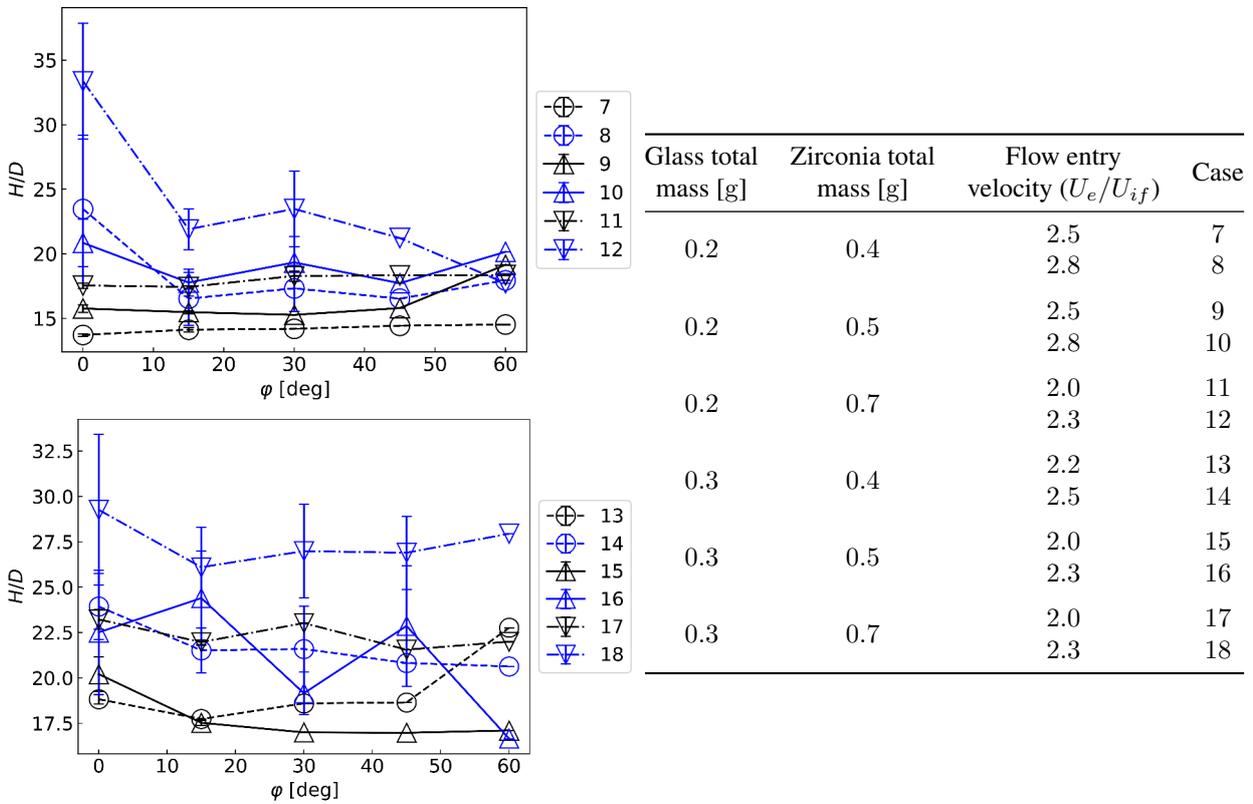


Figure 7. Average bed height of the bidisperse case.

the explanation to this phenomenon is still unknown, and will be investigated with numerical simulations. A possible mechanism may be related with the circulation of particles and the air channel explained ahead.

The experiments indicate that the inclination of the fluidized bed promotes the circulation of the particles while fluidization is undergoing, Fig 8, in agreement with the reported by Chaikittisilp *et al.* (2006) for regular beds. It is important to notice that the bed expands to open a channel above the particles and then behaves as a fixed bed with higher inclination angles (above 45° with the lower fluid velocity and 60° with the higher velocity). In such cases with a fixed bed, a few particles moving can cause great impact on averages, that causes a few larger arrows that do not represent the observed movement.

Figure 9 shows the formation of an air channel in the 60° case, as there is no particle circulation, only the movement of solids on top of the bed before an equilibrium state is reached with a fixed bed condition.

It is also possible to observe a faster movement at the top of the bed, where the packing fraction is lower. The circulation of solids is also present in bidisperse and is one mechanism that leads to the mixing of the layers of each particle type in inclined beds, as shown in Fig. 9. The presented case can explain why some studied cases do not present mixing of layers, since the circulation is present only on the top part of the bed, different from the monodisperse bed. If

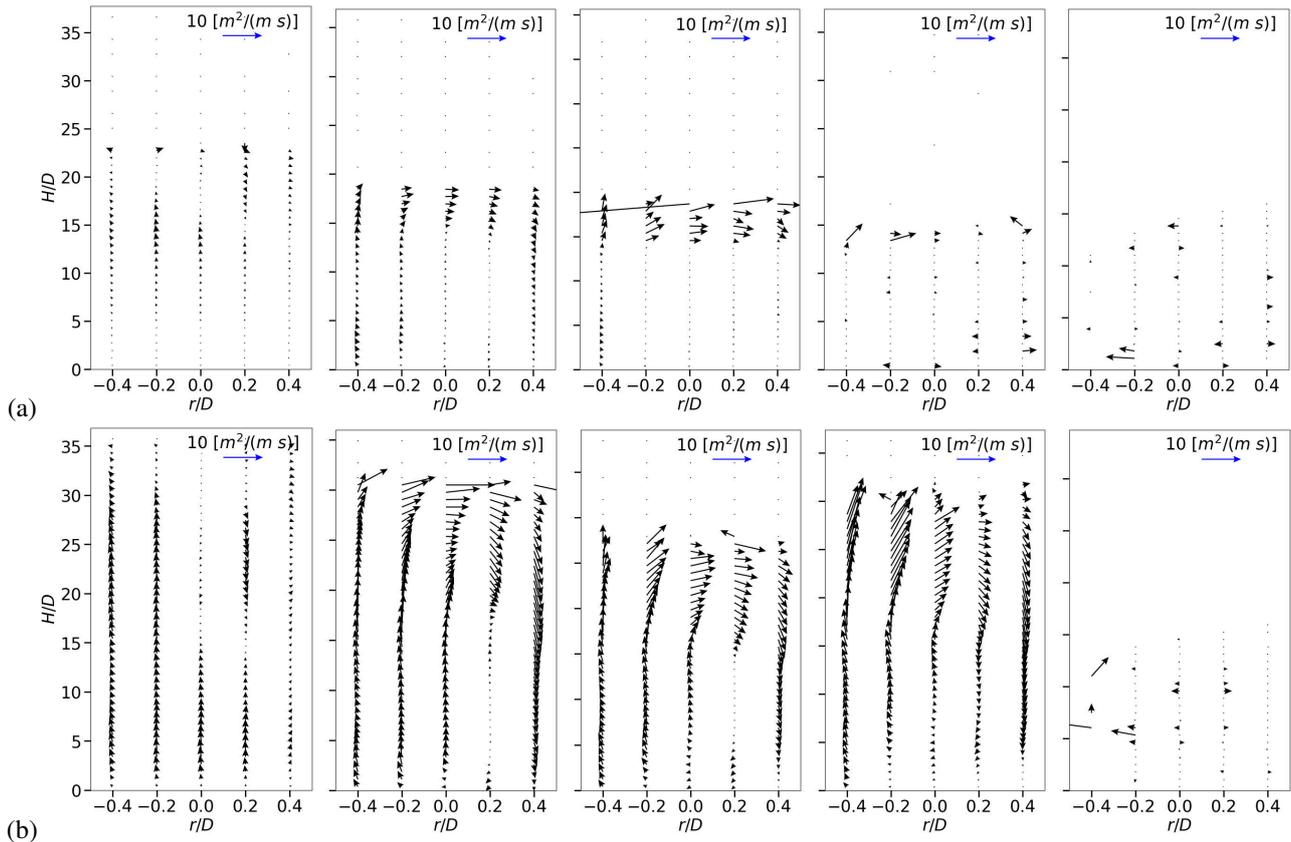


Figure 8. Averaged area flux of the 0.5 g glass bed with entry velocity of (a) 1.57 m s^{-1} and (b) 1.77 m s^{-1} with inclination angles of 0° , 15° , 30° , 45° and 60° .

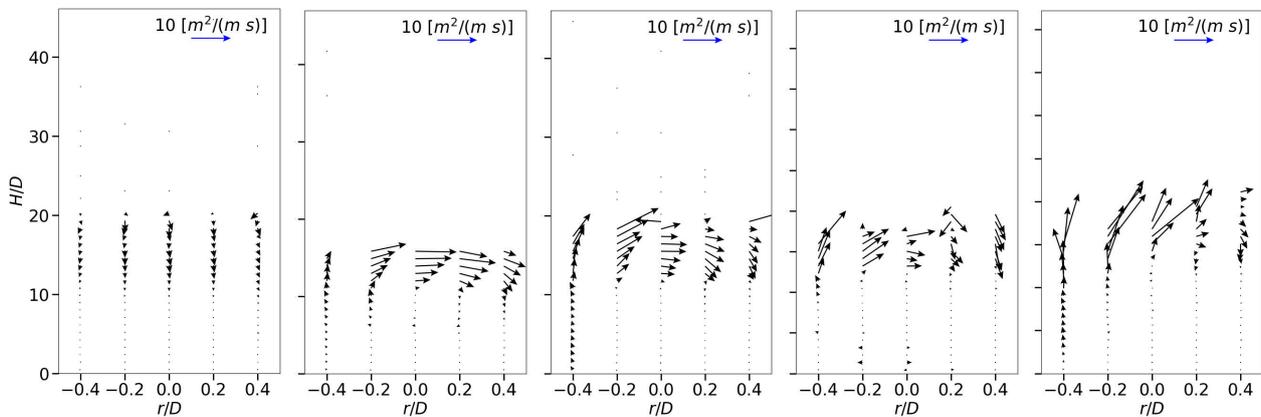


Figure 9. Averaged area flux of a bidisperse bed with 0.3 g of glass beads and 0.5 g of zirconia beads, entry velocity of 1.77 m s^{-1} and with inclination angles of 0° , 15° , 30° , 45° and 60° .

the circulation zone lies entirely in the top layer it does not contribute to the mixing.

Another useful parameter to observe circulation is the moment of the bed (L), presented in Fig. 10 which reflects the same discussions of the vector plot, but capture more studied cases. The measure is presented dimensionless, using relevant parameters previously presented and chosen to represent a scale of distance (H - bed expansion) and velocity (U_e - flow entry velocity).

The last measure to be presented is the mixing layer (Fig. 11). It is possible to see a pattern similar to the bed moment. The well documented segregation of particles in the vertical case is represented by the lack of a mixing layer, similarly the inclination of 60° leads to a fixed bed and no mixing of the particles.

A comparison of the bed moment measure (L) and the mixing layer size relative to the bed volume (M) presented in Fig. 12 shows a direct relation. The absence of points in the upper right corner indicates that there is no mixing without circulation of solids. Though there are points near the x-axis away from the right corner, from cases where circulation is present without mixing, this can be justified from circulation restricted to a single layer that does not promote mixing

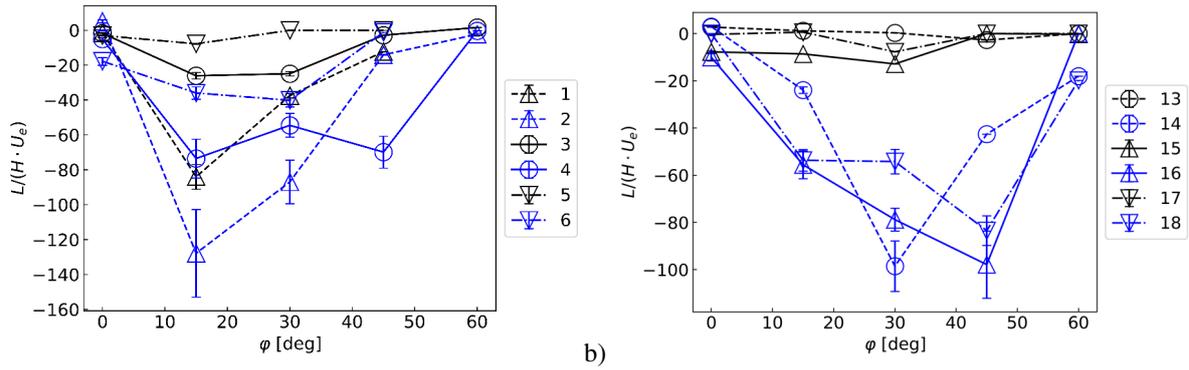


Figure 10. Bed moment (L) for the monodisperse glass case (a) and the bidisperse cases with 0.3 g of glass particles (b) in the inclinations tested.

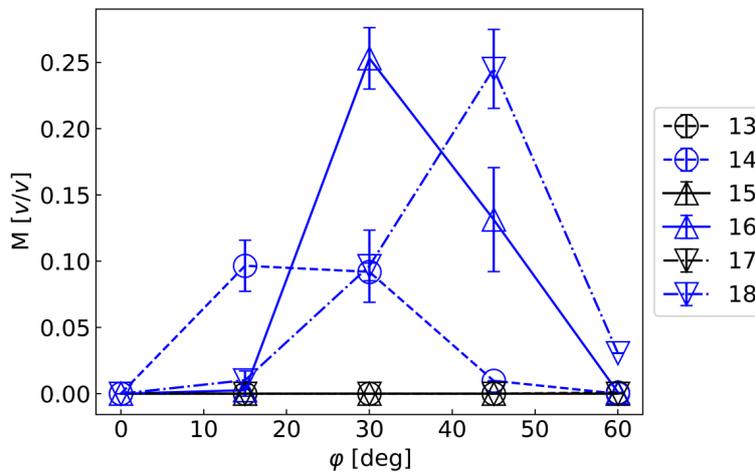


Figure 11. Mixing layer size (M) in the inclinations tested for the bidisperse cases with 0.3 g of glass particles

of the particles. An interesting result in the mixing layer is that a complete mixed bed was not obtained, in fact most experiments were far from this state when a permanent regime was observed. The cause of the saturation of the mixing layer was not directly identified, but may be related to an equilibrium of the circulation promoting mixing and the gravity promoting segregation by density. This equilibrium is also an indicative of out-of-plane motion, that contributes to the agitation of the particles and segregation.

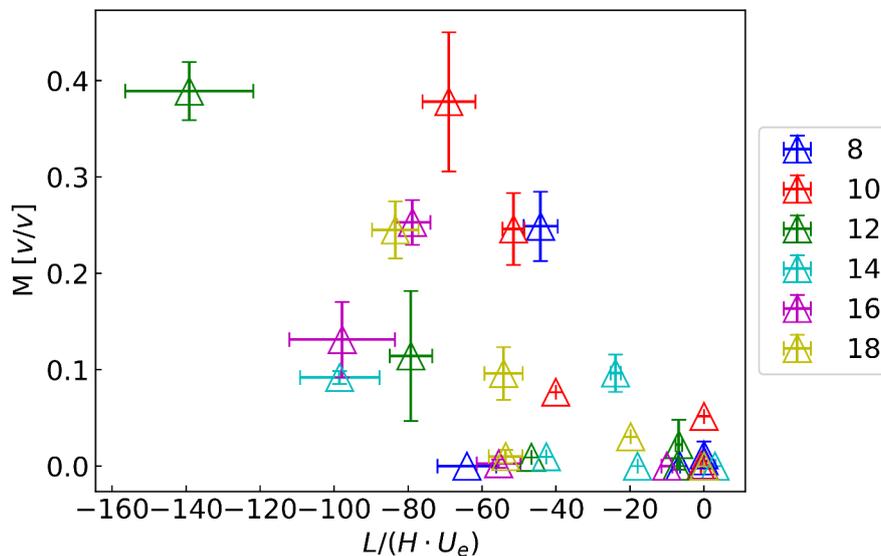


Figure 12. Relation between bed moment (L) and mixing layer (M).

In summary, experiments were performed in bidisperse narrow fluidized beds that showed mixing of solids in tests with the bed inclined in relation to the vertical. Furthermore, the circulation of solids in the bed is shown to be related to the formation of a mixing layer and can be used to explain the new behavior when compared to vertical narrow fluidized beds.

4. CONCLUSIONS

The performed experiments and analyses show that the circulation of particles is present in inclined bidisperse narrow fluidized beds, which promotes the mixing of the layers of solid types seen in the vertical bed. Furthermore, part of the behavior of inclined regular fluidized beds is still present in narrow fluidized beds, as indicated by the formation of an air channel, circulation of particles and reduction of bed height.

More studies are necessary to identify the main mechanisms that promote circulation of solids in the bidisperse beds and identify the cause for a saturation in the mixing. This will be addressed with numerical simulations to access the particles in the interior of the bed and more measurements to better understand the phenomenon.

5. ACKNOWLEDGEMENTS

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