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Laverman, J.A.; Bulte, ten, M.J.; van Sint Annaland, M.; Kuipers, J.A.M.

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Experimental and computational investigation on the macroscopic circulation patterns in a bubbling gas-solid fluidized bed

J.A. LAVERMAN\(^1\,2\), M.J. ten BULTE\(^1\), M. van SINT ANNALAND\(^1\,2\), J.A.M. KUIPERS\(^1\,2\)

\(^1\) University of Twente, P.O. Box 217, 7500 AE, Enschede, the Netherlands
\(^2\) Dutch Polymer institute (DPI), P.O.Box 902, 5600 AX Eindhoven, the Netherlands

Abstract: The hydrodynamics of a freely bubbling, pseudo 2-D fluidized bed has been investigated experimentally for different bed aspect ratios at different superficial gas velocities by using Particle Image Velocimetry (PIV) combined with Digital Image Analysis (DIA). Coupling of both non-invasive measuring techniques allows us to obtain information on both the bubble behavior and emulsion phase circulation patterns simultaneously. In particular, the combination of DIA with PIV allows to correct for the influence of particle raining through the roof of the bubbles on the time-averaged emulsion phase velocity profiles.

Keywords: PIV, DIA, hydrodynamics, fluidized bed, bed material, LLDPE

1. INTRODUCTION

In many industrial applications of bubbling gas-solid fluidized bed reactors, the reactor performance is determined by the macro-scale solids circulation patterns. For example, in gas-phase polymerization reactors, the overall heat removal rate and consequently the overall production capacity is dominated by the solids convection. Unfortunately, a profound understanding of the prevailing mechanisms is still lacking and especially quantitative information on the extent of the macro-scale circulation as a function of the operating conditions in large fluidized bed reactors is still quite scarce. In this work, PIV and DIA are combined to measure the emulsion phase velocity profiles. Using DIA, the instantaneous particle velocity profiles obtained by PIV can be filtered for particles raining through the roof of the bubbles. With this novel approach the entire emulsion phase flow field is obtained instantaneously, contrary to e.g. particle tracking techniques, which allows investigating the interaction between the bubble and the emulsion phases directly. However, because of the required visual access, this technique can only be applied for pseudo-2D fluidized beds.

2. EXPERIMENTAL

The hydrodynamics, viz. the solids circulation patterns and bubble behavior, of a freely bubbling gas-solid fluidized bed filled with either monodisperse glass beads or monodisperse linear low density polyethylene has been investigated experimentally using Particle Image Velocimetry (PIV) combined with Digital Image Analysis (DIA). Particle Image Velocimetry (PIV) is a non-invasive measuring technique developed originally to investigate liquid or gas-liquid systems, but recently extended to gas-solid dispersed flows. The basic principle of PIV is to divide the recorded images into \(N_x \times N_y\) interrogation areas and use a spatial cross-correlation on two consecutive images to obtain the average displacement of the particles. DIA uses the pixel intensity to determine whether the pixel belongs to the bubble or the emulsion phase. When the pixel intensity is below a predefined threshold value, the pixel area is assigned to the bubble phase, and otherwise to the emulsion phase. The threshold was an image independent threshold of 0.9 times the average image intensity. Coupling of these non-invasive measuring techniques allows us to obtain information on both the bubble behavior and emulsion phase circulation patterns simultaneously, in order to study in detail their intricate interaction. In particular, the combination of DIA with PIV allows correcting for the influence of particle raining through the roof of the bubbles on the time-averaged emulsion phase velocity profiles, Figure 1. Because of the required visual access, this technique can only be applied for pseudo-2D fluidized beds.
Figure 1: Number-averaged emulsion phase velocity profiles for 2.5 \( u/\nu_{mf} \) in the 0.30 m fluidized bed filled with 0.30 m of glass beads. a) before filtering using DIA, b) after filtering using DIA.

The bubble rise velocity as a function of the equivalent bubble diameter, the average bubble diameter and bed material as a function of the position above the distributor were determined with DIA, see Figure 2. It can be seen that the averaged equivalent bubble diameter is larger when the fluidized bed is filled with LLDPE particles. However, the averaged bubble rise velocity as a function of the equivalent bubble diameter is quite similar for the glass beads and the LLDPE particles.

Figure 2: Bubble behavior for a 0.3 m fluidized bed filled with 0.30 m glass beads or LLDPE particles for different fluidization velocities, a) Equivalent bubble diameter vs. the height, b) the bubble rise velocity vs. the equivalent bubble diameter.

The number-averaged emulsion phase circulation patterns have been measured as a function of fluidization velocity, packed bed aspect ratio and bed material, see Figure 3. The macroscopic circulation patterns are qualitatively similar, however, when the lateral velocities at different heights above the distributor are compared (Figure 4), it can be observed that the emulsion phase circulation pattern is much more pronounced.
Fig. 3: Number-averaged emulsion phase velocity profiles for 2.5 u/umf in the 0.30 m fluidized bed filled with 0.30 m of a) glass beads b) LLDPE particles.

Fig. 4: Number-averaged lateral emulsion phase velocity for 2.5 u/umf in the 0.30 m fluidized bed filled with 0.30 m or LLDPE particles.

3. VALIDATION

The novel measuring approach were the PIV measurements are filtered by DIA was validated using dedicated Positron Emission Particle Tracking experiments. It was found that the extent of solids circulation depends strongly on the type of bed material, even when comparing at the same excess velocity. Finally, the experimental findings were studied in detail using Discrete Particle Model and Two-Fluid Model simulations.
4. CONCLUSIONS

Two non-invasive, optical measuring techniques, namely Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA), have been combined to obtain the instantaneous emulsion phase velocity profiles (in a pseudo-2D bed because of the required visual accessibility) together with detailed information on the bubble phase (local bubble size and velocity distribution and bubble fraction), which allows investigating the mutual interaction between the bubble and emulsion phase in detail. Moreover, the combination of PIV with DIA allows correcting for the large influence of particle raining through the roof of the bubbles on the time-averaged emulsion phase velocity profiles.

The DIA results for the average bubble diameter as a function of the height in the bed and the average bubble rise velocity as a function of the equivalent bubble diameter were found to compare reasonably well with literature correlations, considering the differences in experimental set-ups. The filtered number-averaged emulsion phase velocity profiles were measured as a function of the fluidization velocity and bed height. For a fluidized bed filled with LLDPE particles the averaged equivalent bubble diameter was larger in comparison with glass beads at the same excess velocity, however, the bubble rise velocity as a function of the equivalent bubble diameter was found to be the same for both bed materials. The number-averaged emulsion phase velocity profiles show two symmetric vortices with their centers located at the top half of the bed, becoming more pronounced at higher fluidization velocities. Two additional smaller vortices were observed close to the bottom of the bed at lower velocities, which disappear at higher fluidization velocities when the down flow region extends completely to the bottom the bed. Finally, the extent of solids circulation was much higher for the LLDPE particles at the same excess velocity.

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