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Experimental investigation of 3D velocity by Tomographic Particle Image Velocimetry (Tomo-PIV) in a short riser section

R. de L. Amaral, G. J. de Castilho a*, M. A. Cremasco

School of Chemical Engineering, University of Campinas (UNICAMP), Campinas, Brazil

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Abstract

The measurement of instantaneous velocity field with high spatial resolution makes the Tomo-PIV (tomographic particle image velocimetry) technique attractive for the study of complex flows in circulating beds. The Tomo-PIV technique is employed for obtaining the velocity field of the fluid phase in three dimensions using tracer particles which follow the fluid. They are immersed in the fluid and illuminated by a source of pulsed light (laser) within a three-dimensional region. Images of the particles are recorded in the focus of several viewing directions using CCD (Charge-Coupled Device) sensors. The distribution of light intensity is discretized into a 3D array of voxels and then analyzed by interrogation of cross-correlation in three dimensions. The information field is returned in the form of instantaneous velocities of the measurement volume. This paper aims to present an experimental setup for an initial investigation of the velocity field of the particulate phase of a riser section of a circulating bed. The calibration errors were between 0.209 and 0.066 pixels and after the self-calibration errors were below 0.097 pixels. The volume investigated was 82 x 100 x 10 mm^3 with a resolution of 1571 x 897 x 113 voxels. The reconstructed volumes were processed using 3D cross-correlation with a volume interrogation size of 110 voxels decreasing to a final size of 16 voxels with a 75% overlap between adjacent interrogation volumes. The velocity field produced has 224 x 393 x 28 voxels.

Keywords: Tomo-PIV; riser; velocity field

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* Corresponding author. Tel.: +55-19-35213931; fax: +55-19-35213922.
E-mail address: guilhermejc@feq.unicamp.br.

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1. Introduction

The measurement of instantaneous velocity field with high spatial resolution makes the Tomo-PIV (tomographic particle image velocimetry) technique attractive for the study of complex flows. With the development of such technique, it can be applied in the analysis of gas-particle flow in the riser section found in a circulating bed. Gas-solids reactors are fundamental to many processes in chemical, petrochemical and metallurgical industries. A specific type of gas-solid reactor, the circulating fluidized bed (CFB), is found in relevant industrial applications because of their intrinsic properties of many such as efficiency and operational flexibility [1]. The gas-solids flow in the circulating fluidized bed is often characterized by the existence of dense clouds of particles referred to as particle aggregates or clusters [2]. Due to the different phenomena that occur in the gas-solids flow in a riser, the concentration of the particulate phase and other variables vary strongly with time. Among these phenomena, we highlight the formation and dissociation of clusters [3], the particle-particle interactions and particle-wall [4]. The phenomenon of aggregation and resulting back-mixture compromise the performance of the riser providing a non-uniform distribution of concentration of the particulate phase increasing the residence time distribution of particles [5]. This paper aims to present an experimental setup for an initial investigation of the velocity field of the particulate phase of a riser section of a circulating bed using the tomographic particle image velocimetry (Tomo-PIV) technique.

2. Tomographic PIV

The development of Tomo-PIV technique was motivated by the need to achieve a 3D measurement system that combines the optical arrangement of simple photogrammetric approach with a robust volume reconstruction process of the particles. Particles immersed in the flow (gas or liquid) are illuminated by a pulsed light source in a specific region of the 3D space. The pattern of scattered light is recorded simultaneously from multiple viewing directions using CCD (Charge-Coupled Device) cameras. The distribution of particles in 3D (object) is reconstructed as an intensity distribution of light in 3D from their projections on the CCD arrays. A single set of projections may result in different 3D objects. The determination of the 3D distribution of particle images is the topic of the tomography. The particle displacement (velocity) within a chosen interrogation volume is then obtained by the 3D cross-correlation of the reconstructed particle distribution at the two exposures [6].

The reconstruction of the object (the distribution of particles in 3D) images from digital requires prior knowledge of the mapping function F between the planes of the image **x**=(x,y) and the physical space **X**=(X,Y,Z). This is achieved by through a calibration procedure. The mapping function F is shown in Equation 1.

$$\boldsymbol{x} = F(\boldsymbol{X}) \qquad (1)$$

The procedure requires that the mapping function is set to a volumetric field [7]. The physical coordinates are the mapped to pixel coordinates (Equation 2).

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} X + dX(X,Y) \\ Y + dY(X,Y) \end{bmatrix} \qquad (2)$$

$$\begin{pmatrix} dX \\ dY \end{pmatrix} = \begin{pmatrix} a_0 + a_1 s + a_2 s^2 + a_3 s^3 + a_4 t + a_5 t^2 + a_6 t^3 + a_7 st + a_8 s^2 t + a_9 st^2 \\ b_0 + b_1 s + b_2 s^2 + b_3 s^3 + b_4 t + b_5 t^2 + b_6 t^3 + b_7 st + b_8 s^2 t + b_9 st^2 \end{pmatrix} \qquad (3)$$

The method of Soloff *et al.* (1997) is used to determine the mapping function in a plane perpendicular to the direction of observation. In this approach, the displacements dx and dy are determined using the normalized coordinates $s = 2(X - X_0)/n_x$ and $t = 2(Y - Y_0)/n_y$, where n_x and n_y are the image size in pixels and (X_0 , Y_0) is the origin, and are approximated by a third-order polynomial, as a function of s and t. The images calibration process is performed manually by the previous orientation of lines of sight of cameras, adjusting the camera lens, making sure that the complete image is in focus and targeting a calibration plate. The design of the calibration target is the most important part of carrying out a calibration. In general, different tests can require different calibration targets [8]. The deviations between the specific coordinates and the coordinates of the point are a good estimate of the accuracy of the method. The average deviation to the brands must be submitted between 0.05 and 0.1 pixel [9]. In order to reduce errors in mapping function, Wieneke (2008) proposed a procedure for self-calibration volumetric using images recorded after a pre-processing. The pre-processing of the image is an important step in self-calibration of the volume and consequently the quality of the tomographic reconstruction. It is used to remove the background image (intensity level of light different from zero) and equalizing the intensity of light scattered by particles in the image.

A tomographic reconstruction technique has been extensively discussed by Elsinga *et al.* (2006). The accuracy of the tomographic reconstruction depends on the number of parameters including the number of cameras, the concentration of particles in the images and the angles between the directions of view. The configuration adopted is four cameras with viewing angles within the range of 15 and 40 degrees [11]. In the Tomo-PIV technique, the three-dimensional distribution of light intensity can be divided into smaller volumes of interrogation, which are correlated by the cross-correlation 3D to provide data flow field. The determination of the particles images displacement throughout the volume requires the division of the pairs of particle volume intensity for a series of reconstructed 3D sub-volumes which are then interconnected in 3D [12]. The cross-correlation effects have been extensively studied by Raffel *et al.* (2007) and Keane and Adrian (1992). The cross-correlation analysis can be performed with an iterative technique based on the window deformation technique of interrogation [14], extended to fields of intensity three dimensional, in which the volume of interrogation are displaced / deformed based on the result of the interrogation before. Multiple steps may be employed in the interrogation, where the interrogation volume size may be progressively decreased.

3. Experimental set

Experimental tests were performed using a fluid phase and solid phase. The fluid phase is the ambient air and the solid phase is composed by FCC (fluid catalytic cracking) particles (dp = 70 microns). The multipurpose unit is a circulating bed which is composed of: blower, with maximum flow of 3.9 m^3/min and pressure of 3600 mmH2O; riser; downer; 1st stage cyclone, 2nd stage cyclone; storage tank; solids screw-type feeder which provides a maximum flow of 3.5 kg of catalyst/min, frequency inverter, with maximum speed of 60 rpm; rotameters for flow rates from 11.7 to 117 m^3/h; rotameters for flow rates from 0 to 50 m^3/h, orifice plates and water columns for measuring the flow in the riser. The riser section region used for Tomo-PIV measurements to find the velocity vectors presents 10 cm height, 8.20 cm of internal diameter and it is located approximately 80 cm far from the entrance section of the riser. The air flow is 140m^3/h and the particulate phase flow rate is equal to 60 g/s. The schematic of the circulating bed is shown in Figure 1a.

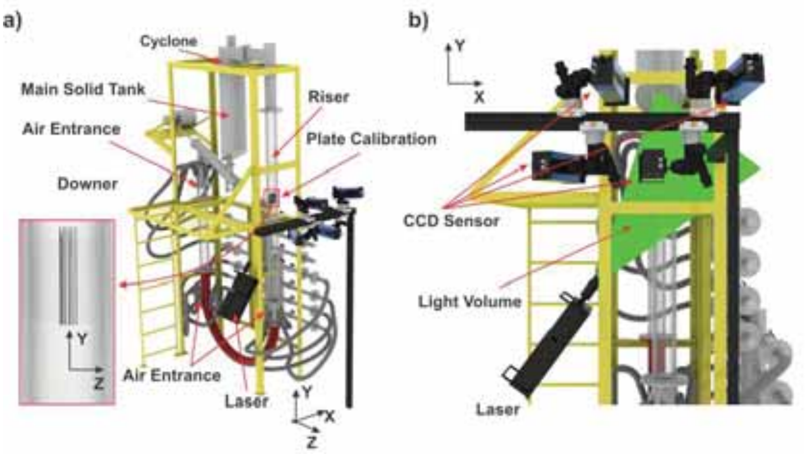

Fig .1. a) Circulating bed highlighting the position of the calibration plate; b) Tomo-PIV arrangement.

The PIV system used is a tomographic one (Tomo - PIV) developed by LaVision, which allows speed measurement in three dimensions with up to one million vectors per volume , requiring four cameras. These cameras can display resolutions up to 1648 x 1214 pixels with 14-bit digital output with 30 frames/s. In the system employed, it was used the Nd:YAG with an interval of 80 µs between pulses. As shown in Figure 1b, the CCD sensors are positioned perpendicularly to the volume of light. This is the condition of light scattering in the particles and to prevent the laser beam in direct contact with the CCD sensor. Cameras and laser were controlled with a programmable time unit (PTU). The imaging system was calibrated by the scanning of a plate through the volume in the direction of depth Z. The first view calibration was recorded at the center of the riser (z = 0) and it was then recorded for a position Z equal to -8 mm, - 4 mm, 4 mm and 8 mm. Figure 1a shows the positions of the calibration plate on the riser. A third order polynomial fit describes the calibration for each plane, the relationship between the physical coordinates (X, Y, Z) and the image coordinates (x, y).

The recorded images were preprocessed to remove the background image to match the intensity of light and to decrease the amount of ghost particles (false peaks of intensity of light) in the image. Seven procedures of preprocessing were made: subtract minimum sliding over an area of 3 x 3 pixels to remove the background image (intensity level of light different from zero); normalization of the light intensity on the sliding area of 100 x 100 pixels to equalize the low spatial frequency differences in the intensity of laser light sheet; Gaussian smoothing of 3 x 3 pixels to improve the quality of the reconstructed volume; applying of a sharpening filter; applying a filter which subtracts 200 counts of each pixel; applying a filter which multiplies each pixel in intensity by 5; use of a mask to limit geometric region to be studied. The maximum allowable error in the self-calibration was of 3 pixels.

The distribution of the volume intensity of measurement was reconstructed using MART (multiplicative algebraic reconstruction technique) algorithm discussed by Elsinga *et al.* (2006) in a volume of 82 x 100 x 10 mm^3 with a resolution of 1571 x 897 x 113 voxels using 10 iterations. The reconstructed volumes were processed using the cross-correlation 3D with a size of the interrogation volume 110 voxels decreasing to a final size of 16 voxels with an overlap of 75% between adjacent interrogation volume, producing a velocity field 224 x 393 x 28 voxels. The computer used is an Intel Xeon X5650 2.67 GHz, 36 GB of RAM. The software used was the Davis 8.0 LaVision.

4. Results

Figure 2 shows the images of the "Camera 1" recorded in the riser section for different time intervals. One can easily see two phases present in the riser: a disperse one and a phase with clusters. The form of clusters is generally irregular and its size is highly variable. Figure 3 shows the original image and its preprocessing. As expected, the preprocessed image presented a background level (intensity different from zero) smaller than the original one. The normalization of the intensity light decreases the intensity differences due to changes in scattering angles (mainly in air) and the intensity differences between the first and second laser pulse. The use of Gaussian smoothing and sharpness of the filter assembly results in a good noise reduction without increasing the intensity of ghost particles.

The error mapping function, quality of camera calibration, can be given by the Euclidean distance between the average of the measured points and the projected points x calculated on the camera model and the known global coordinates X. This error criterion also called the error back-projection, based on calibration of a single camera and gives no information about the accuracy of multiple cameras configuration [15]. The error mapping function, Equation 5, for calibration and self-calibration is presented in Table 1 for each camera and each plan.

$$\varepsilon_{cam} = \frac{1}{N}\sum_{i=1}^{N}\left\| F(\boldsymbol{X}) - \hat{\boldsymbol{x}}_i \right\| \qquad (5)$$

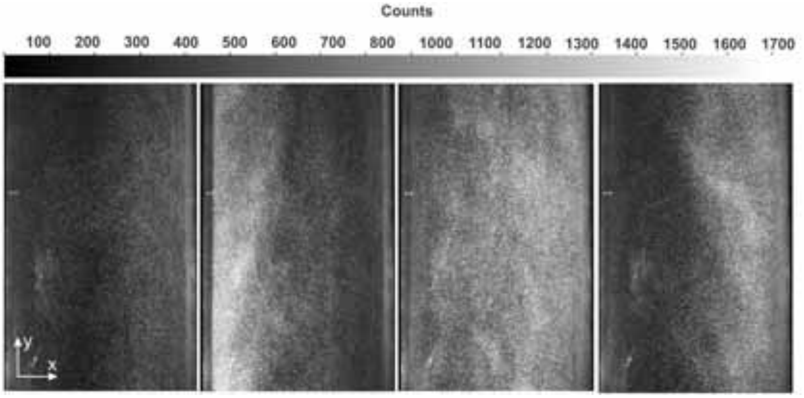

Fig. 2. Images from Camera 1.

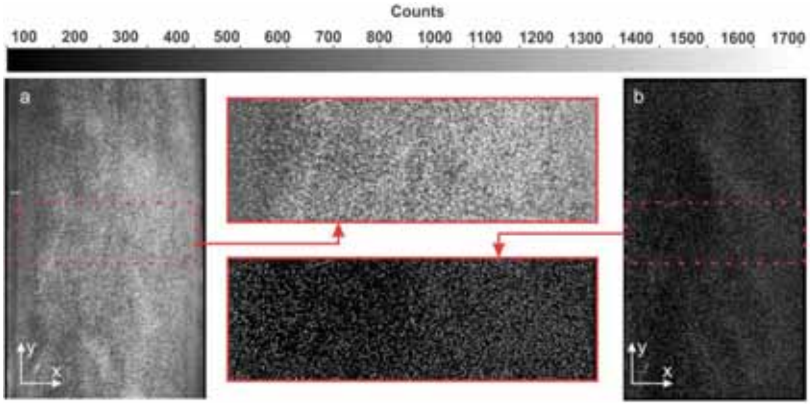

Fig. 3. Image of a camera (a) without preprocessing and (b) with preprocessing.

Table 1. Parameters of calibration and self-calibration

z(mm)	Error in calibration (pixel)				Error in self-calibration (pixel)			
	Camera 1	Camera 2	Camera 3	Camera 4	Camera 1	Camera 2	Camera 3	Camera 4
-8	0,1420	0,1172	0,2089	0,0873	0,0777	0,0796	0,0754	0,0873
-4	0,1365	0,0848	0,1673	0,0664	0,0613	0,0647	0,0598	0,0664
0	0,1365	0,1164	0,2015	0,0722	0,0719	0,0637	0,0661	0,0722
4	0,1157	0,1130	0,1791	0,0858	0,0884	0,0731	0,0769	0,0724
8	0,1057	0,0945	0,1605	0,1035	0,0875	0,0971	0,0867	0,0770

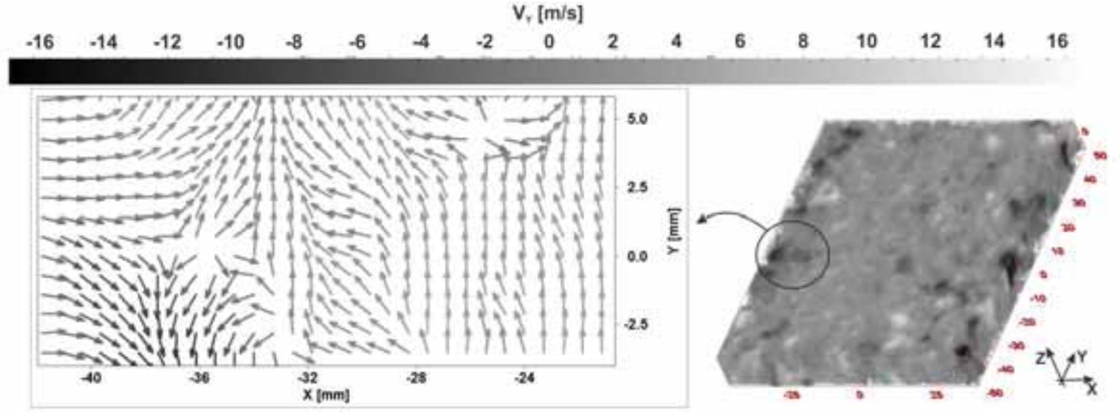

Fig. 4. Instantaneous velocity field of the riser section.

A volume mapping is achieved by the interpolation between the calibration of multiple plans. The depth of the measuring volume should not exceed four times the depth of calibration (LaVision, 2010). It is noted that the mapping function had initial errors between 0.2089 and 0.0664 pixels. After the self-calibration errors are reduced to less than 0.0971 pixels. Figure 4 show the instantaneous velocity field obtained. The “Y” velocity component (V_Y) is highlighted. The maximum velocity was of 28 m/s and minimum of 0.01 m/s. In Figure 4 it can be seen that particles are falling near the wall (dark regions). In the center of riser (x = 0), particle velocities are higher ($Vy \approx 4$ m / s).

5. Conclusion

This paper presented an experimental setup for initial investigation of particulate phase velocity field in a riser section of a circulating bed, using the Tomo-PIV technique. A system of four cameras positioned perpendicularly to the volume of light has been used. The calibration errors were between 0.209 and 0.066 pixels and after the self-calibration, errors were below 0.097 pixels. The volume investigated was 82 x 100 x 10 mm^3 with a resolution of 1571 x 897 x 113 voxels. The reconstructed volumes were processed using the cross-correlation 3D with a size of the interrogation volume 110 voxels decreasing to a final size of 16 voxels with an overlap of 75% between adjacent interrogation volume. The velocity field produced has 224 x 393 x 28 voxels. The maximum velocity found was 28 m / s and minimum was 0.01 m / s.

Acknowledgments

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References

[1] Berruti F, Chaouki J, Godfroy L, Pugsley TS, Patience GS. Hydrodynamics of Circulating Fluidized Bed Risers: A Review. *Can J Chem Eng* 1995;**73**:579-602.

[2] Grace JR, Matsen JM, *Fluidization*, Plenum Press, New York; 1980, p. 537–544.

[3] Zou B, Li H, Xia Y, Ma X. Cluster structure in a circulating fluidized bed, *Powder Technol* 1994;**78**:173 – 178.

[4] Jing Xu, Zhu JX. Visualization of particle aggregation and effects of particle properties on cluster characteristics in a CFB riser. *J Chem Eng J* 2011;**168**:376–389

[5] Wei F, Jin Y, Yu Z W, Chein W. Lateral and Axial Mixing of the Disperse Particle in LFC, *J Chem Eng Jpn* 1995;**28**:506 - 510.

[6] Elsinga GE. *Tomographic particle image velocimetry: and its application to turbulent boundary layers*, PhD Thesis, Faculty of Aerospace Engineering, Delft University of Technology, Delft, Netherlands, 2008.

[7] Raffel M., Willert CE, Wereley ST, Kompenhans J. *Particle Image Velocimetry - A Practical Guide*. 2rd ed. Heidelberg, Springer; 2007.

[8] Soloff SM, Adrian RJ, Liu ZC. Distortion compensation for generalized stereoscopic particle image velocimetry. *Meas Sci Technol* 1997;**8**:1441-1454.

[9] La Vision. *Product-Manual FlowMaster Tomographic PIV*. Göttingen; 2010.

[10] Wieneke B. Volume self-calibration for 3D particle image velocimetry. *Exp Fluids* 2008;**45**:549-556.

[11] Elsinga GE, Scarano F, Wieneke B, Van Oudheusden BW. Tomographic particle image velocimetry. *Exp Fluids* 2006; **41**:933-947.

[12] Humble RA. *Unsteady Flow Organization of a Shock Wave/Boundary Layer Interaction*, Master Dissertation, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, 2009.

[13] Keane RD, Adrian RJ. Theory of cross-correlation analysis of PIV images. *Appl Sci Res* 1992;**49**:191–215.

[14] Scarano F, Riethmuller ML. Advances in iterative multigrid PIV image processing. *Exp Fluids* 2000;**29**: S051–S060.

[15] Machacek M. *A Quantitative Visualization Tool for Large Wind Tunnel Experiments*, Master Dissertation, Swiss Federal Institute of Technology Zurich, Zurich, 2003.