



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



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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 [6] 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 illuminance 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 lab-scale 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 illuminance 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 of 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., $\langle\varphi_s\rangle + n\cdot\sigma$, where $\sigma = \sqrt{\langle(\varphi_s - \langle\varphi_s\rangle)^2}$. 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 σ . 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 $\langle\varphi_s\rangle + n\cdot\sigma$ 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 $\langle\varphi_s\rangle + 2\cdot\sigma$ can be simultaneously detected.

It is 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-variant 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 specularly-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 PIV 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.

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