2013

Particle Mixing and Segregation in Gas-Solid Fluidized Beds Containing Binary Mixtures

Olasaju O. Olaofe
Eindhoven University of Technology, The Netherlands

K.A. Buist
Eindhoven University of Technology, The Netherlands

N. G. Deen
Eindhoven University of Technology, The Netherlands

M.A. van der Hoef
Eindhoven University of Technology, The Netherlands

J.A.M. Kuipers
Eindhoven University of Technology, The Netherlands

PARTICLE MIXING AND SEGREGATION IN GAS-SOLID FLUIDIZED BEDS CONTAINING BINARY MIXTURES

Olasaju O. Olaofe, K.A. Buist, N.G. Deen*, M.A. van der Hoef and J.A.M. Kuipers
Eindhoven University of Technology; Chemical Engineering and Chemistry Dept.
PO Box 513, 5600 MB Eindhoven, The Netherlands
*T: 1-40-247-3681; F: 1-40-247-5833; E: n.g.deen@tue.nl

ABSTRACT

A newly developed Digital Image Analysis (DIA) technique has been used to study the dynamics of axial segregation of binary mixtures in gas-solid fluidized beds. Experimental results have been compared with a soft-sphere Discrete Element Model (DEM) in which bed conditions were formulated to be in conformity with laboratory experiments.

INTRODUCTION

In recent times, there has been a remarkable increase in electronic computational capacities making it possible to successfully simulate complex systems. However, in order to fully validate the models used in these simulations there is the increasing need to get accurate and detailed quantitative experimental data. Over the years, different techniques for probing the dynamics of fluidized bed have been developed. These techniques can be categorized as being either intrusive or non-intrusive. The intrusive techniques, to some extent, interfere with the dynamics of beds, unlike the non-intrusive techniques.

In recent years, there has also been significant advances in digital imaging systems and processing which have led to an increase in the application of photography in the study of lab-scale fluidized beds. It is particularly suitable for pseudo-2D gas-solid systems where the inter-phase boundary is easy to detect and the effect of bed depth is minimal. Goldschmidt et al. (1) developed a whole-field, non-intrusive, Digital Image Analysis technique to study the dynamics and segregation rates in pseudo-2D dense gas-fluidised beds. In their work, a 3-CCD colour camera was used to demonstrate that, using binary mixture of particles, the local mixture composition could be determined within 10% accuracy. Furthermore, they showed that even small bubbles and voidage waves could be detected with their technique. Shen et al. (2), using the image processing toolbox of Matlab achieved a high level of automation in the acquisition, processing and analysis of digitized images of two-dimensional bubbling fluidized beds captured with a digital video camera. Bokkers et al. (3) substituted the fluid seeds in PIV with bed particles to obtain particle velocity fields in 2D fluidized bed experiments monitored with a monochrome high-speed digital camera.

The mixing and segregation of particles of various types in gas-solid fluidized beds is a common phenomenon that is observed in experimental investigations [(1), (4), (5), (6), (7) etc], and the importance of understanding the dynamics of this phenomenon cannot be overemphasized. Mixing and segregation behavior of systems with different particulate species affect the particle distribution in such systems and this in turn influences the heat and mass transfer, bed expansion and chemical reaction rates in the systems. In this work, the non-intrusive Digital Image Analysis (DIA) technique implemented by Goldschmidt et al. (1), which has been improved by utilizing a state-of-the-art photographic apparatus and a new image processing procedure, has been used to measure in-situ the degrees of segregation in fluidized beds, particularly in binary systems. Furthermore, the experimental results have been compared with predictions from the Discrete Element Model (DEM).

EXPERIMENTAL SET-UP

The fluidization experiments were carried out for binary mixtures in a pseudo-2D fluidized bed with a width of 30 cm, a height of 80 cm and a depth of 1.5 cm, and pressurised utility air is applied as the fluidisation gas. For visual access to the bed contents the column front wall was made of transparent glass, and to minimize the electrostatic effect associated with the particle glass interface the back wall of the column was made of anodized aluminum.The bed was illuminated with 2 adjustable LED lamps and the bed dynamics was captured in real time, through the transparent front glass wall, using a mounted digital camera, and the images are streamed to a desktop PC. Matted glass particles particles (density = 2.5 x 10^3 kg/m^3) were specifically chosen for the experiments conducted in order to minimize the reflection of the white light from the LED lamps on the particles. A schematic of the set-up is illustrated in Figure 1.

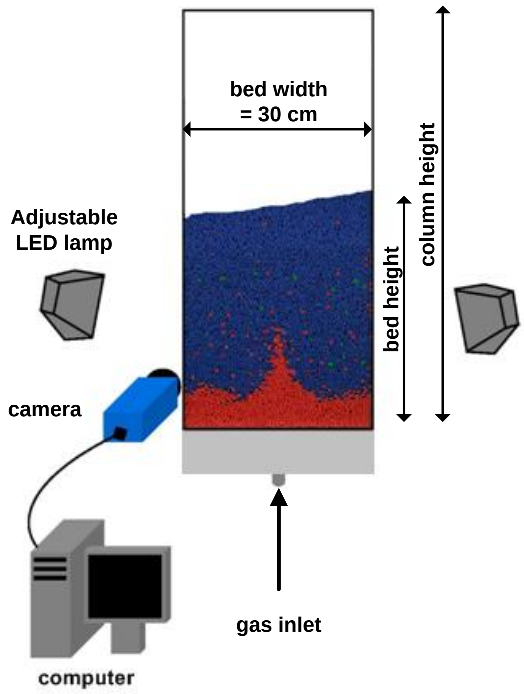


Figure 1. Fluidized bed schematic of segregation experiments.

Initially, the required amount of particles of the various types were weighed and then poured into the bed. Then the mixture was fluidized vigorously for thorough mixing and then shut abruptly for the bed to collapse. Thereafter, the mass flow controllers are switched to the desired fluidization rate. Digital frame shots of the fluidized bed are taken at 15 fps, and the images obtained are processed by a Matlab program script that identifies the colored particles on the basis of the unique HSV color space attributes that they express in pixels. This processing is done after the bubble void areas have been removed. In the script, after the bubble removal and particle detection, cells are drawn across the bed and the actual compositions in these cells are evaluated using a calibration fit that takes into account the disproportion in the representation of particles of different sizes at the wall. The actual compositions, together with their positions, are then substituted in the relations introduced by Goldschmidt et al. (1) for the evaluation of extents of segregation.

SEGREGATION INDEX

The extent of segregation for binary mixtures is defined here (1) by:

$$s = \frac{S-1}{S_{\max}-1} \tag{1}$$

where the actual degree of segregation, S , is given as:

$$S = \frac{\langle h_{small} \rangle}{\langle h_{large} \rangle} \tag{2}$$

and the maximum degree of segregation, $S_{\max}$, when the packing densities of both fully separated zones of the small and large particles are equal, is obtained from:

$$S_{\max} = \frac{2-x_{small}}{1-x_{small}} \tag{3}$$

The segregation index, s , essentially measures the degree of axial segregation, and it has been used in this work because of its durability and robustness in quantifying the demixing of binary mixtures, of various compositions and bed heights, with time.

To quantify the extent of segregation from each snapshot of a fluidized bed, the average heights of the component particles have to be evaluated. For a particle type *p* the average height, $\langle h_p \rangle$, is given as:

$$\langle h_p \rangle = \frac{\sum_{I=1}^{NG_H} \sum_{J=1}^{NG_V} \left(x_{p,\mathrm{act}} \cdot h_p \cdot V \right)_{I,J}}{\sum_{I=1}^{NG_H} \sum_{J=1}^{NG_V} \left(x_{p,\mathrm{act}} \cdot V \right)_{I,J}} \tag{4}$$

Generally, for a bidisperse mixture, the calibration profile of the larger specie can be represented by:

$$x_{p,\text{act}} = (1-a)x_{p,\text{app}} + a(1-e^{bx^{c}_{p,\text{app}}}) \quad (5)$$

where $x_{p,\text{act}}$ and $x_{p,\text{app}}$ represent respectively the actual and apparent composition of particle type *p*.

SEGREGATION EXPERIMENTS

To study binary mixtures, the 1.5 – 2.5 mm system studied by Goldschmidt et al. (2003) has been re-examined because this combination has been shown to segregate well. In addition, a 2.5 – 3.5 mm mixture has been investigated. Details of the mixtures used in this study are given in Table 1.

Figure 2 shows the time evolution of the extents of segregation when the Case A mixture is fluidized at several velocities, U_{bg}. When the fluidization velocity was increased from $1.1U_{mf}$ to $1.2U_{mf}$, the rate of segregation also increased.

Thereafter, further increase only led to a smaller segregation rate, and clearly, any increase above $1.5U_{mf}$ will only succeed in keeping the particles evenly distributed. The occurrence of a peak segregation rate in the fluidization of binary mixtures when the fluidization velocities is between the incipient fluidization velocities of the flotsam and jetsam has not been distinctively identified by most of the earlier studies. Furthermore, it is interesting to note that the segregation trend was rather smooth between 1.1 to $1.3U_{mf}$. However, at $1.4U_{mf}$, fluctuations in the segregation profile become more visible, and even larger fluctuations occur at $1.5U_{mf}$. These fluctuations were caused by the bubbling activities in the bed. It is also interesting to note that the slopes of the segregation profiles remained more or less constant throughout the observation time. Figure 3 shows some snaphots of the bed at various fluidization velocities.

Table 1. Mixtures studied.

Mixture	Component	colour	Amount	U_{mf} measured (m/s)	*U_{mf} Predicted* (m/s)	Fluidization velocities (x U_{mf} measured)
Case A	1.5 mm 2.5 mm	green blue	50% 50%	0.91	*0.92#*	1.10, 1.20, 1.30, 1.40, 1.50
Case B	2.5 mm 3.5 mm	red green	50% 50%	1.41	*1.30#*	1.20, 1.80

U_{mf} *is minimum (or incipient) fluidization velocity*
\# U_{mf} *Predicted was calculated from Ergun (8) equation and a correlation from Cheung et al. (9)*
Initial static bed height was 30 cm.
The measured U_{mf} *of the 1.5 (green), 2.5 (blue) and 3.5 (blue) mm particles are 0.77, 1.21 and 1.63 m/s respectively.*

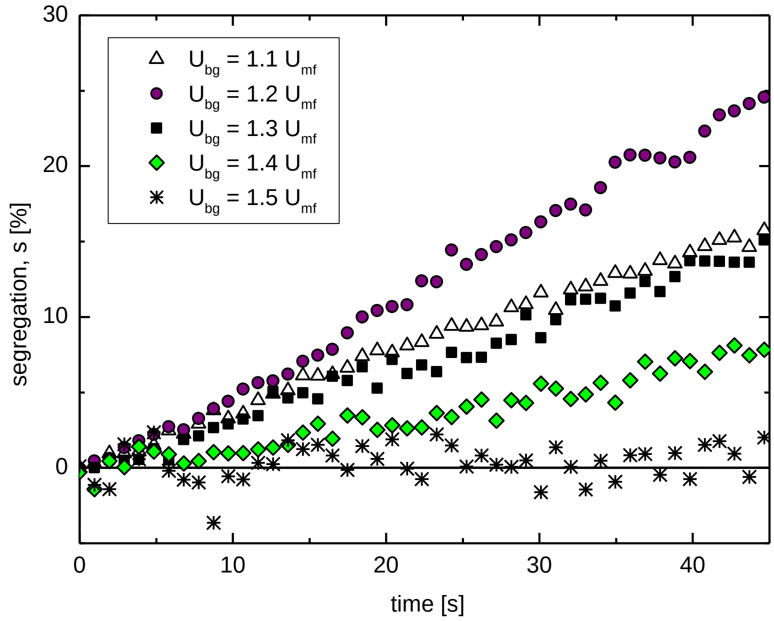
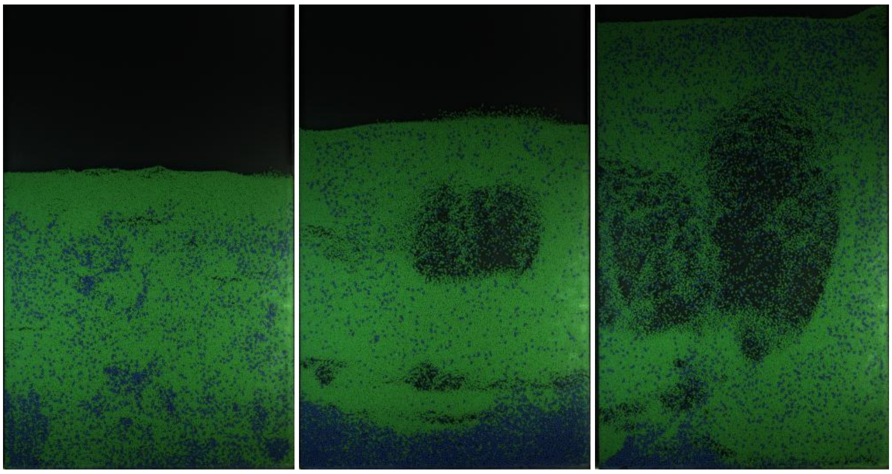


Figure 2. The time profile of the extent of segregation for a bidisperse mixture, containing 50% 1.5 mm particles and 50% 2.5 mm particles, at various fluidization velocities, U_{bg}, where U_{mf} = 0.91.



(a.) 1.1U_{mf} *(b.) 1.3U_{mf}* *(c.) 1.5U_{mf}*

Figure 3. Bidisperse mixtures, containing 50% 1.5 mm particles (green) and 50% 2.5 mm particles (blue): (a.) (b.) and (c.) are actual bed snapshots after 40 seconds of fluidization at indicated velocities.

Figure 4 shows the time evolution of the extents of segregation when Case B is fluidized at 1.2 and 1.8U_{mf}. From the figure, it can be seen that while the 2.5 and 3.5 mm particles were expectedly the flotsam and jetsam respectively for fluidization at 1.2U_{mf}, there was instead a slight layer inversion at 1.8U_{mf}. This observation seems to support the findings of Rasul et al. (10) that layer inversion occurs under certain fluidization conditions.

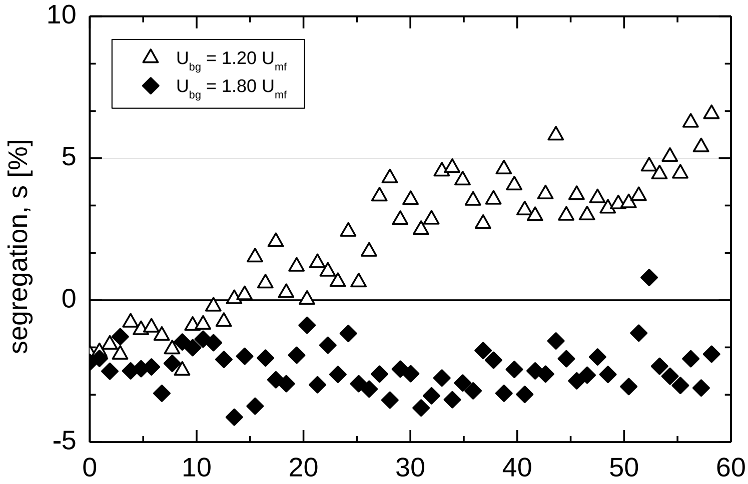


Figure 4. The time profile of the extent of segregation for a bidisperse mixture, containing 50% 2.5 and 50% 3.5 mm particles at various fluidization velocities in experiments.

EXPERIMENTS VERSUS DEM

Hydrodynamic models that predict the behavior of fluidized beds have been in development in the past few decades. It is essential to evaluate the performance of these models with available experimental data. For this, the experimental results from Goldschmidt et al. (1) has been used because of the smaller computational resource requirement resulting from the smaller dimension of the bed used in their work. Figure 5 shows a graphical representation of the results

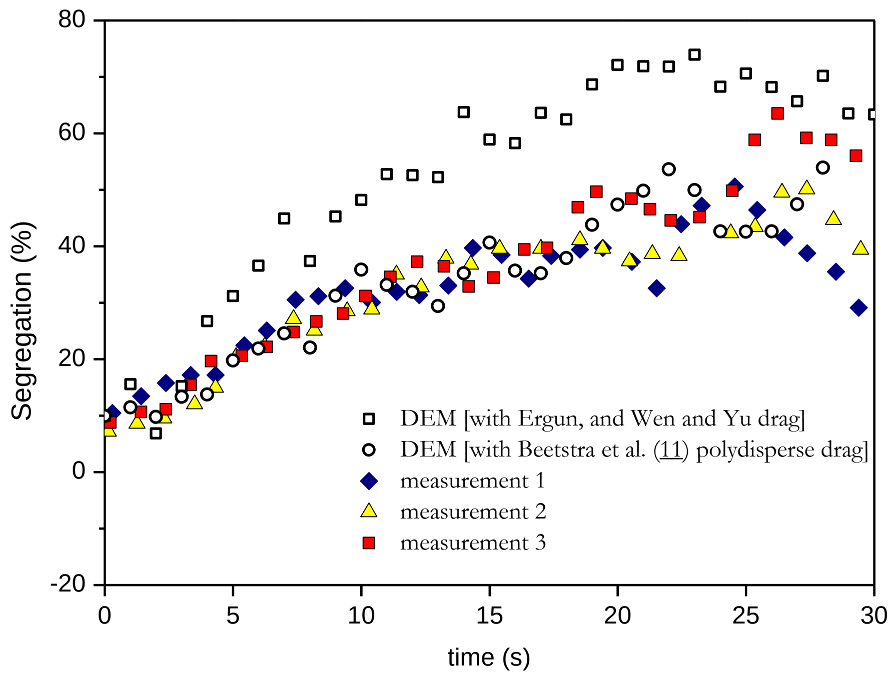


Figure 5. Segregation: DEM versus Goldschmidt et al. (3) results for a binary mixture of 50%, 1.5 mm particles and 50%, 2.5 mm particles at a fluidisation velocity of 1.20 m/s. Initial bed height = 7.5 cm.

from Discrete Element Model (DEM) simulation and the experiments conducted by Goldschmidt et al. (1). From the figure it can be seen that the DEM is in agreement with the experiments when an appropriate gas-particle drag relation (11), which specifically takes into the effect of polydispersity, is used. Figure 6 shows bed visualizations of the DEM simulation results with and without the corrections for the effect of polydispersity.

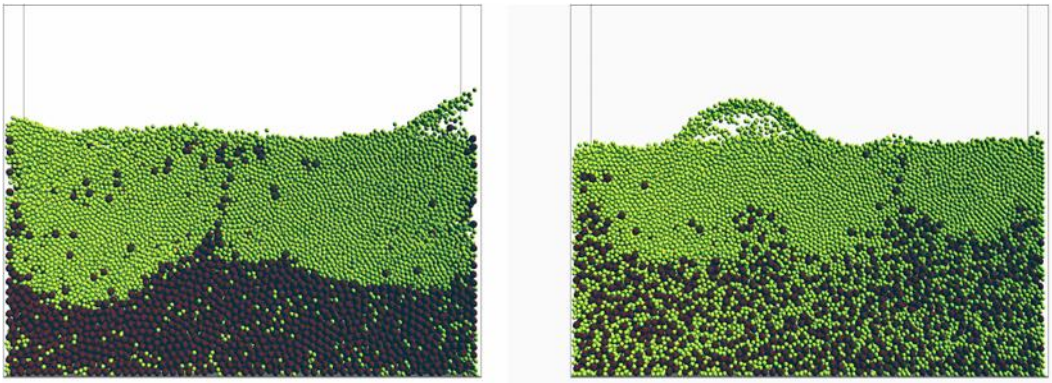


Figure 6. DEM using Ergun, and Wen and Yu gas-particle drag (left) versus DEM using the polydisperse gas-particle drag of Beetstra et al. (11) (right) for a binary mixture of 50%, 1.5 mm particles (green) and 50%, 2.5 mm particles (brown) after 20 s of fluidisation at 1.20 m/s. Initial bed height = 7.5 cm.

CONCLUSIONS

A newly developed non-intrusive Digital Image Analysis technique, in which state-of-the-art instrumentations and procedures are utilized, has been used to study the rates and extents of segregation of binary mixtures in pseudo two-dimensional dense gas fluidized beds. Results show that the binary systems could segregate at fluidization velocities exceeding the incipient velocities of all the individual components. Furthermore, in a comparison between DEM and experiments, the simulation results were in good agreement with experiments when the model incorporated a gas-particle drag relation that specifically takes into account the effect of polydispersity.

ACKNOWLEDGEMENT

The authors wish to thank the The Netherlands Organization for Scientific Research (NWO) for the financial support of this work.

NOTATION

a,b,c	fit parameters
NG_H	number of cells in the horizontal direction of bed
NG_V	number of cells in the vertical direction of bed
$\langle h_p \rangle$	average height of component particles of type *p*, m
I	column index
J	row index
p	particle type
s	extent of segregation
S	actual degree of segregation

S_{max}	maximum degree of segregation
U_{bg}	fluidization velocity, m/s
U_{mf}	minimum fluidization velocity, m/s
V	total index volume of particles in a cell
$x_{p,act}$	actual fractional composition of particle type *p* in the mixture, dimensionless
$x_{p,app}$	apparent fractional composition (in the bed snaphots) of the particle type *p* in the mixture, dimensionless
x_{small}	mass fraction of the smaller particle type, dimensionless

REFERENCES

1. M.J.V. Goldschmidt, J.M. Link, S. Mellema and J.A.M. Kuipers. Digital image analysis measurements of bed expansion and segregation dynamics in dense gas-fluidised beds. Powder. Technol., 138(2-3):135-159, 2003.
2. L. Shen, F. Johnsson, B. Leckner, Digital image analysis of hydrodynamics two-dimensional bubbling fluidized beds, Chemical Engineering Science, Volume 59, Issue 13, July 2004, Pages 2607-2617.
3. G.A. Bokkers, M. van Sint Annaland, J.A.M. Kuipers, Mixing and segregation in a bidisperse gas–solid fluidised bed: a numerical and experimental study, Powder Technology, Volume 140, Issue 3, 25 February 2004, Pages 176-186.
4. V. Mathiesen, T. Solberg, B.H. Hjertager, An experimental and computational study of multiphase flow behavior in a circulating fluidized bed, International Journal of Multiphase Flow, Volume 26, Issue 3, March 2000, Pages 387-419.
5. F. García-Ochoa, A. Romero, J.C. Villar, A. Bello, A study of segregation in a gas-solid fluidized bed: Particles of different density, Powder Technology, Volume 58, Issue 3, July 1989, Pages 169-174.
6. A.C. Hoffmann, E.J. Romp, Segregation in a fluidised powder of a continuous size distribution, Powder Technology, Volume 66, Issue 2, May 1991, Pages 119-126.
7. P.N. Rowe and A.W. Nienow, Particle mixing segregation in gas fluidised beds. A review, Powder. Technol., 15(2):141-147, 1976.
8. S. Ergun, Fluid flow through packed columns, Chem. Eng. Proc., 1952, 48:89.
9. L. Cheung, A. W. Nienow, P. N. Rowe, Minimum fluidisation velocity of a binary mixture of different sized particles, Chemical Engineering Science, Volume 29, Issue 5, May 1974, Pages 1301-1303.
10. M. G. Rasul, V. Rudolph, M. Carsky, Segregation potential in binary gas fluidized beds, Powder Technology, Volume 103, Issue 2, July 1999, Pages 175-181.
11. R. Beetstra, M.A. van der Hoef and J.A.M. Kuipers. Drag force of intermediate Reynolds number flow past mono- and bidisperse arrays of spheres. A.I.Ch.E. Journal, 53: 489-501, 2007.