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PARTICLE SEGREGATION IN TAPERED FLUIDIZED BEDS

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ABSTRACT

In practical situations, a bed of particles often has a wide range of sizes or is a mixture of differently sized components, and this allows a number of different segregation structures to form depending on local flow conditions. These vary systematically in tapered beds. This paper is an experimental investigation of the interaction between size segregation and the effects on local flows in a tapered bed.

INTRODUCTION

Tapered fluidized beds are used for a wide range of processes where it is desirable for there to be a reduction in gas speed with height in the bed so that slugging, limitations in operating gas flows, and non-uniform fluidization can be reduced (1). It is also believed that the angled walls improve particle mixing (2). Recent work, motivated by understanding the emplacement of minerals, has shown that tapered beds are heterogeneous, but form regular and robust structures where particles in one region behave very differently from particles in another (3,4) and the state of different regions within the bed varies from defluidized to vigorously bubbling.

Structure is important in bubbling fluidized beds and much of the work them has been confined to relatively simple systems with mono-sized particles and straight-sided beds, which can be treated as largely homogenous systems through which bubbles pass. It is not only the shape of the bed that generates structure within a bed: when mixtures of particles of different sizes are introduced into a fluidized bed, the different components segregate and form structures that run vertically or horizontally (5).

This work is an experimental study that describes the interaction between two methods for introducing non-uniformity into the fluidized bed: the ibehaviour of a mixture of particles and the use of a tapered bed. The non-uniform nature of the bed is demonstrated, as well as the linked nature of particle arrangement and gas flow. It is also shown that one of the effects of a multi-sized particle distribution is to change the structure of a tapered bed and hence its performance.

Tapered Fluidized Beds

Bed behaviour is largely determined by the bubbling within them. Because the bubbles interact and coalesce, they collect towards the centreline of a bed as they coalesce (6, 7, 8). The bubbles induce particle motion up the bed so that they move up the centre of the bed where the bubbling is most vigorous, and return along the margins, giving rise to ``gulf streaming'' (9).

In a tapered bed, there are two significant changes. First, the walls do not affect the bubbling pattern, so parts of the bed become ever more remote from the central bubbling region through which the gas flow is channelled. Secondly, the mean gas flow speed drops with distance up the bed from the distributor. These effects generate a heterogeneous bed structure where on either side of the fluidized region there is a non-fluidized region where there is no bubbling (3). Here, the particles are static relative to one another, and are arranged in dipping laminar layers, similar to those formed when mixtures of particles are poured onto a solid surface (3). These non-fluidized regions exist even at high gas flow rates (4). The central fluidized region has a waisted (hyperboloid) shape moving inwards above the distributor and then flaring out towards the top of the bed where the bubbles burst.

Segregation in a Straight-Sided Bed

When a mixture of particles is fluidized then the structure of the bed changes markedly according to the gas velocity through it. The particles can be differentiated by density or by size. The classic segregated structure is horizontal segregation where two regions form in the bed: a top layer (flotsam) formed from a mixture of the lighter or smaller particles and some of the larger particles, and a lower layer (jetsam) dominated by the heavier or larger particles. At lower gas flow rates it is also possible to form vertical chimneys of coarse particles (5). Which structures form depends on the speed of the gas flow relative to the minimum fluidisation velocities for each of the components, and that of the mixture, which is significantly lower (5). These different structures can have important consequences for the behaviour of the bed as the change in structure not only changes the pattern of gas flow through the bed, but also the manner in which the particles respond to the gas flow.

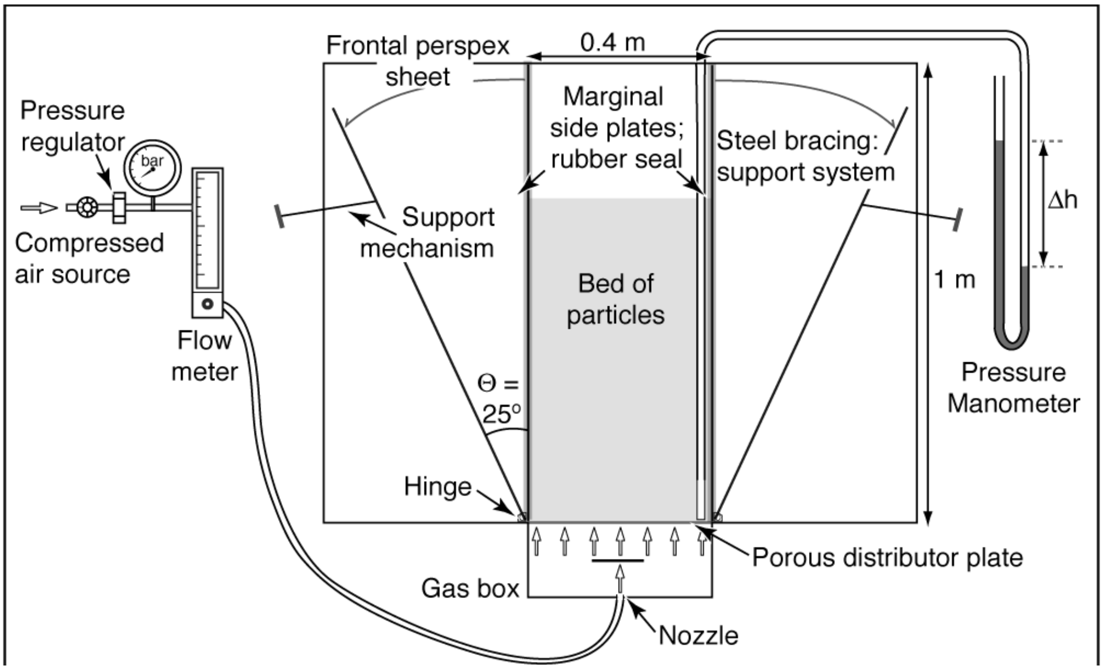

Figure 1. Schematic diagram of the experimental apparatus

EXPERIMENTAL ARRANGEMENT

The experimental apparatus is illustrated schematically in Figure 1. The tank was planar in shape with a rectangular cross-section and constructed from 15 mm-thick Perspex and PVC. It measured 1.4 m in breadth, 1.0 m in height, and 0.04 m in width. A wind box measuring 0.4 m across was attached to the base of the tank and supplied with pressurised air via a regulator and rotameter. The gas was introduced to the bed via a 10 mm-thick porous sintered plastic distributor (Porvair Vyon D). Two marginal rigid plates were hinged at the base of the tank, so that the angle of taper θ) could be changed. The tank was externally clamped by steel bracing to maintain a constant separation.

The particles used in the experiments were glass beads (Ballotini) with an average sphericity of 80%. Spherical particles were chosen since their behaviour is well established (10, 11, 12). The particles had a grain size range of 45-90 µm and a density of 1492 kg/m^3 and belonged to group A of the Geldart classification (13). Coarser group B particles had a grain size range of 106-212 µm and a density of 1467 kg/m kg/m^3. The group B particles had a sufficiently narrow size distribution that they could be considered to have a single grain size characterised by a mean particle diameter (14). The minimum gas flow rate for fluidisation, Q_{mf}, varies with conditions, but corresponds roughly to 20l/min for the bed used.

The tank was filled with a weighed amount of particles to a minimum packed bed height of 0.1m. This procedure was repeated at intervals of 0.1m until a maximum height of 0.6m was achieved. Experiments were performed at three taper angles: 0^o, 15^o, and 25^o. Before undertaking experiments, beds were strongly bubbled for several minutes, to reduce cohesion between particles, and produce a homogeneous bed. All experiments were recorded by a digital video camera. For each experiment, the extent of non-fluidized regions with bed height was delineated and marked on the front Perspex panel. Images of the boundary between fluidized and non-fluidized regions at increasing Q were digitised in Adobe Illustrator, and the area of the non-fluidized regions determined through the use of image analysis software program, ImageJ (US NIH, 2006).

RESULTS

Segregation patterns

It is thought that the segregation behaviour in bubbling fluidized beds is determined by the local flow rate in the bed (5). It then follows that the types of segregation in the tapered bed would be expected to be the same as in a straight-sided bed. This was borne out in the experiments as shown in the phase diagram in Figure 2: at low flow rates, the bed is static; above the mixture U_{mf} then vertical segregation takes place; at higher gas flow rates, horizontal segregation takes place; when the gas flow rate is large enough, the bed is well mixed.

Though the classification of segregation structures is broadly the same as for the straight-sided bed, there are some distinct features for the tapered bed which reflect its heterogeneous character. First, there is the presence of region IV, shown in Figure 3, intermediate between a purely horizontal segregation pattern and a well mixed bed. In region IV, there is still a layer of coarse particles on the base of the bed, the thickness of which decreases with increasing flow rate; however, it also forms a near-vertical layer along the edge of the aerated regions at either edge of the bed. As shown in the figure, the growth of these near-vertical regions is slow and can take several minutes. Adjacent to these regions, vertical segregation takes place in the non-fluidized regions at the edge of the bed. The size of the near-vertical regions is increases with angle of taper.

A further difference between the phase diagram for segregation in the tapered bed compared with that in a straight-sided bed is that all dependence on gas flow rate has been eliminated, notably for the transition between vertical segregation (region II) and horizontal segregation (region III). Furthermore, the gas flow rate at which the bed becomes well mixed is increased by 25% (roughly the width of region IV in Figure 2).

No path dependence could be found in the development of segregated regions. For example, both the final state and the transient development of the horizontal structures were found to be the same irrespective of whether the flow rate was increased from zero or decreased from a high flow rate for which the bed was well mixed. When decreasing the gas flow rate in stages from a high flow rate to one sufficiently low for vertical segregation to take place, this was observed, as expected; however, the horizontal segregation generated at the intermediate flow rates was preserved.

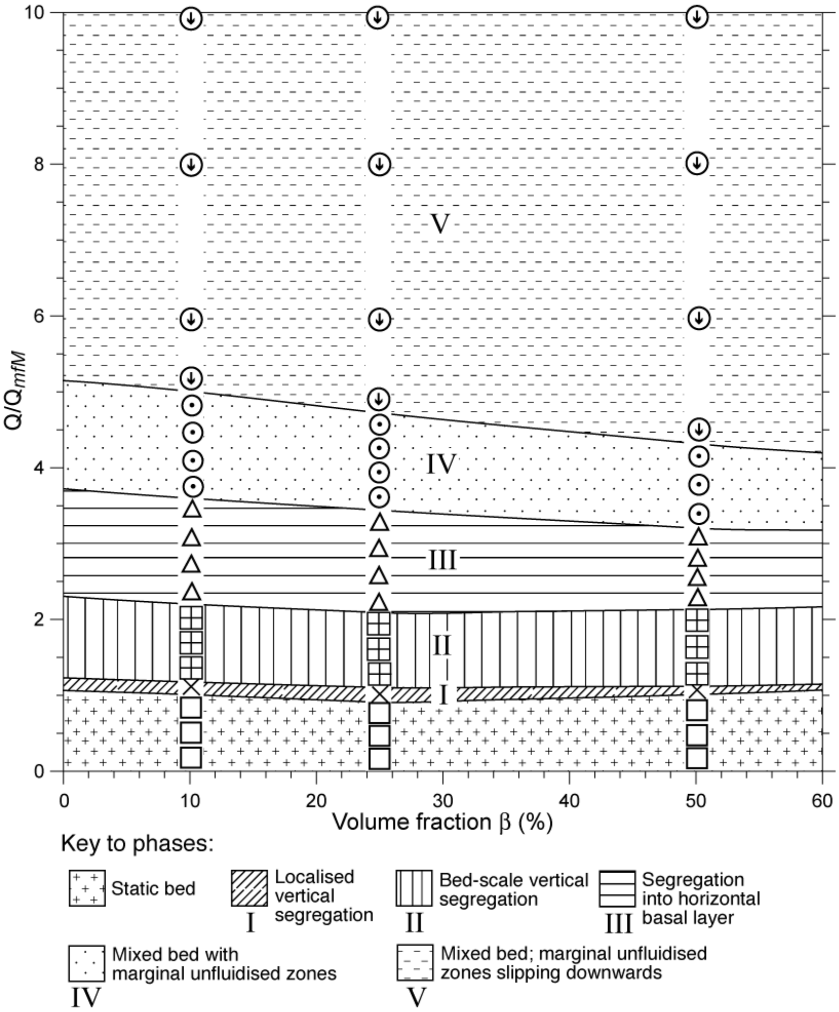

Figure 2: Phase diagram for segregation in a tapered fluidized bed.

THE EFFECT OF PARTICLE MIXTURES ON THE STRUCTURE OF A TAPERED FLUIDIZED BED

In a fluidized bed of mono-sized particles, then a waisted central region forms containing the bubbles and there are two non-fluidized wedges of particles either side of the bed. This structure reflects the flow pattern of the gas through the bed, which can be observed through the pattern of the particle motion generated by it, with strong central channelling at the expense of gas flow through the extremities. When the gas flow rate is at least large enough for there to be horizontal segregation, then the same pattern as for a monosized set of particles is obtained.

This is true quantitatively as well as qualitatively. For example, as the gas flow rate is increased, the size of fluidized region increases, and the angle of the interface between it and the surrounding particles (the white dashed line shown in Figure 3) decreases from around 100 degrees to the horizontal close to the minimum point of fluidisation to around 75 degrees for a strongly fluidized bed (seven times Q_{mf}). For a given flow rate, this angle is the same irrespective of the proportion of fine particles contained in the mixture.

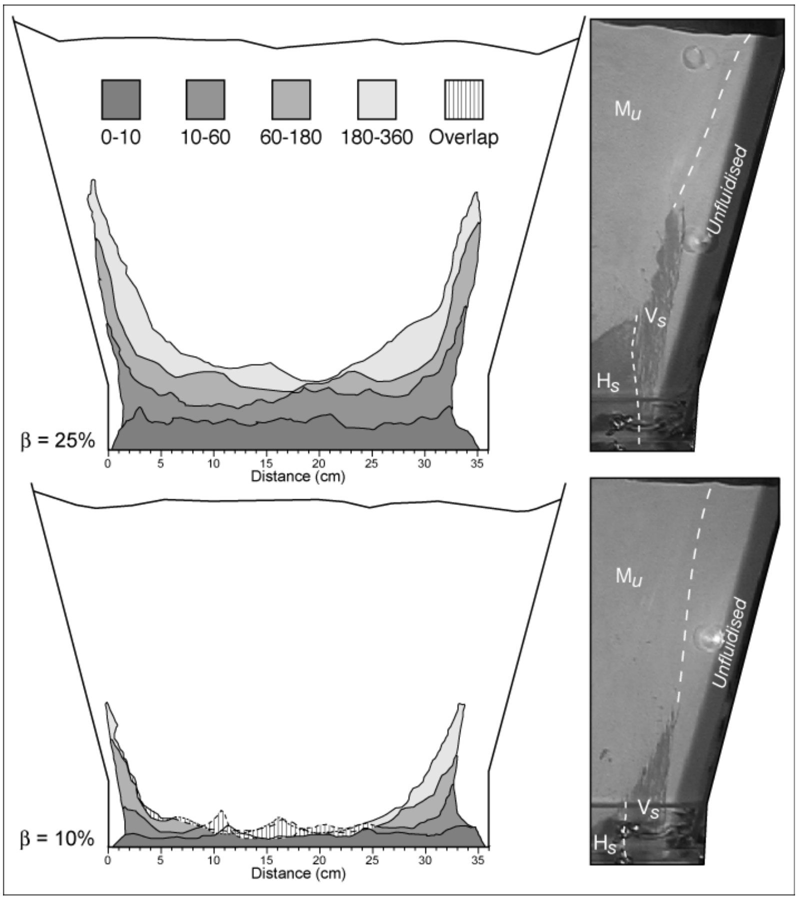

Figure 3: Pictures of the effect of particle mixtures on the structure of the tapered fluidized bed with horizontal segregation in the fully fluidised region of the bed into a bottom layer of coarse particles (H_0) and a mixed upper region (M_u), and vertical segregation in the non-fluidized region (V_s). θ= 15°, Q = 30 l/min (Q/Q_{mf}=2.5). Shading indicates material segregated in the given time interval (in seconds).

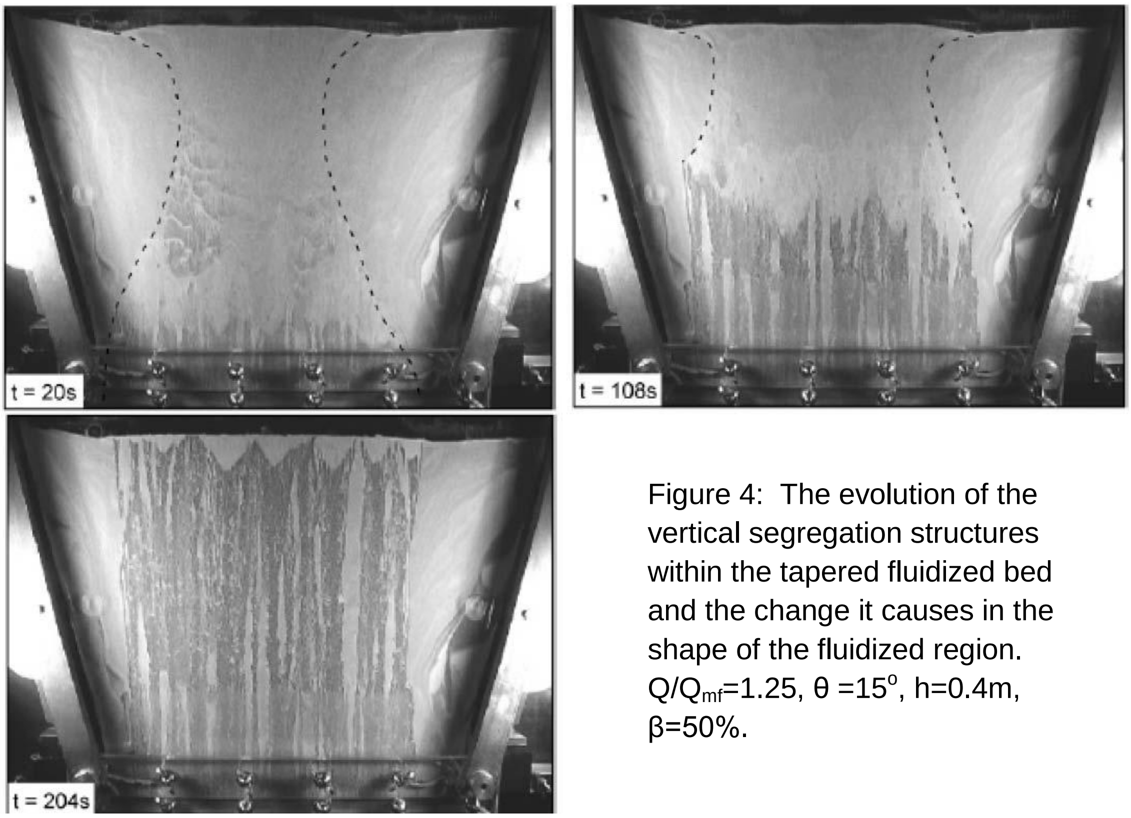

Figure 4: The evolution of the vertical segregation structures within the tapered fluidized bed and the change it causes in the shape of the fluidized region. Q/Q_{mf}=1.25, θ =15°, h=0.4m, β=50%.

The same is true for the area of the bed occupied by the central fluidized region with height: it occupies the same proportion of the bed for a given gas flow rate irrespective of the proportion of fine particles in the mixture.

Very different behaviour is seen for lower flow rates which are only sufficient for vertical segregation to occur (region II in Figure 2), as shown in Figure 4. Initially, the well mixed bed behaves like a bed of monosized particles with a waisted central area; however, this region is wholly displaced by the growth of the vertical pipes of coarse particles. This region of pipes appears to be wholly unaffected by the tapered shape of the bed and effectively forces its central region to behave like a straight-sided fluidized bed.

DISCUSSION AND CONCLUSION

A striking aspect of the experiment is the robustness of the system both in terms of segregation of particles and the structure of the bed, provided that the gas flow rate is sufficiently large for at least horizontal segregation to take place. This makes the performance of a tapered fluidized bed predictable and reliable. An exception is for low gas flow rates where vertical segregation takes place. Under these conditions, the segregation structures nearly totally displace the usual flow structures, and the bed performance will be very different.

There is no evidence that the tapered shape improves the mixing of particles. If there is a sufficiently large gas flow rate, then there is vigorous mixing in the central region of the bed owing to the action of bubbles; however, this would also take place in a straight-sided fluidized bed, and the gas flow rate at which vigorous mixing takes place is lower. In a tapered bed, there are also always marginal non-fluidized regions which are only reduced in extent, not eliminated at high gas flow rates. These regions are not totally defluidized, but are aerated so they are not static, but move down slowly from the top to the bottom of the bed in a series of slips and are replenished at the top from the central fluidized region. The particles in the marginal regions do therefore circulate in the bed, but the time taken is increased markedly: from measurements in the bed, particles in the central fluidized region take about 4s to move from the top to the bottom of the bed; in the margins, they take 80s for a gas flow rate of 4 Q_{mf} and 25s for a gas flow rate of 10 Q_{mf}. Overall, in terms of particle mixing, while it does take place in a tapered bed, its performance is likely to be inferior to that of a straight-sided bed.

The observations from the experiments also underline the extent to which segregation is a simple process that is determined by the local flow field. The flow structure within a tapered fluidized bed is heterogeneous with different average gas flow rates in different regions, and so it is possible for different segregation patterns to be observed in one bed. An example is shown in Figure 3 where horizontal-type segregation and vertical segregation patterns can be seen in adjacent regions. In most circumstances, with the exception of when vertical segregation is dominant, the coupling of the flow structure to segregation behaviour appears to be weak with the proportion of fine particles in the particle mixture making little difference to the structure of the bed

ACKNOWLEDGEMENT

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NOTATION

β	Proportion of fine particles in a mixture
θ	Angle of taper of apparatus
h	Depth of bed
Q	Gas volume flow rate
Q_{mf}	Gas flow rate for the minimum speed of fluidization of a particle mixture

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