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Experimental investigation of dilute solid-liquid suspension in an unbaffled stirred vessels by a novel pulsed laser based image analysis technique

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The availability of experimental information on solid distribution inside stirred tanks is a topic of great importance in several industrial applications. The measurement of solid particle distribution in turbulent multiphase flow is not simple and the development of suitable measurement techniques is still in progress. In this work a novel non-intrusive technique for measuring particle concentration fields in solid-liquid systems is employed. The technique makes use of a laser sheet, a high sensitivity digital camera for image acquisition and a Matlab procedure for post-processing the acquired images.
Experimental data are here obtained for the case of an unbaffled stirred tank. Stable toroidal attractors for particles are observed under given circumstances. Their existence, consistency and extension depends on particle type, fluid properties, tank geometry and impeller velocity.

1. Introduction

Suspensions of solid particles in liquids are largely employed in a number of applications. Such operation is commonly carried out in tanks stirred by suitable mechanical agitators. Most industrial stirred vessels are equipped with baffles, which ensure better axial circulation and mixing with respect to the case without baffles. However, there are many applications (Assirelli et al., 2008; Pacek et al., 2001), in which the use of baffles could generate some specific drawbacks. For example, in food and pharmaceutical industries it is matter of primary importance to keep the reactor as clean as possible. In crystallization processes (Hekmat et al., 2007) and biological application (Aloi and Cherry, 1996) where it is necessary to avoid any damage on growing particles or on cells culture, respectively. In precipitation processes baffles could be suffer from incrustation problems (Rousseaux et al., 2001). Moreover unbaffled vessels are preferentially adopted for the case of laminar mixing: they are preferred for this flow regime because in baffled systems some dead regions may exist in front of baffles.
In order to study the suspension of solid particles in stirred tank, a novel technique has been purposely developed, taking into account all the main, positive and negative, features of the measurement techniques available in literature for stirred tanks. Today, in scientific literature, two macro-categories of methods for the solid particle distribution assessment inside a stirred vessel exist: the *invasive techniques* and the *non-invasive techniques*.

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The sampling method and the measurement probes techniques belong to the first class and will not be described in the present work.

The main non-intrusive techniques known in literature are: the light attenuation, the radiative and the tomographic techniques. The first two categories measure the attenuation that a ray light (Magelli et al., 1990), or a *X*-ray (or a γ-ray, or a neutrons beam) (Fournier et al., 1993) undergoes while it crossing the same vessel. The results obtainable by these two methods are very reliable, but, they concern only the mean solid concentration along the line covered by the beam.

The tomographic techniques (electrical resistance tomography, *ERT* and the positron emission particle tracking, *PEPT*) are advantageous since they allow to get 2D distribution maps of solid concentration in stirred tanks. The *ERT* (Wang et al., 2000) measures the electrical signals, taken from all possible views of sensing electrodes surrounding the tank, but the presence of electrical noise may alter the reliability of the results. The *PEPT* (Barigou et al., 2003) involves the use of a labelled tracer particle, a positron camera and a location algorithm for computing the tracer location. This tomographic technique gives a distribution map of particle position probability, that is an indirect measurement of a concentration distribution map. This technique is also able to characterize suspensions with high concentration, but it is too expensive and it requires very long times-processing.

Considering the limits and disadvantages concerning all the techniques described so far, the idea of proposing a new measurement technique arises. Obviously, it would be innovative, non-invasive and able to produce reliable 2D solid distribution maps at acceptable costs and in reasonable times. This new technique has been named *Laser Sheet Image Analysis* and it will be described in detail in the following.

For the purpose of the present work the *LSIA* technique has been applied to the case of a solid-liquid suspension in an unbaffled stirred tank.

2. Experimental apparatus and *LSIA* fundamentals

The experimental system consists of three main parts: the investigated vessel, the degassing unit and the *LSIA* apparatus.

The vessel is a cylindrical, flat-bottomed, standard geometry unbaffled tank with a diameter T=0.19m, equipped with a six-bladed Rushton turbine. To avoid any optical distortion problems, the stirred vessel was inserted inside a bigger tank with a rectangular plant, accurately placed with the faces perpendicular to the laser and the videocamera action directions. In order to prevent the presence of air or simply air bubbles within the stirred vessel a purposely prepared degassing system was connected with the tank. The *LSIA* apparatus is depicted in Fig.1: it consists of the illumination system, the acquisition system, the synchronization system and a PC with the relevant software (*Flow Manager ver.3.7* and *Matlab)*. The illumination equipment is a double cavity ND:YAG pulsed laser of the *NEW WAVE RESEARCH*, *Solo III 15Hz* model. The acquisition system is a *Dantec 80C60 Hisense PIV* characterized by a 1280x1240 pixels CCD. The synchronization of the emitting-acquisition times of laser and videocamera are guaranteed by an acquisition-control unit with a *DANTEC* processor, *Flow Map 1500* model. This processor is connected via Ethernet peer to peer connection to a PC.

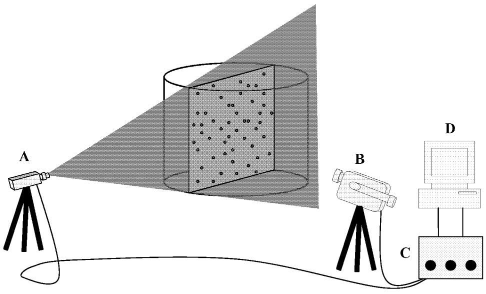

Figure 1: LSIA apparatus: A) pulsed laser; B) videocamera; C) control-acquisition unit; D) personal computer

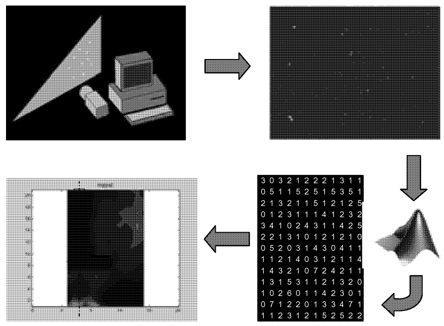

Figure 2: LSIA main phases

The novel *Laser Sheet Image Analysis* technique is based on the probabilistic elaboration of acquired images (Fig.2). A horizontal or vertical section of the investigated vessel is illuminated by a pulsed laser sheet; in this work only half diametrical vertical section is investigated. Solid particles are stochasticly intercepted by the laser blade and appear as bright little points, whose spatial distribution is captured by the videocamera, purposely placed perpendicularly to the illuminated plane. By suitably synchronizing the pulsed laser and the videocamera, it is possible to obtain an image. It is a grey-scale background image with some white peaks that correspond to the presence of particles. The images obtained in this way are elaborated in order to identify the particles and their position, accurately filtering those spurious white peaks that are not linked to the presence of particles. Then, by acquiring a high number of images (i.e. 2000) and by summing all their relevant position matrixes, it is possible to get a particle presence probability bidimensional distribution map. Such a map, multiplied by a constant, corresponds to a solid phase distribution map on the same vessel section. The final sum-position matrix is compressed of about 50 times in order to average the results and consequently reduce the data probabilistic scattering . All these elaborations are carried out by means of specific functions of the *Matlab image tool-kit*.

All the experiments were performed by filling the tank with deionised water and particles with a concentration of 0.2 g/l. Glass ballottini (density of about 2500 kg/m^3) of different sizes were utilized in the experiments. Besides, a number of angular velocities were investigated. All the data are summarized in Tab.1.

All the concentration maps are normalized with respect to the mean concentration C_m inside the vessel. In accordance with the cylindrical symmetry of unbaffled vessels, this concentration was estimated by summing all the pixel values of the final sum position matrix and dividing such a value by the total pixels number.

GLASS BALLOTTINI (density = 2500 kg/m^3)			
Diameter 125-150 µm	*Diameter 250-300 µm*	*Diameter 425-500 µm*	*Diameter 750-810 µm*
Agitation Speed			
300 RPM	300 RPM	300 RPM	300 RPM
400 RPM	400 RPM	400 RPM	400 RPM
500 RPM	500 RPM	500 RPM	500 RPM
600 RPM	------	600 RPM	600 RPM

Table 1: Experiments performed summary data

3. Results and discussion

If one starts to operate the stirred unbaffled vessel from still conditions, it can be observed that, as the impeller starts rotating, all the particles begin to move from the bottom until they form the first torus (the *lower torus*) which stands below the impeller. Increasing the impeller rotational velocity, it can be noted that some particles run away from the lower torus to reconstitute the *upper torus* in the upper part of the vessel. Increasing further the agitation velocity, the number of particles which move from the lower torus towards the upper torus increases consequently. Therefore, at high impeller velocities the upper torus is more favourite than the lower one. This evolution is well captured by the *LSIA* technique and it is visible for 250-300 microns glass ballottini in Fig.3: at 300RPM particles are all over the bottom, circulating within the lower torus, at 400 RPM many of them move towards the upper part of the vessel and form the second upper torus, at 500RPM almost all the particles shift from the lower torus to the upper one. Therefore it is clear that even at very high rotation speeds, no homogeneous condition is achieved with the presence of an upper torus only. It is worth noting that, for all cases with particles bigger than 125-150 microns, negligible concentration of particles are present in other vessel zones at any agitation speed, because almost all particles are essentially attracted by the two tori. The tori formation has been insufficiently investigated so far (Abatan et al., 2006). They are likely to result from the complex equilibrium arising among: gravity, buoyancy, walls constraining reactions, centrifugal forces, drag forces and particles inertia. If particles were without their own inertia they would be distributed more or less homogeneously in all the vessel, on the contrary, increasing particles inertia, their tendency to constitute the tori likely increases consequently. Evidence is given in Fig. 4, where 125-150 microns glass ballottini particles are compared with 412-500 microns ones at 400 RPM (i.e.particles of different inertia). Observing such a figure it is visible that bigger particles are less dispersed and more concentrated in the tori zones. In relation to this evidence, a quantitative investigation of the influence of particle size on dispersion was carried out. It was decided to quantify the particle dispersion degree by assessing the standard deviation of all the final particles distribution maps: the resulting trend is depicted in Fig.5. It confirms that particles with higher size intrinsically have got a higher inertia, a higher tendency not to follow the liquid main flow and concentrate in the toroidal attractors, thus resulting in a lower dispersion degree and therefore in a higher standard deviation.

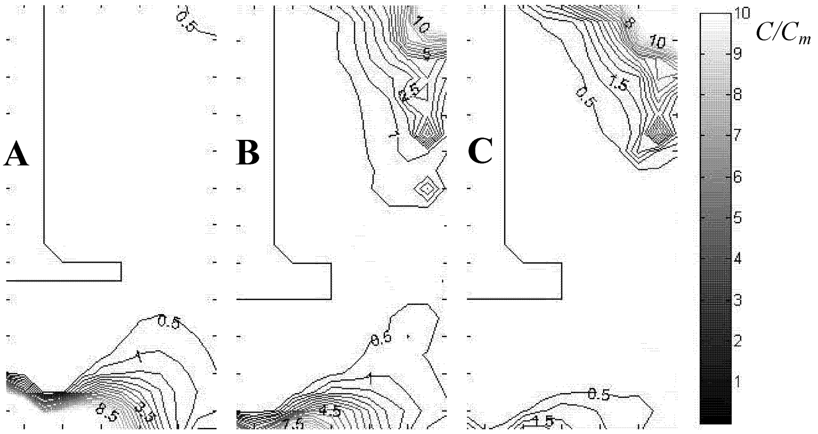

Figure 3: 250-300 microns glass ballottini solid concentration maps at: A) 300RPM; B) 400 RPM; C) 500 RPM

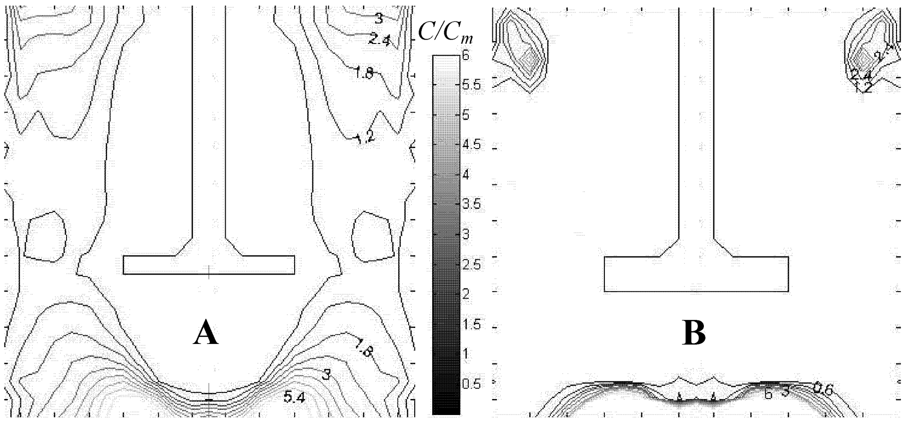

Figure 4: Qualitative particle size influence. Glass ballottini concentration maps at 400 RPM: A) 125-150 microns, B) 425-500 microns.

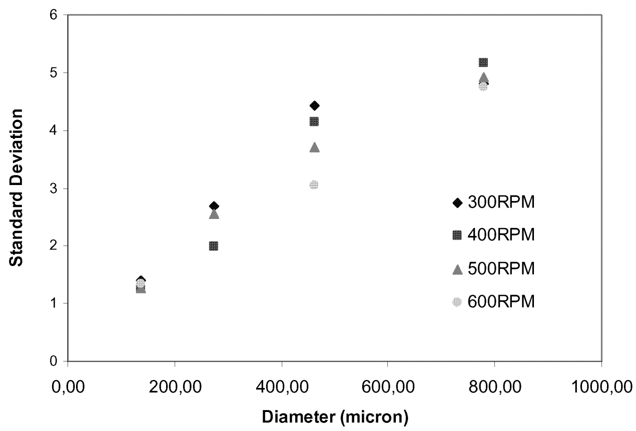

Figure 5 Quantitative particle size influence on particle dispersion degree.

3. Conclusions

A novel technique named *Laser Sheet Image Analysis* was developed and applied to a dilute solid-liquid suspension in an unbaffled stirred tank. The existence conditions and possible influences on the formation of two stable toroidal attractors for solid particles were investigated. *LSIA* technique appear to be very useful and promising: it was able to reproduce the same system behaviour visually observed. Moreover, it can be stated that the tori formation, opposing to particle dispersion, is favourite by an increase in particle inertia properties. Authors hope that this study could constitute a good validation tool for computational studies.

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References

Abatan, A.A., McCarthy, J.J., Vargas, W.L., 2006. Particle migration in the rotating flow between co-axial disks. AIChE Journal, 52 (6), 2039-2045.

Aloi L.E., Cherry, R.S., 1996. Cellular response to agitation characterized by energy dissipation at the impeller tip. Chem.Eng.Sci., 51 (9), 1523-1529.

Assirelli, M., Bujalski,W., Eaglesham, A., Nienow, A.W., 2008. Macro- and micromixing studies in an unbaffled vessel agitated by a Rushton turbine. Chem.Eng.Sci., 63, 35-46.

Barigou M., Fairhurst P.G., Fryer P.J., Pain J.P., 2003. Concentric flow regime of solid-liquid food suspension: theory and experiment. Chem.Eng.Sci., 58, 1671-1686.

Fournier, T. and Jeandey, C., 1993, "Optimization of an experimental setup for void fraction determination by the X-ray attenuation technique", in J.M. Delhayr and G. Cognet (Eds.), *"Measuring techniques in gas-liquid two-phase flows"* (pp. 199-228), Berlin, Heidelberg, New York, Tokio: Springer.

Hekmat , D., Hebel, D., Schmid, H., Weuster-Botz D., 2007. Crystallization of lysozyme: from vapor diffusion experiments to batch crystallization in agitated ml-scale vessels. Process Biochemistry, 42, 1649–1654

Magelli F., Fajner D., Nocentini M. and Pasquali G., 1990. Solid distribution in vessels stirred with multiple impellers. Chem.Eng.Sci., 45 (3), 615-625.

Pacek, A. W., Ding, P., Nienow, A.W., 2001. The effect of volume fraction and impeller speed on the structure and drop size in aqueous/aqueous dispersions. Chem.Eng.Sci., 56, 3247-3255.

Rousseaux, J.M., Muhr, H., Plasari, E., 2001. Mixing and micromixing times in the forced vortex region of unbaffled mixing devices. Can.Jour.Chem.Eng. 79, 697–707.

Wang M., Dorward A., Vlaev D. and Mann R., 2000. Measurements of gas-liquid mixing in a stirred vessel using electrical resistance tomography (ERT). Chem.Eng.Jour., 77, 93-98.