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Segregation Patterns in Gas-Fluidised Beds

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ABSTRACT

A systematic experimental study has been made of segregation in fluidized beds. Phase maps have been measured which show that their structure can change markedly if the size ratio or the mass ratio of the two components is changed. Experiments also indicate the central importance of particle percolation might have on the segregation patterns within fluidized beds.

INTRODUCTION

An important feature of bubbling fluidized beds is the mixing and segregation of the different components of a mixture of particles in the bed. At high gas flow rates, different sets of particles can be efficiently mixed; however, at lower gas flow rates these can segregate into different regions within the bed. The classical form is horizontal segregation where one region (the 'flotsam') overlies another (the 'jetsam') (e.g. [1]). This behaviour can be caused by differences in both size and density of the bed components, with density as the greater driver of this form of segregation [3].

Particles move owing to the balance of forces acting on them. When particles are fluidized or partially fluidized, then their behaviour is determined by the balance of the net buoyancy force and the drag on them caused by the local fluid flow. The local balance of these forces can vary significantly within one bed with the local proportions of the bed components (so that the value of the minimum fluidization velocity (U_{mf}) varies e.g. [2]), and with the local voidage. Both of these variations can affect the local flow velocity (the domination of large particles and greater voidage will encourage higher gas velocity). The result is that it is possible in some neighbourhoods of a fluidized bed for one component of the bed to be fluidized and the other not to be, and for this not to be true in other regions of the same bed.

It may not be sufficient alone for the local force balance on the bed components to promote segregation: the particles that make up one component of the bed must also be able to move relative to those that make up the other component. Rowe *et al.* [3] proposed three processes that enabled segregation. Two of them are associated with the local disturbances generated by bubbles, which when present can cause either good mixing or segregation between different components of the bed. The third mechanism is percolation, which takes place when the local flow field enables small particles to move but the larger particles surrounding them are at least partially defluidized. Because there are interstitial gaps between the large particles, Rowe *et al.* proposed that segregation could take place when small particles could drop down through the gaps provided they are sufficiently small enough when compared with the larger particles to do so. The length-scale ratio between the two bed components that would allow percolation to happen depends upon the arrangement of the particles in the bed: the most open sort of packing is open cubic packing of the coarse particles, which corresponds to a maximum length scale ratio of 0.41; the densest form of regular packing of the coarse particles is hexagonal packing, and this corresponds to a maximum length scale ratio of 0.155 [3]. It is likely that the actual percolation limit lies between these two limits [4].

As well as horizontal segregation, vertical pipes of coarse particles have been observed [2,5]. In this configuration, the particles arrange themselves so that there are columns of fine particles present within intervening regions of mostly coarse particles. The initiation of this sort of structure can take place because U_{mf} for a mixture of particles can be less than U_{mf} for each of the components [2]. A hypothesis of how pipes can continue to grow once segregation has started is that the fine particles can move through the gaps between the large particles.

This paper describes experimental work examining the effects of particle size and density ratios on the segregation behaviour of bidisperse mixtures of particles.

EXPERIMENTAL MATERIALS AND METHODS

Most of the experiments took place within a planar fluidized bed 299mm wide and 6mm deep. The bed had a porous plastic distributor (Vyon D, Porvair Ltd). Air was used as the fluidizing gas and was controlled by rotameters

The planar bed allowed the unambiguous observation of segregation behaviour within it. Planar beds have been successfully used to study many aspects of fluidized bed behaviour, including segregation, e.g. [3], without it being dominated by the presence of the walls. However, to confirm this, some of the experiments were also performed in a 145mm diameter cylindrical bed. The gas velocity was set at an appropriate value and then after a period of time stopped. A section through the bed was taken and it was confirmed that the same patterns of segregation took place. In addition, the pressure curves of some of the mixtures in the planar and cylindrical beds were compared and found to be similar.

The values of U_{mf} for the particles that made up the mixtures used most were estimated in both beds through pressure measurements and are summarised in Table 1. Overall, they were comparable apart from for the IER particles. The discrepancy in the value of U_{mf} is likely to be because of the material of the bed generating significant electrostatic forces in the planar beds of IER particles, rather than the geometry of the bed itself. The estimated value of U_{mf} using the Wen and Yu correlation was 27.5cm/s.

Particles used in the experiments

Several different sorts of particles were used in the experiments with the properties shown in Table 1. These particles were used to form twelve different combinations of particles of different sizes and densities as listed in Table 2. The combinations of particles were selected so the coarser particles were the heavier (though not denser) component.

RESULTS

Segregation structures

A wide variety of segregation structures were seen in the fluidized beds when gas was passed through them. Some of these structures are shown in Figure 1 for mixture (4) at different gas velocities (U_g) and proportions by volume of fine particles (α). It was relatively easy to generate a bed dominated by vertical pipes (though often with a thin band of fine flotsam above it), Fig 1a. However, other configurations were seen such as in Fig. 1b where there is an area of mixed fluidisation above a layer where vertical pipes exist, and Fig. 1c where there is a coarse flotsam above an area dominated by fine particles, with a thin layer of short pipes at the bottom. It was also possible to obtain horizontal segregation but with a horizontal band of coarse jetsam lying under a zone of mixed fluidization (Fig. 1d).

Not all the structures could be seen for all the mixtures. Of particular interest is when vertical pipes may be observed. A mixture might demonstrate one or more of the following three regimes depending on conditions in the bed:

1. some form of horizontal segregation
2. short pipes at the bottom of the bed (with other segregation structures perhaps being present);
3. vertical pipes throughout the fluidized bed.

These three regimes may be treated as a hierarchy and are represented in Figure 2. The symbol of each mixture represents the highest regime in the hierarchy seen in the bed for any value of α and U_g. Each mixture is located on the diagram by the ratio in bulk densities of its components and the ratio between their mean diameters. With the exception of mixture (1), it can be seen that at large size ratios only horizontal segregation is seen; at low size ratios it is possible to obtain vertical pipes throughout the bed; in between short pipes can be found that do not extend throughout the bed. The two vertical dashed lines in the figure represent the two critical size ratios calculated by Rowe *et al.* [3], and appear to delimit the different regimes well.

An outlier in these experiments was mixture (1) for which vertical pipes could not be generated despite its low mean diameter ratio. The reason for this appeared to be the large absolute difference between the sizes of the two components of the mixture. The result of this was that it was not possible for the larger particles to be sufficiently supported for pipes to form without the smaller particles being transported upwards through the spaces between the large particles and forming a horizontally layered segregation pattern.

Detailed segregation behaviour

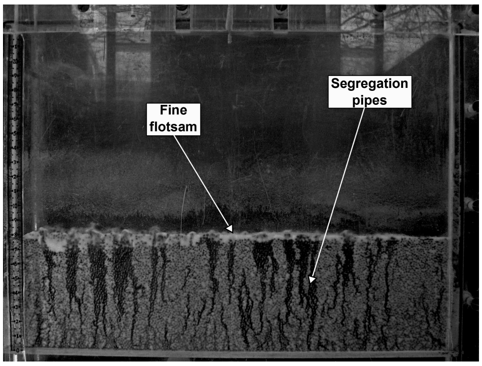
The detailed segregation behaviour of three of the mixtures with different size and density ratios was examined. The three mixtures selected were (4), (5), and (6), all of which were capable of generating pipes. In all mixtures, the particles making up the finer component were lighter than those making up the coarser component.

Type	Reference	Sauter mean diameter (μm)	Standard deviation (μm)	Particle density (kg/m^3)	Measured U_{mf} (cm/s)
Glass ballotini	GB 53-90	69	15	2500	3.3†,3.5‡
	GB 106-212	161	38	2500	4.0†, 5.0‡
	GB 250-425	399	48	2500	15.1‡
	GB 600-800(I)	457	127	2500	27.7‡
	GB 600-800 (II)	316	142	2500	17‡
Glass dust	GD 0-250 (I)	81	83	2500	2.7‡
	GD 0-250 (II)	84	73	2500	2.8‡
Silica beads	SB 2800-3350	3075	-	2439	~200†
	SB 3350-4750	4050	-	2439	-
Ion exchange resin	IER	855	-	1415	45†-27‡
Mustard seeds	MS	1500	-	1155	45‡

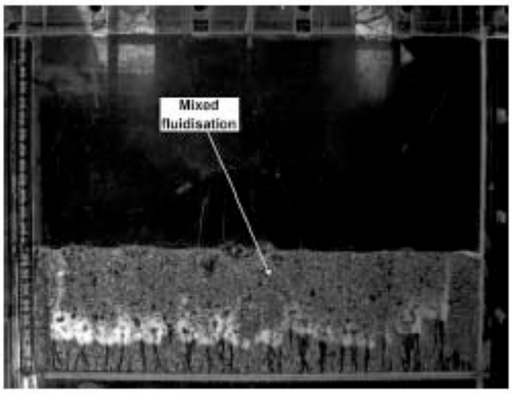
Table 1. Properties of the particles used in the experiments. All the particles were spherical in shape apart from the glass dust, which was irregular. † refers to a measurement of U_{mf} in the planar bed and ‡ to a measurement in a cylindrical bed.

Ref. number	Components		Size ratio SR	Bulk density ratio BDR	Particle density ratio	Particle mass ratio ($\times10^{-4}$)
(1)	SB2800-3350	GB106-212	0.05	0.94	1.03	1.47
(2)	SB2800-3350	GD0-250(II)	0.03	0.73	1.03	0.21
(3)	MS	GB710-1000	0.57	2.07	2.17	4010
(4)	MS	GB106-212	0.11	2.03	2.17	26.7
(5)	MS	GB53-90	0.045	2.05	2.17	2.10
(6)	IER	GB75-90	0.10	1.77	1.77	15.9
(7)	MS	GD0-250(II)	0.06	1.56	2.17	3.80
(8)	IER	GD0-250(II)	0.10	1.35	1.78	16.7
(9)	MS	GB250-425	0.24	2.04	2.17	311
(10)	MS	GB600-800(I)	0.28	2.18	2.17	477
(11)	IER	MS	0.57	1.16	1.23	2270
(12)	MS	GB500-710	0.40	2.05	2.17	1420

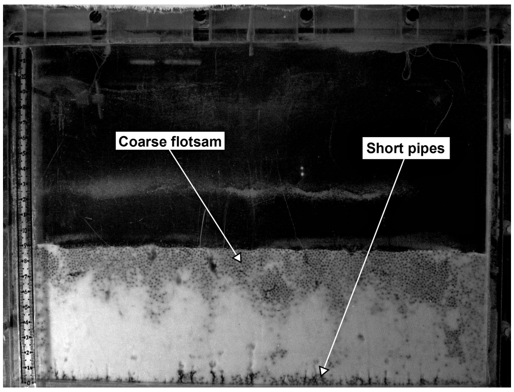
Table 2. Properties of the different mixtures used in the experiments. The ratios are for the smaller component divided by the coarser component.



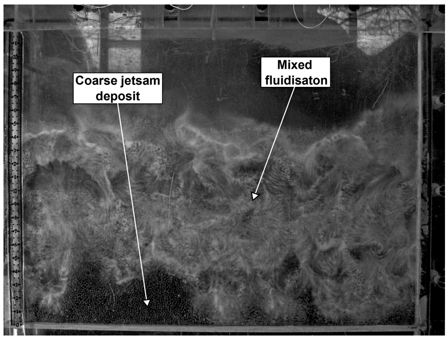
(a) α=30%, U_g=13.94 cm/s



(b) α=40%, U_g=9.29 cm/s



(c) α=70%, U_g=9.29cm/s



(d) α=30%, U_g=83.61 cm/s

Figure 1. Examples of the different segregation regimes observed in a fluidised bed made of of two sets of particles of different size and density. The particle mixture is number (4) as described in Table 2 (MS and GB106-212).

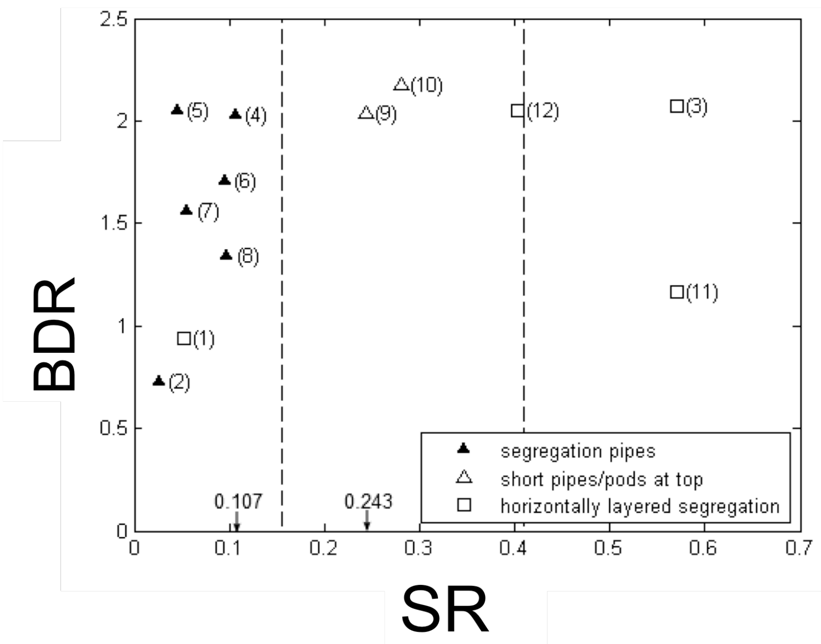
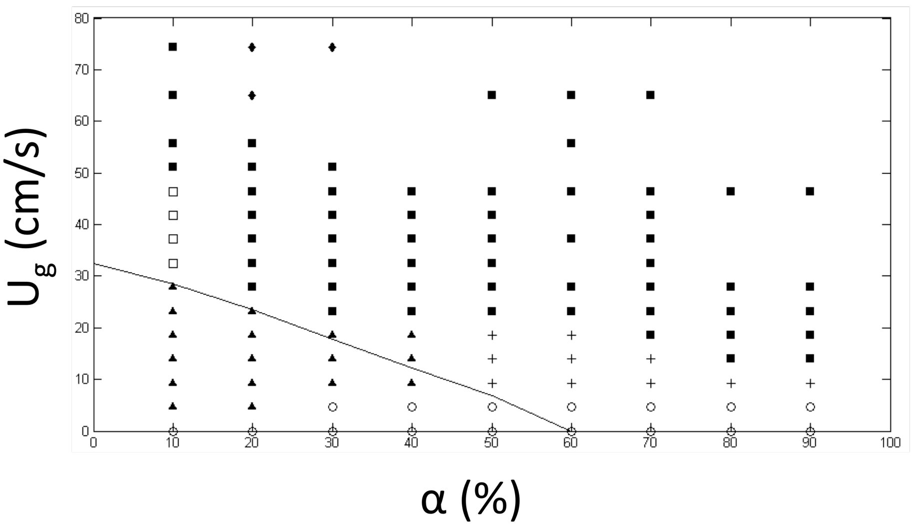
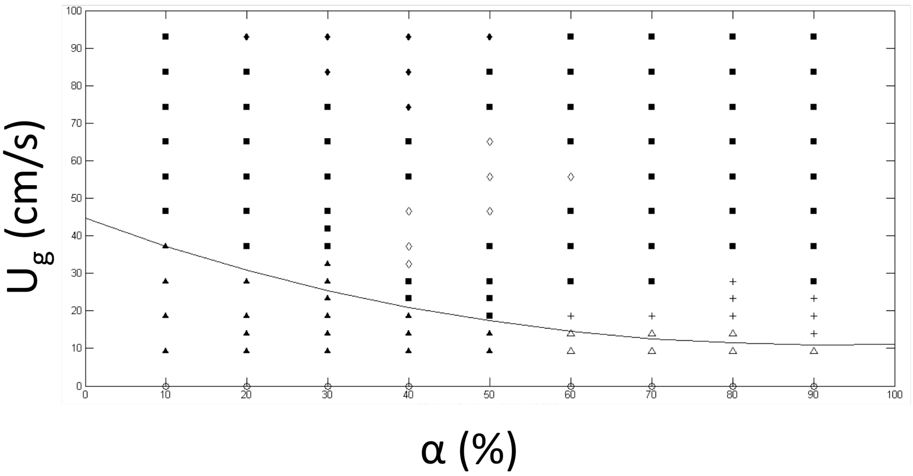


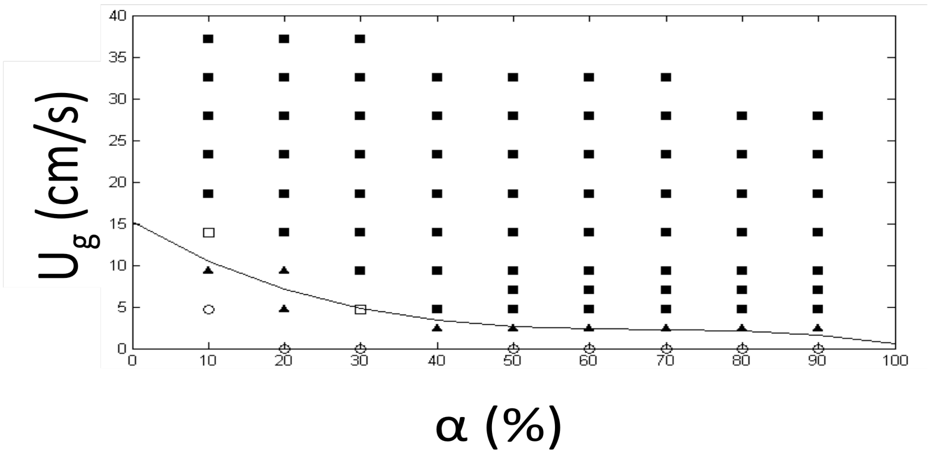
Figure 2. Map of the different size and density rations of the different binary particle mixtures and the regimes seen. The points are only assigned to a regime if it is seen at all in the experiments. The two dashed lines represent the critical size ratios.



(a) Base case phase diagram for MS and GB53-90, mixture (5).



(b) Phase diagram with the same particle mass ratio, but a different size ratio from the base case. The particles are MS and GB106-212, mixture (4).



(c) Phase diagram with a different particle mass ratio, but a similar size ratio to the base case The particles are IER and GB75-90, mixture (6)

Figure 3: Phase diagrams for different binary mixtures of particles. The lines are illustrative and represent polynomial fits for the boundary between the pipe and non-pipe regimes. The key to the diagrams is: ○no motion; ▲pipes; Δ short pipes; □ fine flotsam; ■ mixed fluidization; ◊ periodic jetsam; ♦ coarse jetsam; + Coarse flotsam.

Phase diagrams showing the segregation behaviour displayed for different values of U_g and α are shown in Fig.3. Fig. 3a is the phase diagram for mixture (5), a mixture with a low size ratio between its components. At high values of U_g the bed is well mixed for all but the lowest values of α (for α=10%, the fine particles separate from the coarse and form a thin layer on top of the bed). At lower values of U_g two types of behaviour can be seen. At or above α=50%, then horizontal segregation takes place with the lighter, finer particles forming a jetsam layer with a mixed flotsam layer containing the coarse particles above; however at lower values of α, this behaviour is not seen, and instead pipes form. The range of U_g over which pipes are present increases with decreasing α.

Fig. 3b is the phase diagram for mixture (4), which had the same density ratio as mixture (5), but a larger size ratio. A consequence of this is that the ratio between the weight of a single particle of the light, fine component and the heavy, coarse component was very much larger. It can be seen that as for mixture (5), pipes form when α<50% . Above this threshold, horizontal segregation with a mixed flotsam layer containing the coarse particles forms, again as for mixture (5). There is a significant difference in that at the lowest gas velocities for α>50%, short pipes like those shown in Fig. 1c also form. There is also an intermediate region in the centre of the phase diagram where an unsteady structure dominated where the heavy, coarse particles formed a jetsam layer whose thickness fluctuated with time.

Fig. 3c is the phase diagram for mixture (6). This has a similar size ratio as mixture (4), but the particle mass ratio between the heavy, coarse component and the light, fine component is about half that of mixture (4). This simplifies the phase diagram a great deal so it is now dominated by pipe formation for all values of α, but only at low velocities, and mixed fluidisation. No short pipe formation, no transient jetsam, and only a very few instances of any sort of horizontal layering was seen. There is a possibility that the behaviour of IER particles might be significantly affected by electrostatic forces, but this does not seem consistent with the observed behaviour where extensive mixed fluidization was seen. In addition, experiments were also conducted in a cylindrical bed where the electrostatic effects were much less and the same hierarchy of structures was seen.

The segregation patterns observed were robust and repeatable. The transition between the formation of pipes and a well-mixed bed occurred at a similar gas velocity irrespective of whether it was being increased or decreased.

DISCUSSION AND CONCLUSION

It is clear that segregation can be a complex process with many different configurations possible with different horizontal and vertical structures. It was possible to obtain much more complex behaviour than simple horizontal segregation just by changing the size ratio or the density of particles.

The key to appreciating the complexity of segregation is the interplay between the local particle arrangement, the local value of U_{mf} that results, the fluid flow that this generates, and hence the net force experienced by particles within the bed and their subsequent movement. Furthermore, the balance of these factors is changed as the bed components move relative to each other. When the gas flow rate is fairly high, well mixed behaviour is predictable; however, at lower gas velocities the behaviour of a fluidized bed can be difficult to predict.

When the value of U_{mf} for the smaller component is approached, the behaviour of a bed depends on the proportion of fine particles. For smaller values of α, pipes extending through the whole height of the bed appeared for all three of the mixtures tested in detail. These pipes are easy to generate and are widely known in geological observations of deposits where particles and gas have interacted. Gilbertson and Eames [2] proposed that pipes could be generated when the gas velocity equalled the value of U_{mf} of the mixture of particles (which can be significantly lower than the value of U_{mf} for either of the components). However, the current work suggests that it is also necessary for the small particles to be able to migrate through the interstices between the larger particles (which will be defluidized after the small particles have been removed). From Figure 2, it appears that there is a limit to the size ratio between the components of the mixture for which pipes can appear, and that limit seems to be close to that proposed by Rowe *et al.* [3].

For values of α greater than about 50% and at low values of U_g, horizontal segregation can take place with the coarse particles concentrated in a mixed flotsam layer. A feature of these experiments is that the coarse particles were individually heavier than the fine particles, but less dense than them. Also horizontal segregation only takes place when the concentration of coarse particles was low. These suggest that a coarse particle acts like a body immersed in a fluid and will float when its density is less than the bulk density of the bed surrounding it.

NOTATION

U_g- Superficial gas velocity

U_{mf}- Superficial velocity of minimum fluidization

α- Proportion by volume of the finer component of a mixture

REFERENCES

1. S.Wu and J.Baeyens, Segregation by size difference in gas-fluidized beds, Powder Tech. 26(1), 1-10, 1980.
2. M.A.Gilbertson and I.Eames, Segregation patterns in gas-fluidized systems, J.Fluid Mech. 433, 347-356, 2001.
3. P.N.Rowe, A.W.Nienow and A.J.Agbim, The mechanisms by which particles segregate in gas fluidised beds- binary systems of near-spherical particles, Trans.I.Chem.E, 50, 310-323, 1972.
4. B.Formisani, De Cristofaro, G. and Giramonte, R, A fundamental approach to the phenomenology of fluidization of size segregating binary mixtures of solids, Chem.Eng.Sci. 56(1), 109-119, 2001.
5. A.Nermoen, C.Raufaste, S.D.deVilliers, E.Jettestuen, P. Meakin, and D.K. Dysthe, Morphological transistions in partially gas-fluidized granular mixtures, Phys.Rev.E, 81, 061305, 2010.