Experimental study of full field riser hydrodynamics by PIV/DIA coupling

A.E. Carlos Varas, E.A.J.F. Peters*, J.A.M. Kuipers

Multiphase Reactors Group, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, Eindhoven 5600 MB, The Netherlands

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ABSTRACT

A full-field hydrodynamic study under riser flow conditions is performed, by using a combined Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA) technique. The employment of a temporal histogram-based method (THM) enables an accurate measurement of the solids volume fraction over the full field of a pseudo-2D riser unit. The full visual access to the riser section enables a complete characterization of the complex transient particulate phase flow patterns. Full-field riser hydrodynamics are quantified at different operating conditions defined by the superficial gas velocity. Under these conditions, a cluster detection method is utilized to characterize the heterogeneity of the riser flow.

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1. Introduction

1.1. Riser hydrodynamics

Riser reactors have been extensively applied in numerous industrial chemical processes that require intense gas-solid interaction. The performance of risers has been extensively investigated over the past decades to acquire an in-depth insight on their hydrodynamics [1–5], which are nevertheless still not fully comprehended.

Risers are usually operated at high superficial velocities under fast fluidization conditions. These systems exhibit a so-called “core annulus” flow pattern, which is characterized by a dilute solids upflow in the core of the reactor, and a dense downflow close to the walls [1–5]. The dense regions zone typically contain particle clusters, where the gas permeance is reduced which consequently could negatively impact the performance of a riser. Pneumatic transport is reached at very high gas velocities, where the system is characterized by a very dilute bulk solids phase, transporting upwards all the particles that are fed into the riser.

Several experimental techniques have been utilized to collect key hydrodynamic data in an attempt to relate riser operational conditions to cluster-related phenomena. Capacitance probes [6,7], Laser Doppler Anemometry [8] fiber optical probes [9–14] and non-intrusive imaging techniques [15,16] have been employed to obtain local hydrodynamic data in circulating fluidized beds (CFB). Other techniques such as γ-ray densitometry [10] and DIA [16,17] have also been applied to determine solids volume fraction and study riser hydrodynamics.

In literature, contradictory observations have been reported related to clusters appearance probability and size versus axial position and gas superficial velocity. As Chew et al. [11] summarized, the appearance probability can decrease [8] or increase [13] with height. Thus, there is a clear lack of understanding of cluster-related phenomena, probably due to the lack of the existence of complete data sets [11] and a clear definition of what a cluster is [18]. Numerous experimental data on cluster phenomena are available in literature [9,11-16,18]. However, these data are limited to small sections of a riser; using local measurements that often require intrusive probes to collect radial profiles of solids volume fraction. The growing demand for accurate CFD models, requires as well the availability of more detailed and complete experimental data sets for comprehensive model validation. Thus, one of our motivations is to perform a hydrodynamic study by means of a non-intrusive technique that provides full-field hydrodynamic data sets of a well-defined pseudo-2D riser geometry. Another incentive is to perform a full-field cluster characterization of cluster dynamics to assess the influence of the superficial gas velocity on the total degree of heterogeneity of a fast fluidized system.

Particle Image Velocimetry (PIV) and Digital Image Analysis (DIA) are non-intrusive techniques that can be applied to pseudo-2D fluidized systems. These techniques require excellent visual conditions to be sufficiently accurate. The combination of these techniques enables the measurement of relevant hydrodynamic information of

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the whole recorded area of a pseudo-2D fluidized bed, without altering the fluid dynamics of the system. Concerning granular systems, PIV/DIA has mostly been applied to pseudo-2D fluidized beds in the bubbling regime [19–23], which requires a relatively small recording area that can be easily illuminated. However, riser reactors are characterized by high superficial velocities to enhance gas–solids mixing, demanding high units to enlarge the gas residence time in the system. At these conditions, the presence of shadows becomes more problematic, affecting the quantification of solids volume fraction measurements. Constant illumination conditions over relatively small sections of a riser can overcome these issues [17], but this becomes challenging when the full field of a pseudo-2D labscale riser reactor is aimed to be recorded.

In this work, the application of a recently developed novel DIA technique, enables accurate solids volume fraction measurements under riser flow conditions [24] over a relatively large section of a riser (without the need of having such constant illumination conditions). A temporal normalization procedure is performed to only quantify for particles’ intensities and correlate these values to solids volume fraction data. This method is further explained in Carlos Varas et al.[25]. Thus, this novel DIA technique enables full field measurements of solids volume fraction that in combination with PIV becomes a powerful tool to fully characterize the particulate phase flow patterns under riser flow conditions, including cluster characterization in the entire flow field.

In literature, numerous data sets on particle clusters in risers have been reported [9,11-16,18]. However, little or no data have been reported regarding cluster frequency over the entire riser domain. The framework, given by this PIV/DIA technique, provides well-optimized conditions to perform cluster detection and characterization, in order to analyze the influence of hydrodynamic parameters over cluster-related properties over the whole field of view. Experiments with Geldart D particles at changing superficial gas velocity are performed, covering fluidization conditions from turbulent to a transition regime close to pneumatic transport conditions.

Providing detailed full-field experimental data of a compact pseudo-2D riser for CFD validations is one our main objectives of this paper. Full field visual access and solids holdup quantification results to be a very powerful resource to analyze the influence of cluster definition with respect to the obtained results; and contributes to enhanced understanding of the heterogeneous flow structures.

1.2. Clusters

Concerning clusters, a lot of effort has been dedicated to their characterization or/and quantification [1,6,7,12,15,18,24,26-28]. However, definition of what constitutes a particle cluster is still not firmly established due to the wide variety of shapes, structures and densities they can attain and the added difficulty to quantify their properties with available experimental techniques. Clusters have been visualized as particle paraboloid-shaped strands or streamers [15,29]. Yerushalmi and Cankurt [29] assumed that clusters consist of closely packed particles strands that fall downwards in densest regions and move upwards in the lean phase. Clusters, have also been found as particle groups with a core-wake structure [1,16,17], consisting of a very dense region that faces the cluster trajectory and a more dilute region that follows the cluster core path. Soong et al. [6] established quantitative criteria to enable systematic cluster detection by means of optical probes. They defined a cluster as a group of particles with a size of at least 1 or two orders of magnitude larger than the particle diameter with a solids fraction above the mean plus n times its standard deviation, i.e., $(\phi_s) + n \cdot \sigma$, where $\sigma = \sqrt{\langle (\phi_s - (\phi_s)^2 \rangle}$. This definition was slightly modified by Sharma et al. [7] regarding the sampling time required to detect a cluster. Although different definitions of clusters have been proposed in the literature, one common feature that is not questioned, is that clusters are composed of groups of particles that adopt ellipsoidal shapes with an internal solids volume fraction significantly greater than their surroundings [18].

The Soong criteria established quantifiable properties to identify clusters in a systematic manner. Actually, these criteria have been employed by several authors to perform cluster detection and/or characterization [6,7,13,30,31]. However, these criteria seem to be less suited for very dense systems where the solids are highly segregated [12], and the presence of dense clusters is sufficiently frequent to obtain too high values of $\sigma$. The cluster definition proposed by Soong et al. [6] offers a pragmatic procedure to detect clusters, not only with wavelength analysis, but also amenable to computational investigations [30,31]. It has to be remarked however that the Soong criteria were originally proposed for local cluster detection with needle probes. Thus, a cluster is identified when the concentration perturbation is above $(\phi_s) + n \cdot \sigma$ for a time interval equivalent to sampling volumes one or two orders of magnitude larger than the diameter of a particle. When this definition is applied during post-processing of a set of images, regions above $(\phi_s) + 2 \cdot \sigma$ can be simultaneously detected.

It also worth to mention that the large research effort to develop wavelet decomposition techniques to appropriately capture the solids volume fraction fluctuations caused by clusters [11,32,33] with optical probes, classifying signals into micro (noise or particle), meso (cluster or bubble) and macroscale fluctuations [32] (equipment). Multiresolution analysis techniques were also employed to find an appropriate subsignal that captured the time-variable feature of solids volume fraction fluctuations due to macroscale fluctuations as well as neglected signal noise to only account for signals caused by cluster presence. Although the measured cluster properties are slightly affected by the subsignal choice [30], the cluster detection method is not dependent on the local flow fluctuations.

Others used a threshold-based cluster definition by setting an arbitrary value of solids volume fraction above which particle groups were considered as clusters [34, Casleton et al. [35] employed specificity-based particle detection techniques to measure solids volume fraction with optical probes. Mondal et al. [36] applied grayscale thresholding techniques to obtain cluster length scale distributions over the domain of a cold flow CFB unit by means of DIA. Yang and Zhu [17] applied an original methodology to detect clusters by a two-pass Otsu filter [37] that not only worked to detect clusters, but also to identify their respective cores and wakes, by means of image processing techniques. This core-wake cluster definitions match with observations that were reported by other authors in the past; namely that clusters are formed by a dense particle core and a dilute particle wake [1,28].

However, probably due to inappropriate cluster definitions or/and limitations of the employed experimental techniques, contradictory patterns have been reported in literature. Cluster size has been reported to increase [14,38], decrease [1,17] or even remain constant [7,12] when superficial velocity was increased. Thus, among our goals is to provide results related to clusters, which properties do not depend on solid flow fluctuations and remain constant throughout the whole experimental domain as well.

In this paper, dimensions and main features of the pseudo-2D riser reactor are described. The methodology section consists of three subsections: in the first one the details of PV measurements are explained; in the second subsection, the novel DIA method is introduced as well as the employed correlations are presented; and in third subsection the background of cluster definitions is discussed in detail. Also a detailed description of the employed cluster detection methods in this work is explained.

In the Results and discussion section, characteristic features of riser hydrodynamics are presented, namely solids volume fraction, solids mass flux and intermittency index. Moreover, the convenience of using thresholds-based methods to detect clusters is discussed.
The influence of hydrodynamic parameters over cluster-related phenomena is analyzed as well. To conclude, a summary of the most relevant contributions of this research will be provided.

2. Experimental setup

The experiments were performed in a circulating fluidized bed, which is composed of a pseudo-2D riser coupled to a cylindrical fluidized bed or downcomer. The downcomer, fluidized at minimum fluidization conditions acts as a particles reservoir, containing the major part of the solids inventory. These particles flow from the downcomer to the riser bottom by means of a recycling pipe, which cross section is almost fully covered, except for a small opening to smoothly flow the particles.

The recycling pipe is a rectangular-shaped duct of $0.17 \times 0.04 \times 0.006$ m with an inclination of $45^\circ$. The base of the recycling pipe is 4 cm above the gas distributor. The cross section of the recycling pipe is covered by a metallic insertion which has an opening of 4 mm at the bottom to let solids flow through the bottom plane of the recycling pipe. This configuration provided a solids mass flux of $32$ kg/m²s when particles carryover was performed.

The experiments were recorded with a high resolution camera (LaVision ImagerproHS4M) of $2016 \times 2016$ pixels. A picture of the experimental setup is shown in Fig. 1.

The pseudo-2D riser dimensions are $1.5 \times 0.07 \times 0.006$ m and it has a lateral top outlet coupled to a cyclone, where gas and particles are separated. Glass beads ($\rho_s = 2500$ kg/m³) of 0.8–0.9 mm are fluidized at room temperature and atmospheric pressure. It has to be noted that Geldart D particles are employed for visualization purposes.

The experiments were recorded at such a distance that a resolution of at least 2 pixels per particle was attained [25,39]. Each experiment consists of two recordings, one that covers the top-half of the reactor, and another recording the top-bottom half of the pseudo-2D riser reactor.

3. Method

3.1. Particle Image Velocimetry

PIV is a non-intrusive technique that has been traditionally applied using small tracer particles to collect information about the flow field. In fluidized systems, the particle motion is clearly separated from the fluid motion. The application of PIV to fluidized systems is aimed to measure the particle velocity and characterize the hydrodynamic behavior of pseudo-2D fluidized systems. By means of a cross-correlation technique, the mean velocity of the particles inside an interrogation area between two consecutive images is estimated with the equation given below [40]:

$$\bar{v}_p(\bar{x}, t) = \frac{\bar{s}_p(\bar{x}, t)}{M \Delta t}$$

where $M$, is the magnification factor, $\bar{v}_p(\bar{x}, t)$ the solids velocity vector and $\bar{s}_p(\bar{x}, t)$ the solids displacement in a time interval $\Delta t$.

It has to be noted that the time interval between the frames should be adapted to the recording characteristics of each experiment. The quality of the PIV/DIA data can be improved, when suitable parameters of the camera and trigger frequency are set. The image frequency was optimized in such a way that the particle displacement between images was not too large and trackable between adjacent interrogation areas. Thus, the rapid movement of particles under riser flow conditions, required a time frame of 1 ms for an optimal solids velocity determination using PIV.

The time when the camera’s shutter is open to take a single image, is called the exposure time. The illuminance of the image is
proportional to exposure time, which should be sufficiently high to distinguish the particles in the image and not too low to avoid blurring of moving particles. An exposure time of 500 μs met the required conditions.

To achieve sufficiently long recording times and not exceed the camera capacity, a pulse generator was coupled to the high resolution camera. This apparatus generates voltage signals to open/close the shutter of the camera. A signal function is fed to the pulse generator to collect pairs of images with a frequency of 100 Hz. The internal frame time between two consecutive images (for PIV computation) was 1 ms. In this way, experiments of 4997 image pairs were obtained, covering a total experimental time of 50 s. It has to be noted that each experiment was running for at least 3 min to reach steady state prior to starting the recording.

3.2. Temporal-histogram based DIA method

3.2.1. Method

THM post-processing technique is a suited post-processing algorithm for the hydrodynamic study of riser flows. THM builds pixel data histograms in the temporal space. This histogram can be used to discard static image information and capture only the dynamic features. In this way, irrelevant details of the image are automatically discarded leading to a higher accuracy (by removing shadows, spots and light gradients) in the solids volume fraction measurements.

This method performs a first processing pass to register minima and maxima intensities of each pixel over all the images that are collected during a DIA experiment. Then, each pixel intensity is normalized using its respective temporal data histogram to quantify the particle area fraction that is covering the pixel. Each image was windowed into 8 × 8 pixel grids to couple solids velocity field data supplied by PIV. After windowing, the image intensity is correlated to solids volume fraction data by means of the empirical equation shown below:

\[
\psi_s = \begin{cases} 
A \cdot B \cdot \tanh^{-1} \left( \frac{s}{s_{\text{max}}} \right) & \text{for } 0 < \psi_s < 0.6 \\
\psi_{s_{\text{max}}} & \text{for } \psi_s > 0.6
\end{cases}
\]  

(2)

The 2D-3D correlation integrates the influence of \(d_p/D\) ratio of the pseudo-2D system and \(f\), that represents the particle intensity fluctuations [25]. The particle intensity fluctuations, due to light reflections or even due to inhomogeneity of the particles color are modeled through this \(f\) variable, which has to be experimentally determined.

The dependency of all the mentioned parameters are collected in constants \(A\) and \(B\) given by:

\[
A(d_p/D) = 0.6818 \cdot d_p/D + 0.081 \cdot f + 0.024 \pm 0.001
\]  

(3)

\[
B = 0.99 - 0.45f \pm 0.01
\]  

(4)

The combination of PIV and the novel DIA technique enables the quantification of solids mass flux in riser flow. The solids mass flux at each interrogation area is computed as follows:

\[
\langle \tilde{G}_s \rangle = \rho_s \langle \psi_s(x,t) \psi_p(x,t) \rangle
\]  

(5)

3.2.2. Image characterization

The 2D-3D correlation that is expressed in terms of Eq. (2), was developed by means of data calibration using synthetic images that were generated from CFD-DEM data. In the synthetic images, particle and background phases corresponded to minima and maxima intensities respectively. One of the basic features that was assumed in the calibration of this technique was that particles’ intensity was lower than background’s in all locations of the domain. In order to confirm this, maxima and minima intensities are stored over the whole length of a single experiment.

Evidence of the robustness of this method is shown in Fig. 2. The maximum intensity field closely corresponds to the image of the setup background when this is empty. Steel scratches, sampling ports and other manufacturing imperfections are even captured by image Fig. 2b, which perfectly describes the reactor background. It should be noticed that these intensity fields were registered during an experiment where particles are present throughout the whole domain (as image Fig. 2a shows). The minimum intensity field is interpreted as the intensities of the particle phase.

Thus, it can be assumed then that the calibration performed in a previous work [25], is a suitable method to perform solids volume fraction measurements with the visual characteristics we have in our experiments.

3.3. Cluster detection

Given that PIV/DIA techniques provide full-field data of solids volume fraction and velocity, we can analyze the influence of operating conditions on the total degree of heterogeneity. In order to do so, we

![Fig. 2. a: Original image snapshot. b: Maximum intensity field. c: Minimum intensity field. d: Contrast or difference between maxima and minima intensity fields.](image-url)
suggest to use uniform thresholds of solids volume fraction to detect clusters rather than thresholds based on flow fluctuations, e.g. Soong and Sharma cluster definitions, or depend on data density distributions (e.g. Yang and Zhu cluster definition). Since we attain full-field data of solids volume fraction, we can easily apply a uniform \( \phi_c \) threshold over the whole domain. Since clusters have been found to be consist of a dense core and a more dilute surrounding particulate phase [1], we apply a double threshold definition in order to detect cluster cores and wakes. The probability density distribution of solids volume fraction of one interrogation area is shown below:

From Fig. 3 we can see that the typical probability density distribution is nearly zero between solids volume fraction values ranged between 0.3 and 0.59. The cause resides in the asymptotic behavior of Eq. (2), which tends to \( \phi_c = 0.6 \). Therefore, to distinguish the cluster cores, we set to 0.4 the cluster core threshold, which variability does not affect the number of detected clusters. However wake thresholds around 0.1, led to occasional cluster overlapping, making the cluster detection more complicated. To avoid cluster overlapping issues, we assume that cluster wakes should be denser than \( \phi_c = 0.2 \). Concerning cluster size, we adopted one of the Soong criteria: clusters should be bigger than one order of magnitude above the particle diameter to suppress too much noise in our parametric study (so larger dense areas than \( 5 \times 10^{-3} \text{ m}^2 \), corresponding value to a circular area of 8 mm of diameter). Thus, denser areas than \( \phi_c = 0.2 \) that had core regions above \( \phi_c = 0.4 \) (dense core) were detected as clusters. Although the selection of these thresholds are by some means arbitrary, the provided measurements are not affected by either system fluctuations or the density of the system.

Grayscales are directly correlated to \( \phi_c \) data by Eq. (2). In an idealized case, very dense regions would reach \( \phi_{c2D} \) values very close to 1. However, we observe that fully filled interrogation areas of \( 8 \times 8 \) pixels, reach lower values than 0.99. This might be due to reflections at the pixel level or small variations on the particles’ intensity that slightly decrease the intensity of the fully occupied interrogation area. In a dense experiment, we expect that there are always a few fully covered interrogation areas along the height of the riser. Thus, if we register the \( \phi_{c2D} \) values of interrogations areas during an experiment it is expected that most of the interrogation areas will have been fully covered at least once. In Fig. 4, a 2D bitmap of the maximum intensity at the grid level (\( 8 \times 8 \) pixels) is shown. We see that clusters reach different maxima \( \phi_{c2D} \) values ranging between 0.91 and 0.98 approximately. We also plotted the probability density distribution of \( \phi_{c2D} \) values of an interrogation area over 2500 images. It can be noticed that high \( \phi_{c2D} \) values (dense phase) are more frequently occurring in an experimental snapshot. We also see that the dense phase hardly reaches ideal values equal to 1 and that the high peak starts from values \( \phi_{c2D} > 0.92 \) approximately. When we apply the cluster detection algorithm we do not want to miss out particle clusters that due to reflections, prevent the realization of the ideal 2D value of 1. Accordingly we set a \( B \) value of 0.92, which according to Eq. (4) corresponds with a \( f \) value of 0.156.

For comparison purposes, two other cluster detection methods are also employed, namely, a method based on the Soong criteria and one based on a two-pass Otsu filter [16] (the cluster size requirement from Soong’s criteria was common in all three cases).

Brereton and Grace introduced the concept of intermittency index [26] (\( \gamma \)), which is defined as the ratio between the standard deviation of the local solids volume fraction fluctuations and the one existing in a fully segregated flow with an identical time-averaged value. An idealized fully segregated flow (\( \gamma = 1 \)) would be characterized by clusters surrounded by a particle-free gas phase. If pure core annulus flow is found (\( \gamma = 0 \)), this would be characterized by a sharp solids volume fraction gradient between the riser core and the region near the walls. The study of this parameter with operating conditions can be quite revealing when cluster detection is performed [41].

As previously mentioned, Yang and Zhu [16] employed a two-pass Otsu filter to detect clusters. This method is quite efficient to detect dense particle groups and requires constant illumination conditions, which has to be calibrated in advance. In our case, constant illumination conditions over the whole flow field are difficult to apply (due to the large recorded area). Thus, we normalize the images with the temporal histogram method and apply two local Otsu filters to discriminate clusters from the lean particle phase, making use of a cluster search detection method suggested by Yang and Zhu [16]. In the Results and discussion section, this method will be compared to two other cluster detection methods (e.g. Soong and Sharma, and uniform core-wake \( \phi_c \) thresholds) to observe how the cluster definition can influence the properties of the identified clusters.

### 3.3.1. Cluster quantification

Experimental images were post-processed with a Matlab® script in order to compute solids volume fraction (Eq. (2)), solids mass flux (Eq. (3)) and perform a quantitative analysis of cluster properties. The centroid, location, diameter and aspect ratio of all clusters are detected by means of the Matlab® function "regionprops". The centroid of each cluster corresponds to the center of mass of a group of particles. To estimate this parameter, the centered coordinates of the occupied interrogation areas of a cluster were weight-averaged according to the image density.
By spatially binning the cluster-centroids the wall influence of cluster formation can be investigated. The coordinates of the centroids are binned into 10 equally spaced bins across the cross sectional direction of the system. The number of centroids in each bin is determined. Another way to determine the spatial distribution is the cluster time fraction, $F_c$. This number is computed for each interrogation area. It is the fraction of time an interrogation area is residing in the cluster phase.

Last, the cluster volume fraction ($m^3$ of cluster phase/$m^3$ of riser), $\varphi_{\text{cluster}}$, is computed as the total volume of solids in clusters divided by the total volume of the riser. By dividing the cluster volume fraction by the average solids volume fraction, $\varphi_{\text{cluster}}/\varphi_s$, the cluster hold up is obtained, i.e., the fraction solids that is part of clusters.
4. Results and discussion

4.1. Fluidization regime

To clearly identify the fluidization regime of our experiments we have complemented our experiments with pressure drop measurements. These have been performed at 2 cm above the gas distributor. Although we have full visual access to the flow field, in industrial units, visual analysis is not possible to perform and pressure sensors are extensively employed in order to characterize the fluidization regime.

These experiments were performed at a constant solids mass flux of 32 kg/m²s over a range of superficial velocities. In Fig. 5, when increasing the gas superficial velocity, a sudden increase of the pressure drop standard deviation occurs around 0.9 m/s, the point at which bubbling fluidization (BR) starts. Beyond this point and upon further increasing the superficial velocity to approximately 2.8 m/s, a maximum in the standard deviation of the pressure fluctuations (σ) is found, revealing that the transition point between bubbling and turbulent regimes takes place [29,41]. The onset of the turbulent fluidization regime is reached when the pressure drop oscillations start to decrease with the gas superficial velocity. For a broad range of U, the experimental recordings describe a turbulent regime (TR) without carryover of particles to the top of the riser. The flow, under these conditions, is characterized by a continuous gas phase, where particle aggregates form and slug flow takes place. Bai et al. [41] determined that a gradual decrease in σ is a sign of that fast fluidized regime was reached with Geldart A particles, while conveying regimes were characterized by a constant σ value. However, for our particles (Geldart D) we find that σ is continuously decreasing, even at turbulent regime conditions, within the range U = 2.8–5.16 m/s.

In our experiments, particles carryover was possible at velocities beyond U = 5.16 m/s (U_TR - onset velocity of particles transport). Although the pressure drop decreases at slightly lower velocities, partial carryover of the particles was not possible until U = 5.16 m/s. Thus, as Fig. 5 shows, the pressure drop, which has been constant during the whole turbulent regime, starts to drop as soon as the solids inventory in the riser is reduced (FF - fast fluidization regime). When further increasing the velocity the pressure drop reduction becomes sharper and the pressure drop fluctuations decrease as well. Very occasional cluster formation takes place under these conditions, where particles heavily collide with the top wall, generating a solids reflux.

The PIV/DIA experiments that are presented in this manuscript are done under the following U = 5.16, 5.55, 5.95, 6.35 and 6.74 m/s, i.e., in the turbulent to fast fluidization regime.

Fig. 8. Time-averaged solids fraction profiles at different superficial velocities at several gas superficial velocities. a) U=5.16m/s. b) U=5.55m/s. c) U=5.95m/s. d) U=6.35m/s. e) U=6.74m/s.
4.2. **Solids volume fraction**

4.2.1. **Full field hydrodynamic data**

In this subsection we display an example of a full-field data set of a single experiment. The aim is to show that the combined PIV/DIA technique is able to generate hydrodynamic data of the whole experimental domain. In Fig. 6, we show the 2-D field of the time-averaged solids volume fraction data in a single snapshot. Such a data set provides complete information of the spatial solids distribution of each experiment, making feasible the detection of particle clusters in the whole system. It can be seen that denser regions are located close to the walls, whereas the core of the reactor is very dilute describing well the core-annulus behavior of the fast fluidization regime. This is consistent with the pressure measurements at $U = 5.95$ m/s (see Fig. 5).

4.2.2. **Axial profiles**

Axial profiles of time-averaged solids volume fraction were obtained at different gas superficial velocities. In Fig. 7, it is illustrated that an increase in the gas superficial velocity decreases the solids holdup of the system.

As it has been previously explained the solids mass flux in the system was regulated by a small opening in the recycling pipe. It has to be noted that in the experiment corresponding to the lowest $U = 5.16$ m/s, only few particles were carried over to the top of the reactor, leading to solids accumulation at the bottom. These densified regions were also present at the lateral inlet, blocking the particles feeding point after reaching steady state. Thus, it is more correct to say, that in this experiment, the system experienced a fluidization regime (where particles carryover was not complete), with a solids mass flux smaller than the value that is achieved at higher superficial velocities when there is a full carryover of the solids (32 kg/m$^2$ s).

At this transition point (see $U_{tr}$ in Fig. 5), the experiment is characterized by a high solids content at the bottom of the reactor, with a flat axial profile from the bottom region till a height of approximately 0.5 m. This can be a sign of saturation of the particle carryover at the densest region of the system. Beyond this point, the profile decreases along the axial direction describing a quasi-sigmoidal shaped edge between the dense solids bed and the freeboard section. This transitional shape has been previously associated by other authors to transient states from turbulent to fast fluidization regime [42,43].

In the rest of the experiments, the sigmoidal profile is lost and a gradual drop along the axial direction in the solids volume fraction is found instead. Beyond the minimum transport velocity, a rise in the superficial velocity, decreases the solids content of the system, measuring lower pressure fluctuations as well (see also Fig. 5). At a further increase of the superficial velocity to $U = 6.74$ m/s, particles travel upwards, even close to the walls, leading to solids volume fraction values below 0.02 at the freeboard section. Such low values of $(\phi_s)$, can be characteristic of pneumatic transport regime for this type of particles as Bai et al. [41] suggested.

4.2.3. **Cross sectional profiles**

Since the PIV/DIA technique supplies full-field data, we can also analyze the cross-sectional profiles of solids volume fraction at different axial locations. In Fig. 8, cross-sectional profiles at 4 different heights throughout the axial dimension of the pseudo-2D riser are plotted at different $U$ values. It can be seen that at $U = 5.16$ m/s and 0.2 m over the gas distributor, the solids density of the system is very high, reaching values up to $\phi_s = 0.3$. It is noticed that the profiles describe a symmetric U-shaped profile. At axial coordinates beyond 0.8 m, the solids holdup becomes significantly lower, what could delimit the edge between dense and freeboard sections under such operating conditions.

Further increasing the superficial velocity, at $U = 5.95$ m/s, the solids density gradient along the axial direction becomes narrower, showing a very slight drop in the solids volume fraction along the axial direction. In the experiment at $U = 6.35$ m/s, it can be seen that an asymmetry in the profiles is present at higher axial positions. This is most probably due to the high impact frequency of the particles with the top curved wall, which opening is on the left side (at $x = 0$ m). Last, at $U = 6.74$ m/s, the solids volume fraction profiles become flatter, indicating a very dilute bulk phase at all locations of the riser.

4.3. **Solids mass flux**

Solids volume fraction and solids velocity vector fields were combined to compute a solids mass flux field for each experiment. In each interrogation area the time-averaged solids mass flux was computed by means of Eq. (5).

In Fig. 9, the time-averaged solids mass flux vector field is plotted. It has to be noted that the time-average was performed during steady state of each experiment. There, we observe that the solids mass flux profiles develop along the axial direction. At the very bottom, the solids flow upwards at the riser core, while there is a strong solids downflow close to the walls. This trend gradually changes along the riser height. Above the top-half of the riser, the developed solids mass flux profiles are characterized by flatter profiles. This trend becomes more pronounced in the vicinity of the riser outlet, due to the solids impact with the top curved wall of the riser.

4.3.1. **Cross sectional profiles**

In the following set of figures, cross-sectional profiles of time-averaged solids mass flux are shown. At $U = 5.16$ m/s, the solids motion is characterized by a very high solids upflow in the center of the riser and downflow close to the reactor walls at the bottom section of the system. At higher axial locations, the solids mass flux is close to zero, since very few particles reach the top of the riser. In
Fig. 10a, it is seen that at the top the solids mass flux is very close to zero, meaning that particles do not reach the exit of the system. Thus, particles carryover does not take place under these operating conditions and turbulent fluidization prevails. This feature is consistent with previous shown results (see Figs. 5 and 8a). Upon increasing the gas superficial velocity to 5.55 m/s, solids recirculation is possible, leading to dense regions at the bottom and dilute ones in the top. In Fig. 10b, the solids mass flux increases at top positions, leading to a lower axial gradient of the solids mass flux and the core annulus behavior is well described. Actually, Fig. 10b, c and d show symmetric parabolic profiles that show a strong solids downflow close to the walls. At $U = 6.74$ m/s (see Fig. 10e) it is found that solids mass flux profiles adopt a biased shape, showing a solids upflow in the left part of the riser. It is worth to note again that the lateral outlet is found on the left side of the system, what causes a noticeable drop in the solids mass flux profiles on the top–right side due to the constant impact of particles with the curved stainless steel. The solids mass flux profiles describe a net solids upflow, even at the closest interrogation areas to the wall for $z = 1.1$ and 1.4 m. This result is consistent with previous results (see Figs. 5 and 8e).

It has to be noted that the net solids mass flux in axial direction was always conserved within $G_s = 32 \pm 12.8$ kg/m$^2$ s, when particles carryover took place (experiments b, c, d and e). However, it is observed that in densest bottom regions the deviation was even larger (up to 56 kg/m$^2$ s in densest bottom regions). It has to be noted that the solids volume fraction measurements have an error up to 18.33% [25]. This deviation resides in the difficulty to measure $\varphi_s$ between 0.3 and 0.6, where Eq. (2) tends to an asymptote $\varphi_s = 0.6$. This error is propagated into the computation of the solids mass flux. Although significant efforts have been made to elucidate the specific cause of this error built up in time, the only found explanation is that the solids volume fraction of mild dense phase ($\varphi_s = 0.3$–0.6) traveling upwards is systematically overestimated to 0.6. For this reason, time-averaged cross-sectional profiles of solids mass flux have been only reported above a height of 0.5 m, where the mass balance closes under tolerable margins. Thus, we do find this method suitable to measure time-averaged solids mass flux only under dilute riser flow conditions.

Observing Fig. 5, it can be seen that the pressure fluctuations decrease more gradually when the gas superficial velocity increases from 6.35 to 6.74 m/s, providing another feature that suggests regime transition from fast to conveying fluidization regime [38]. Thus, we assume that these experiments cover turbulent regime and fast fluidization regimes. Although, a very dilute an homogeneous flow is attained at $U = 6.74$ m/s, we observe that there is a solids downflow close to the right wall due to the solids impact with the top wall. This subtle feature refrains us to say that conveying fluidization is reached.
In Fig. 11b, a core-wake threshold is applied to detect clusters. The novel DIA technique enables the detection of particle clusters that meet the same criteria at all locations and independently of the flow intermittency or uneven lighting. All clusters with \( \phi \) above 0.2, which also have a dense particle core above 0.4 are identified in the snapshot. Furthermore, it can be noticed that detected clusters are denser than their surroundings.

In Fig. 11c, clusters detected with the Yang method are shown. It has to be noted that a two-pass Otsu filter was applied after image normalization in order to detect clusters. It can be observed that different entities than in Fig. 11a and b are detected. A first Otsu filter was employed to detect the dense phase of the riser, for which a second Otsu filter was applied. It can be noticed that densest regions of the system are efficiently detected. However, it is observed that thresholds computed with the Yang method significantly change between images. This is due to the fact that the image density data distributions change over time and therefore cluster definition changes as well. So cluster detection methods based on uniform thresholds (core-wake method) of solids volume fraction are more suited for quantitative purposes.

4.4. Cluster quantification

4.4.1. Full field cluster detection

Full field visual access and an accurate measurement of the solids volume fraction data field makes reliable cluster detection possible. In Fig. 11b, we show an instantaneous snapshot of an experiment where few clusters are detected by setting uniform core-wake thresholds. In the Introduction, different cluster concepts reported in literature were mentioned. It has to be noted that our observations are in accordance with those of other authors [1,16]. These are that clusters are ellipsoidal groups of particles, composed by a dense core and a dilute phase. Green circles represent clusters flowing upwards whereas red ones represent clusters falling downwards.

In Fig. 11, we show detected clusters using the three different methods that were introduced in a previous section (core-wake thresholds, Yang method and Soong criteria). The same experimental image has been employed to illustrate the influence of the cluster detection method. Noticeable differences can be observed. When we apply Soong criteria, we observe in Fig. 11b that cluster regions do not correspond to those regions exhibiting a solids volume fraction above \( \phi \) + n \cdot \sigma \) (see Fig. 11a). For instance, in Fig. 11c, it can be observed that dilute clusters located at the middle of the riser are identified as clusters. This is a consequence of the low thresholds when Soong criteria are applied. In this area a more homogenous flow prevails and lower \( \phi \) thresholds are computed in the most dilute regions of the system. This feature has a direct impact on the cluster frequency quantification when Soong criteria are applied, since this could lead to the detection of dilute groups of particles at the riser core, while there are significantly denser clusters close to the walls.

In this subsection, we perform the core-wake cluster detection and quantify the cluster frequency. In this way, only clusters with internal solids holdup above 0.2 and core solids volume fraction above 0.4 were detected.

These results confirm that clusters are more prevalent close to the walls while the riser core is always more dilute within the fast fluidized regime. When the gas superficial velocity is raised, cluster formation is less frequent. Fig. 13 shows that a cluster detection method based on solids volume fraction threshold provides consistent results with previously reported findings, i.e. intermittency index (Fig. 11).
Cluster time fraction. In Fig. 14 we also show the cluster time fraction of the five performed experiments. We observe that cluster phase is highly present at onset velocity of particle transport ($U_{TR}$), reaching values close to 50% of the duration of the experiment, in the bottom region close to the walls. The cluster time fraction decreases at higher superficial velocities and axial positions. We can see as well that bottom and freeboard sections are quite distinguishable at low velocities, while these quantitative differences become significantly less pronounced at $U = 5.95$ m/s. Under pseudo-pneumatic transport conditions ($U = 6.74$ m/s), cluster time fraction is very low, with rare cluster detection events on the right side of the domain. As it was previously explained, here we capture again the cluster formation due to the high collisional frequency of the particles with the top curved wall, which right side is bented towards the outlet on the left side.

It is therefore noted that the cluster time fraction strongly depends on the height, and the superficial velocity. In this way we can confirm that the obtained constant profiles by other authors of the cluster time fraction at changing operating conditions can be a consequence of the employed criteria to detect clusters, as other authors already suggested [18,47].

Cluster size and holdup. In this section, the cluster phase holdup has been quantified according to definitions mentioned in Section 3.3. From Fig. 15, it can be seen that at 5.16 m/s, the cluster holdup is around a 60% of the total solids volume in the system, while it is almost zero at conveying fluidization conditions ($U = 6.74$ m/s). The solids content in the experimental unit changes with operating conditions.
The average cluster mass significantly decreases with increasing the air to solids mass flux ratio. Close to turbulent fluidization regime conditions, clusters are much larger than those formed under fast fluidization conditions.

**Internal solids volume fraction.** By means of this technique, interrogation areas that are occupied by clusters have known values of solids volume fraction. We spatially average the solids holdup of these areas to compute the mean cluster solids holdup. We observe in Fig. 16 that identified clusters have internal solids volume fractions between $\langle \phi_s \rangle$ ranging from 0.25 to 0.6 approximately.

In Fig. 16, cluster mean solids holdup is plotted versus the centroid location in the horizontal direction. From this figure we can see that clusters are more dilute in the core of the riser, while denser clusters are only present close to the walls.

In Fig. 16, we can see as well that the heaviest clusters are concentrated close to the walls, while the lightest ones are located in the core of the domain. We can perceive as well that cluster centroids...
Fig. 16. Left: cluster bulk density vs centroid location. Middle: cluster area vs centroid location. Right: cluster particle number vs centroid location (U=5.95 m/s).

Fig. 17. Left: clusters aspect ratio vs cluster size. (U=5.95 m/s). Right: cluster aspect ratio vs cluster velocity.

Slightly shift from the walls to the center when they grow in size as well as they are larger near the walls than in the core.

Cluster aspect ratio. It has to be noted that results in Fig. 17 are merely reported for qualitative analysis, since clusters aspect ratio are highly influenced by the geometrical characteristics of the pseudo-2D experimental unit.

However, certain observations can be made. According to Zou et al. [48] there exists a certain tendency of the biggest clusters to have higher aspect ratios. Clusters’ aspect ratio seems to be independent of their mean velocity and size.

Cluster velocity. By means of PIV/DIA, we can systematically identify clusters and measure their velocity. In Fig. 18, we show a snapshot sequence of three clusters falling downwards close to the walls and another travelling upwards in the core region. We infer as well how particles impact on the falling clusters and some others circumvent the clustered region (with vectors pointing outwards the cluster trajectory).

The experimental technique provides the cluster velocity and cluster internal solids holdup. In Fig. 19, we plot the velocity and mass of 500 clusters approximately at U = 5.95 m/s. We observe that most clusters have a negative velocity, regardless of their mass. We also notice that there is a certain tendency of biggest clusters to fall downwards instead of travelling upwards. At U = 5.95 m/s, clusters velocities are registered to range between +2 and −2 m/s with significant higher frequency of clusters falling downwards. Whereas, under pseudo-pneumatic transport conditions, cluster velocities are much lower in terms of magnitude, either they are positive or negative. Besides, the heaviest cluster is up to 4650 particles approximately, while at U = 5.95 m/s is composed of around 9730 particles approximately. As Fig. 20 illustrates, clusters fall downwards close to the walls, while these flow upwards in the core.

Fig. 18. Snapshot sequence of moving clusters. In the snapshot we observe an experimental image superimposed with the instantaneous particle velocity vector field. Time difference between the frames is 0.01s.
In Fig. 20 (U = 6.74 m/s), we see that most of the clusters are formed in the right side of the domain and their mean velocities range between −0.5 and +0.5 m/s. Under fast fluidization conditions, core–annular shape of the cluster distributions holds. However, a flat profile is attained at U = 6.74 m/s. Thus, superficial gas velocity has a strong dependence on the cluster characteristics.

5. Conclusions

The application of a novel DIA technique, enables a full-field hydrodynamic study under riser flow conditions. Full-field solids volume fraction, solids mass flux and cluster-related parameters have been reported. Experiments under turbulent and fast fluidization regimes have been extensively characterized and distinguished by means of a combined PIV/DIA technique. Besides, this study provides insight about cluster identification and characterization due to the complete visual access of the riser flow.

This paper shows how PIV/DIA technique can supply a detailed and extensive experimental data. These data can, e.g., be used to validate CFD models predicting riser hydrodynamics and clustering phenomena. Moreover, this technique has been shown to be very powerful to evaluate cluster detection methods. It has been shown as well that the cluster definition strongly affects experimental findings, especially when operational conditions are changed. Although this issue has not been fully solved in this paper, a suited correlation isings, especially when operational conditions are changed. Although this issue has not been fully solved in this paper, a suited correlation

6. List of symbols

Roman symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>A, B</td>
<td>fitting parameters (–)</td>
</tr>
<tr>
<td>D</td>
<td>depth of pseudo 2D domain, m</td>
</tr>
<tr>
<td>d_p</td>
<td>particle diameter, m</td>
</tr>
<tr>
<td>\langle v_s \rangle</td>
<td>time-averaged solids mass flux vector, kg/(m^2·s)</td>
</tr>
<tr>
<td>M</td>
<td>magnification factor, pixel/m</td>
</tr>
<tr>
<td>\bar{\delta}_p</td>
<td>solids displacement vector, m</td>
</tr>
<tr>
<td>\Delta t</td>
<td>time frame between two consecutive images, s</td>
</tr>
<tr>
<td>U</td>
<td>gas superficial velocity, m/s</td>
</tr>
<tr>
<td>\bar{v}_p</td>
<td>solids velocity vector (m/s)</td>
</tr>
<tr>
<td>W</td>
<td>width of pseudo 2D domain, m</td>
</tr>
<tr>
<td>\bar{x}</td>
<td>position vector, pixel</td>
</tr>
<tr>
<td>x/W</td>
<td>dimensionless riser width (–)</td>
</tr>
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</table>

Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>\gamma</td>
<td>intermittency index, –</td>
</tr>
<tr>
<td>\rho_s</td>
<td>solids density, kg/m^3</td>
</tr>
<tr>
<td>\sigma</td>
<td>standard deviation of solids volume fraction fluctuations, \sqrt{\langle (\phi_s - \phi_s^c)^2 \rangle}, m^3 solid/m^3 reactor</td>
</tr>
<tr>
<td>\phi_c</td>
<td>cluster phase holdup, m^3 cluster/m^3 reactor</td>
</tr>
<tr>
<td>\phi_s</td>
<td>solids volume fraction, m^3 solid/m^3 reactor</td>
</tr>
<tr>
<td>\phi_{2D}</td>
<td>normalized 2D intensity, dimensionless</td>
</tr>
</tbody>
</table>

Acknowledgments

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References


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