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Inhomogeneous Segregation of Binary Mixtures in Fluidized Beds

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Abstract

This paper deals with segregation effects in of binary mixtures in a 2D fluidized bed. In the experiment initial inhomogeneities in the particle mixture lead to uneven bed pressure drop. This results in inhomogeneous particle segregation and the formation of heap like structures. The effect is clearly reproducible for small particle mass fractions of 40 to 60\%. A numerical model based on a hybrid DPM/Euler model was developed and shows a similar behaviour for initial disturbances in the binary particle mixture.

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Keywords: fluidized bed; binary mixtures; segregation; experiments; CFD

1. Introduction

Industrial applications of fluidized bed reactors are mainly based on polydispers materials. Therefore mixing and segregation in fluidized bed reactors are important to understand.

Most studies in literature use binary mixtures of particles. While some authors ([1], [2] and [3]) use Geldart B particles of different densities, in the references [4], [5], [6], [7], and [8] Geldart D particles of the same or similar densities but different diameters are used. In [9] Geldart D particles of different size and different densities are used.

One interesting effect, which is not documented in literature is the unstable or inhomogeneous segregation of binary mixtures. As the gas phase encounters a lower pressure drop passing through a segregated area with a high mass fraction of large particles, an initial perturbation in the bed mixing tends to produce local segregation and the formation of channels of large particles in a surrounding bed of small particles or well mixed small and large particles. Through the channel of higher porosity most of the inertia of the gas phase is lost and no further mixing or segregation of the remaining bed volume takes place.

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This article presents experimental results demonstrating this effect and describes a hybrid CFD model which is able to provide good agreement with the experimental findings.

**Nomenclature**

| Symbol | Description                  |
|--------|------------------------------|
| $d_{p,s}$ | small particle diameter, m          |
| $d_{p,b}$ | big particle diameter, m          |
| $v_{sf}$ | superficial velocity, m/s         |
| $v_{mf}$ | minimum fluidization velocity, m/s |
| $S$     | segregation coefficient          |
| $x_s$   | mass fraction of small particles  |
| $t$     | time, s                        |

2. Experimental setup

Perfect mixing of binary particle compositions is not possible in an experiment. Therefore it is easy to reproduce the effect in a lab-scale experiment. Our fluidized bed test rig consists of a rectangular bed of 15x2 cm. The bed is fluidized via a porous plate with 100 $\mu$m pore size covering the whole cross-section of the fluidized bed.

The used particles are soda-lime glass spheres. Table 1 summarizes the most important particles properties. The small particle fraction has a mean diameter of $d_{p,s} = 0.5$ mm, for the bigger particle fraction either 1.15 mm or 2.6 mm particles are used. The small particles are transparent and the large particles are either blue or green colored. The test rig has a homogeneous background illumination. Images are recorded with 125 frames per second with a black and white camera using a red color filter on the lens to improve the contrast between the particle fractions. In addition to the optical recordings, the pressure drop is measured on various bed heights.

| particles                  | color   | mean diameter | material density | bulk density | min. fluid. velocity |
|----------------------------|---------|---------------|------------------|--------------|----------------------|
| small particle fraction    | transparent | 0.5 mm       | 2500 kg/m$^3$   | 1500 kg/m$^3$ | 0.3 m/s             |
| large particle fraction 1  | blue    | 1.15 mm       | 2500 kg/m$^3$   | 1470 kg/m$^3$ | 0.7 m/s             |
| large particle fraction 2  | green   | 2.6 mm        | 2500 kg/m$^3$   | 1470 kg/m$^3$ | 1.6 m/s             |

To extract the particle composition from the video images, a data processing method similar to [5] was implemented. Pictures of well mixed particle compositions from 0% to 100% small particles were taken. The average grayscale value of these images are used to define a calibration function (Fig. 1(a)).

![Grayscale calibration curve](image)

Fig. 1. (a) Grayscale calibration curve, (b) original image example, (c) image after bubble separation and window averaging.
To correctly identify the mass fraction through this calibration function, it is necessary to separate the void areas (bubbles) via a threshold value in the first step. In a second step the image is subdivided with a regular grid (Fig 1(b) and (c)). For each of these grid windows the average grayscale level is calculated and then converted into a mass fraction via the calibration function. A direct conversion for each pixel of the original images would lead to noisy mass fraction data. For the presented results a window size of 27 x 27 pixels turned out to be a good compromise between noise reduction and spatial resolution.

Based on the described image processing method the average particle heights for the small and large particle fraction can be calculated. This allows a quantitative comparison of different segregation experiments. Like in [5] we use a non-dimensional segregation number

$$S = \frac{\langle h_{\text{small}} \rangle}{\langle h_{\text{big}} \rangle}$$

Figure 2 shows an example of a segregation experiment. The whole data processing is also applicable for images resulting from CFD simulations.

### 3. Numerical modelling

During the last decades the analysis of the hydrodynamics or the efficiency of fluidized beds through numerical simulations has become increasingly common. However, due to computational limitations a detailed simulation of poly-disperse reactive industrial scale reactors is still unfeasible. It is, therefore, common to use coarse grids and average particle properties to reduce the demand on computational resources. Such a procedure inevitably neglects on the one hand small (unresolved) scales. On the other hand, mixing, segregation and chemical reactions, which are triggered by the individual particle properties (diameter, particle porosity, etc.), cannot be pictured appropriately.

Therefore, we have developed a computationally efficient hybrid model. The main idea of such a modeling strategy is to use a combination of a Lagrangian discrete phase model (DPM) and a kinetic theory based Eulerian continuum model to take advantage of the benefits of those two different formulations. On the one hand, the local distribution of the different particle diameters, which is required for the gas-solids drag force, can be obtained by tracking statistically representative particle trajectories for each particle diameter class. In particular, one is able to consider the different gas-solids drag force exerted onto the particles with different diameters. An appropriate formulation for such a drag force has been proposed in [10]. On the other hand, the contribution from the inter-
particle stresses, i.e. inter-particle collisions, can be deduced from the Eulerian solution using the kinetic theory of granular flows [11].

For the numerical simulation we use the commercial CFD-solver FLUENT (version 14), whereby we implemented the poly-disperse drag force [10] and the solid stresses of [11] by using user defined functions. For the discretization of all convective terms a second-order upwind scheme is used. The derivatives appearing in the diffusion terms are computed by a least squares method, and the pressure–velocity coupling is achieved by the SIMPLE algorithm, whereas the face pressures are computed as the average of the pressure values in the adjacent cells (linear interpolation). Further details can be found in [12].

Finally, we use a grid resolution equal to three times the diameter of the largest particle fraction. However, such a coarse grid resolution inevitably neglects the small scale flow structures, i.e. sub-grid heterogeneities of the fine particles. Thus, we apply sub-grid modifications for the gas-solid drag force and the solids stresses to account for the effect of those small unresolved scales ([12], [13] and [14]).

A correct numerical model should therefore be able to produce an inhomogeneous bed segregation and a similar channel-building behaviour when initialized by a local inhomogeneity in the particle mixture similar to the experiment.

4. Results and discussion

In the experiments the mass fraction of small particles $x_s$ is increased from 0 to 100%. Figure 3 shows an example for a mixture of 0.5 and 2.6 mm particles with $x_s=60\%$ mass fraction of small particles and a superficial velocity of $v_{sf}=0.44\text{m/s}$. The small particle fraction is fluidized at this gas rate (minimum fluidization velocity $v_{mf,0.5}=0.3\text{ m/s}$) while the large particles are not ($v_{mf,2.6}=1.6\text{m/s}$). Therefore the large particles do not move anymore as soon as they have settled in a certain place. The bed has been premixed with high gas flow rate. However, during settlement of the bed some segregation occurs for this combination of particle sizes. Due to the initial inhomogeneity above the distributor plate, an area of large particles is formed right above this region. The pressure drop over the whole bed decreases during segregation due to this heap like structure.

The effect is reproducible for particle mixtures in the range $x_s=40..60\%$ and superficial velocities in the range $v_{sf}=0.4..0.5\text{m/s}$. However, the effect is not observable in the whole range between $v_{mf,0.5}<v_{sf}<v_{mf,2.6}$. When the fluidization velocity is increased to $v_{sf}>0.7\text{m/s}$ the large particles are still not fluidized but the channeling effect does not occur.

Fig. 3. Inhomogeneous segregation in a binary mixture of 0.5mm (light grey) and 2.6mm (dark grey) particles for (a) $t=0\text{s}$, (b) $t=7\text{s}$, (c) $t=14\text{s}$, (d) $t=21\text{s}$. 
If the 1.15 mm particles are used for the large particle fraction, the same effect is present but the established structures look different. Figure 4 shows the results of a 50% mass fraction for both particle species and increasing superficial velocities. For $v_{sf} = 0.41$ m/s inhomogeneous segregation occurs but no single large heap is formed but several small channels of large particle. In Fig 4(b) the curves for the segregation coefficient demonstrate that the data processing is able to quantitatively describe the segregation behavior correctly. For the inhomogeneous case (blue curve) $S$ increases in the beginning but stagnates at a low level. This is still the case for the green curve ($v_{sf} = 0.46$ m/s) at a higher level of segregation. For increasing superficial velocities $S$ increases likewise until $v_{sf} > v_{mf,1.15}$ where segregation decreases (magenta) or no segregation occurs due to constant mixing (black).

Fig. 4. Segregation of 0.5 mm (light grey) and 1.15 mm (dark grey) particles. (a) Example images, (b) calculated values of $S$.

Fig. 5. Bi-dispers fluidized bed for $v_{sf} = 0.44$ m/s: (a) computed particle volume fraction, (b) computed fraction of 2.6mm particles, (c) diameter of tracer particles (blue: 0.5mm, red: 2.6mm), (d) experiment (light gray: 0.5mm, dark: 2.6mm).
In Fig. 5 a comparison of numerical and experimental results is shown. The CFD simulation was initialized with the same situation as in Fig 3(a). The results demonstrate that the hybrid model yields (including bed expansion, segregation and channeling) fairly good agreement with experiments. Especially, the formation of the heap like structure, which manifests a stationary accumulation of large particles in the center, is predicted appropriately. The formation of this stationary zone leads to a partial de-fluidization. Only the small particles above the heap remain fluidized.

5. Conclusions

The effect of inhomogeneous segregation of binary mixtures in a 2D fluidized bed was show by experiments and CFD simulations. This effect is strongest when the superficial velocity is larger than the minimum fluidization velocity of the small fraction but well below the minimum fluidization velocity of the large particle fraction. In this case large de-fluidized areas are formed based on local inhomogeneities of the initial particle mixture. For numerical simulations a hybrid CFD model was recently developed and the first results delivered fairly good agreement with the experimental results.

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