

## Digital Image Analysis Technique for Mixing Pattern Measurements in Bi-dispersed 2D Gas Fluidized Beds

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This work concerns a new experimental technique based on Digital Image Analysis for the measurement of the mixing behaviour in a bi-dispersed 2D fluidized bed. Two different sets of particles are fluidized with the same density and different size. The technique is based on suitable color-field decomposition of the fluidized bed snapshots, where particles of different colors are employed. The technique here proposed can effectively measure the concentration field in the whole bed during operation and capture the mixing and segregation dynamics of powders. Notably, the technique here developed can be used for both gas- or liquid- fluidized beds.

### 1. Introduction

The fluidization behaviour of mixed powder with different diameter or density strongly depends on the nature and composition of the mixture. One of the main characteristics of fluidized mixed powders is the possible onset of segregation or mixing dynamics, depending on inlet gas velocity and particle characteristics. On this basis, the heavier (or larger) particles, hereafter referred as *jetsam* component, show the tendency to segregate toward the bottom of the bed, while the lighter (or smaller), hereafter referred as *flotsam component*, float above of the segregated particles (Rowe, 1972). The mixing/segregation behaviour and dynamics strongly depends on bubble dynamics, (Chen and Keairns, 1975; Marzocchella et al, 2000; Formisani et al., 2001; Olivieri et al., 2004), because of the bubble wake dynamics that acts as a particle carrier along bed height, from the bottom toward the freeboard.

### 2. Experimental Setup

All the experiments of this study were carried out in a fluid-bed reactor with dimensions equal to 1.000 (height) x 0.240 (width) x 0.015 (depth) m. Glass was used for inner walls to avoid opacity due to particles attrition phenomena, while aluminium was used for the main structural elements. The reactor is therefore almost two-dimensional, thus allowing visual observations of bubble dynamics within the bed. A plastic porous distributor is placed at the bottom of the particle bed. Below the distributor a wind box allows equalization of the gas flow. Air was used as fluidizing gas, whose flow rate was

accurately measured by means of a set of four flow-meters, covering the range 0-140 lt/min. A dehumidifier and an oil filter were also mounted on-line on the gas feed.

Two particle systems were used for the experimental runs: 212-250  $\mu\text{m}$  black corundum particles (*flotsam*,  $u_{\text{mf}}$  equal to 0.952 m/s) and 500-600  $\mu\text{m}$  white corundum particles (*jetsam*,  $u_{\text{mf}}$  equal to 0.405 m/s), with density equal to 4000 kg/m<sup>3</sup>. The particles were filled up to a bed height of 0.490 m, i.e. twice the bed width. In this work, as a preliminary test of the technique developed, an overall powder composition of 50%w/w in *flotsam* component ( $X = 0.5$ ) is studied. This mixture is characterized by an initial fluidization velocity,  $u_{\text{if}}$ , equal to 0.102 m/s and a final fluidization velocity,  $u_{\text{ff}}$ , equal to 0.503 m/s.

Mixing patterns of the powders were visualized with the aid of a purposely arranged front-lighting device and recorded by a digital camcorder (MVBlueFox), equipped with 16mm focal length lenses.

Two types of experiments were performed:

- Transient mixing dynamics of segregated powder (*jetsam* placed at the bottom, *flotsam* placed at the top of the settled bed), at inlet gas velocity equal to the final fluidization velocity,  $u_{\text{ff}}$ , in particular  $u = 0.503$  m/s. In this case 1000 images were taken at 20 fps.
- Transient segregation dynamics of completely mixed powders, at an inlet gas velocities between the range from initial ( $u_{\text{if}}$ ) to final fluidization ( $u_{\text{ff}}$ ), in particular  $u = 0.340$  m/s. In this case 1000 images were taken at 1 fps.

### 3. Mi.Se.D.A. Technique

In this work, a novel technique hereafter referred as Mixing and Segregation Dynamics Analysis (Mi.Se.D.A.) is proposed and tested.

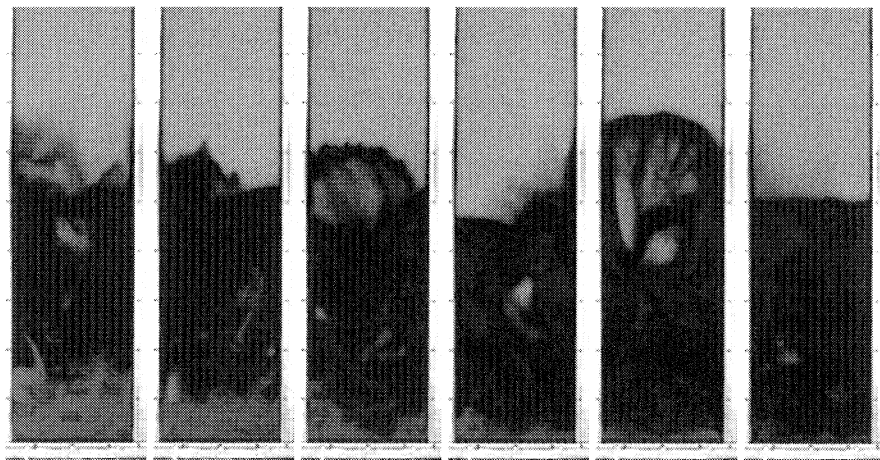


Figure 1. Typical snapshot sequence of the segregating system,  $u = 0.304$  m/s,  $\Delta t = 100\text{s}$ .

The technique is based on advanced color images analysis of a bi-dispersed system with powders of different colors. In Fig.1, a typical sequence of snapshots of the bed during mixing experiment is shown (notably, the original images are taken as color images, with a yellow panel placed behind the bed). The use of different colored powders allows a clear qualitative recognition of the initial mixed condition and its evolution with time, i.e. the decrease with time of the settled jetsam layer at the bottom of the bed and the trails of white particles carried by bubbles, especially in the first snapshots. The Image Analysis Technique here proposed is aimed at obtaining quantitative information on the mixing/segregation dynamics. The first problem to tackle is that of recognizing bubbles in the bed, that are clearly detectable through image analysis. Of course, a sufficiently robust automatic condition based on image pixel values is required.

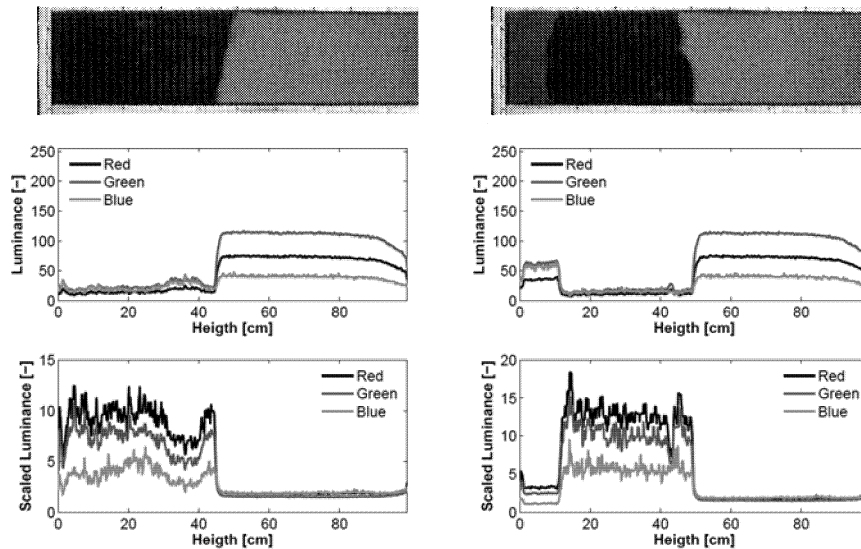


Figure 2. Image mid-line profile of RGB intensities before and after background elimination, (Segregation at  $u = 0.340$  m/s, left,  $t = 0$  s; right,  $t = 500$  s).

In Fig.2, two snapshots of the bed taken at different times, together with the relevant pixel value profiles along bed height are reported. Pixels corresponding to the freeboard and bubbles regions are characterized by a red color intensity having a luminance value between those of green and blue colors. Conversely, pixels in regions occupied by the particle bed exhibit a luminance of the red color lower than those of green and blue colors. On this basis, a pixelwise logical operator is defined in such a way to be able to isolate the pixels which correspond to physical regions occupied by bubbles and freeboard.

The subsequent step of analysis is background elimination. This is accomplished by taking, before each experiment, a snapshot of the fluid bed reactor without particles (i.e. empty bed) at whose back a yellow colored panel is placed. This results into a RGB background image that allows to identify the characteristics of the fluid bed reactor

without particles, while simultaneously compensating any non-uniform illumination. The best results to enhance composition characteristics was found to be the pixelwise division of each color channel of the recorded snapshots of the experimental runs by the corresponding background-image channel. The three divided channels are then summed and rescaled to obtain a pseudo-composition image in which the pixel values are in the range 0-1. In this image, pixel occupied by bubbles are assigned a negative value.

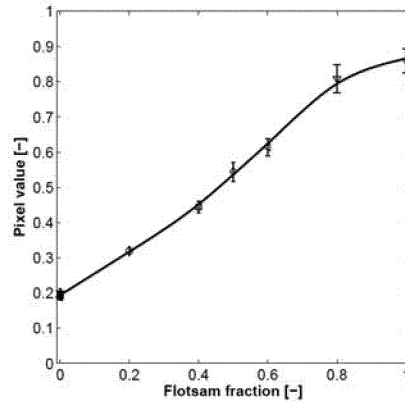


Figure 3: Pixel values versus flotsam fraction.

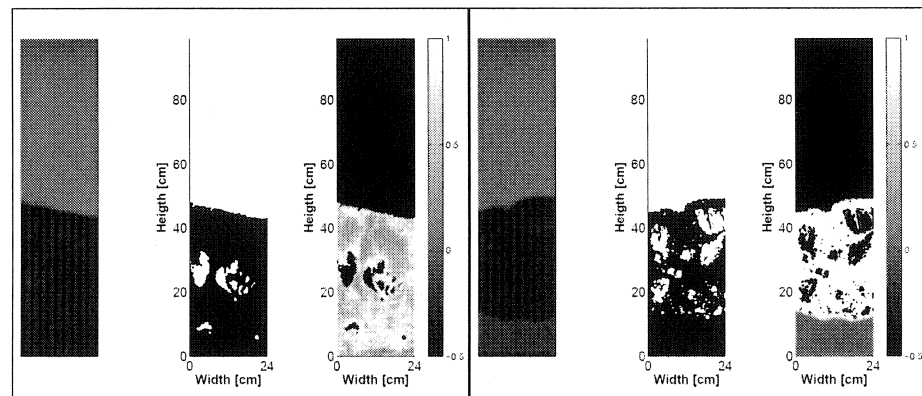


Figure 4. Image elaboration steps: raw image, bubbles selection and composition chart after calibration curve application (Segregation at  $u = 0.340$  m/s, left,  $t = 0$  s; right,  $t = 500$  s).

The latter step is the translation of the above information into composition of the powder mixture. This is achieved by a suitable composition chart obtained from bed images and reported in Fig.3. In particular, the composition chart is obtained by measuring the average value of the above mentioned pseudo-composition image in regions of the bed having known composition (i.e. segregated regions and perfectly mixed regions). This procedure is necessary because some differences in color exist

between images with particles in motion and images with particles at rest. This is likely due to image blurring as a consequence of particle motion or emulsion phase expansion. The final composition maps resulting from the application entire procedure is reported in Fig.4.

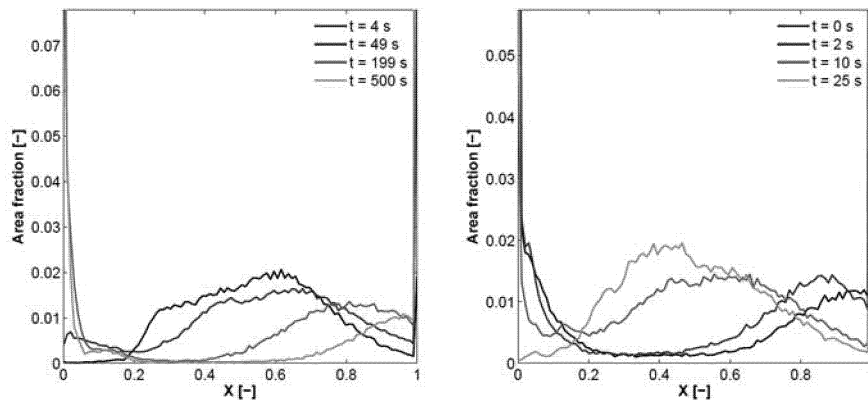


Figure 5: Distribution of pixel composition at different times. (Left) Segregating system,  $u = 0.340$  m/s; (Right) Mixing system,  $u = 0.503$  m/s.

Once the instantaneous composition maps are obtained, the relevant distribution of bed composition is computed. For the investigated systems, some composition distributions are reported in Fig.5 at different times. As it is possible to observe for example in Fig.5.a, the initial distribution is mono-modal. Increasing observation time, a strong bimodality clearly occurs because of segregation. Conversely, in a mixing system the opposite phenomena occurs, as it is possible to observe in Fig.5.b.

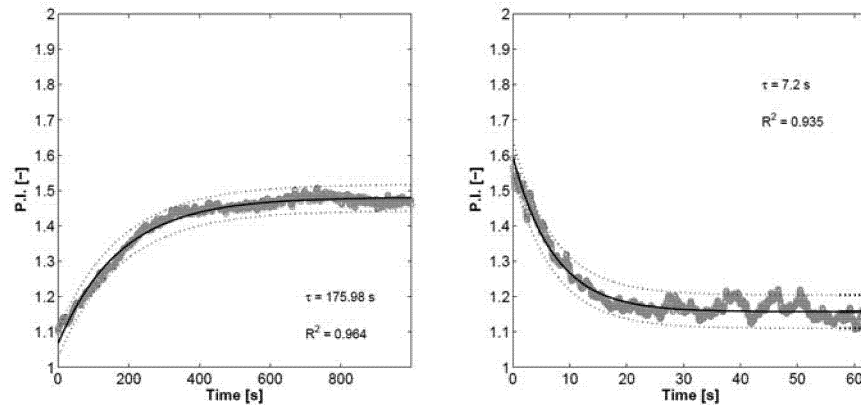


Figure 6: Polydispersity index versus time. (Left) Segregating system,  $u = 0.340$  m/s; (Right) Mixing system,  $u = u_{ff} = 0.503$  m/s.

The polydispersity index  $PI(t)$  was chosen to characterize the instantaneous segregation degree:

$$PI(t) = \frac{X_{21}(t)}{X_{10}(t)} = \frac{\sum X^2(x, y, t) / \sum X(x, y, t)}{\sum X(x, y, t) / \sum X^0(x, y, t)} \quad (1)$$

The  $PI$  evolution over time is reported, for the investigated cases, in Fig.6. The first evidence is a clear difference in characteristic times of mixing and segregation: segregation is almost complete only after 400-500 s, while considerably shorter times are needed to attain complete mixing (about 30-40 s).

To quantify these dynamics, the segregation index was fitted by simple exponential curve, with characteristic time constant  $\tau$ :

$$PI = \begin{cases} (PI_{\max} - PI_{\min})e^{(-t / \tau_{mix})} + PI_{\min} \\ (PI_{\max} - PI_{\min})[1 - e^{(-t / \tau_{seg})}] + PI_{\min} \end{cases} \quad (2)$$

The results of curve fitting are also reported in Fig.6, together with the relevant time constants  $\tau$  and correlation indexes obtained by fitting. Notably, mixing show a dynamic about 25 times faster than segregation.

#### 4. Conclusions

In this work, a novel technique for the investigation of mixing/segregation dynamics of fluidized beds is proposed and preliminarily tested. The first findings show that segregation and mixing of powders in bi-dispersed fluidized beds exhibit well different dynamics with different characteristics time scales. Further analysis and modelling of these phenomena is of course the main objective of future.

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