PIV measurements of mean flow and turbulence modulation in dilute solid-liquid stirred tanks

Giuseppina Montante, Marie-Hélène Occulti, Franco Magelli, Alessandro Paglianti

Department of Chemical, Mining and Environmental Engineering, University of Bologna, Bologna, Italy, alessandro.paglianti@mail.ing.unibo.it

Abstract This work is aimed at investigating the turbulent hydrodynamics of solid-liquid stirred tanks with particular attention to the effects of the dispersed phase on the turbulence levels of the continuous phase. The experimental data are collected by a two-phase Particle Image Velocimetry (PIV) technique in a fully baffled flat-bottomed cylindrical vessel stirred by a standard Rushton turbine. The effect of particle size on the liquid turbulence levels was investigated by adopting two different glass particles mean sizes ($d_p=774 \, \mu m$ and $d_p=115 \, \mu m$); the particle contents was increased stepwise from zero (single phase system) up to 0.2 vol. % with the bigger particles and up to 0.1 % with the smaller one, the difference being due to the different optical behaviour of the two suspensions. Overall, moderate dampening of liquid turbulent fluctuations was found with smaller particles, while turbulence enhancement was observed with the bigger ones. From preliminary interpretation of the results, based on the ratio between the particle diameter and the integral length scale of the continuous phase, our data agree with the Gore and Crowe (1989) findings relevant to pipe flow and free jets.

1. Introduction

Treatment of solid-liquid mixtures in agitated vessels is a widespread unit operation in the chemical, pharmaceutical, food and allied industries. Among the different aspects of interest for equipment design and process control, many open issues concern the turbulent characteristics of the two-phase flow and the capability to predict them by appropriate theoretical considerations or computational models. Indeed, multiphase turbulence has a strong impact on the performance of most stirred apparatuses of industrial interest, since it affects heat and mass transfer as well as chemical reactions: among others examples, catalytic slurry reactors and crystallizers can be mentioned (Derksen, 2003).

In the last decade, the modelling of turbulent solid-liquid flow in stirred tanks has been mostly tackled in the realm of computational fluid dynamics (CFD) techniques based either on Eulerian-Eulerian or Eulerian-Lagrangian approaches (Sommerfeld and Decker, 2004; Van den Akker, 2006), but in most cases the liquid turbulence modification due to the suspended particles has been ignored due to the lack of appropriate models.

Generally, turbulence dampening or augmentation in two phase flow was found to be related to the particle size with respect to a characteristic turbulence scale; specifically it has been often found that small particles tend to attenuate turbulence, while large particles augment it, but firm conclusions and generally accepted models that can be applied to all flow conditions are still not available (Crowe et al., 1998). Several experimental studies on turbulence modulation have been reported since the early 1990’s (Crowe, 2000), mainly for pipe flows or jets and with gas as the continuous phase, while limited information has been collected so far on stirred solid-liquid systems.

Advanced experimental techniques for the determination of detailed local information on turbulent solid-liquid stirred tanks have started being developed recently; therefore, so far the effect of particles on the continuous phase turbulence has been investigated in few solid-liquid stirred
suspensions only (Nouri and Whitlaw, 1992; Guiraud et al., 1997; Micheletti and Yianneskis, 2004; Virdung and Rasmuson, 2007, 2008; Unadkat et al., 2009). In fluid mixing, general consensus on the effect of particle size on liquid turbulence modulation has not been achieved yet, since the experimental data have confirmed the Gore and Crowe criterion in some cases (e.g. Virdung and Rasmuson, 2008) and they have not in others (e.g. Unadkat et al., 2009). Due to the limited amount of data available to date, additional experimental investigations may be useful for providing further insight into the system behaviour and for deeper investigating the effect of the solid-liquid system properties on the continuous phase turbulence.

The experimental data collected in this work are aimed at adding information relevant to different solid-liquid systems and stirred tank geometries with respect to the previously investigated conditions. They may be also adopted as a useful benchmark for CFD modelling validation of solid-liquid stirred tanks.

2. Experimental

The investigation was carried out in a stirred tank of standard geometry consisting of a cylindrical, flat-bottomed vessel of diameter $T=23.2$ cm and height $H=T$. The vessel was made of Perspex, was equipped with a lid and with four vertical baffles of width equal to $T/10$. Agitation was provided by a Rushton turbine of diameter $D=T/3$ placed at a distance $C=T/3$ from the vessel bottom. A schematic diagram of the experimental vessel is shown in Figure 1.

![Figure 1](image)

**Fig. 1** The geometry of the stirred vessel. The green area represents the measurements location.

For avoiding optical distortion at the curved surface, the vessel was contained in a square tank filled with demineralised water, that was the continuous phase adopted in all the experiments. As the solids, spherical glass particles of density $\rho_s=2470 \text{ kgm}^{-3}$ and two different narrow size distributions were used. The average diameter of the smaller particles was equal to $d_p=115 \mu m$ and that of the bigger ones was $d_p=774 \mu m$. Starting from the single phase condition, the mean solids concentration was increased stepwise adding small amounts of particles until the limiting solid concentration for making the PIV measurements possible and accurate was reached. The experiments were carried out at room temperature in batch conditions. The impeller rotational speed, measured with a tachometer, was fixed at $N=14.17 \text{ s}^{-1}$, that is higher than the “just suspended” condition for all the investigated systems. Indeed, the value of $N_{js}$ as calculated from the Zwietering correlation (Zwietering, 1958) for the bigger particles at the higher investigated concentration of 0.2 vol. % is
The flow regime was fully turbulent, being the rotational Reynolds number, Re, based on the physical properties of water equal to $8.8 \times 10^4$.

The vessel was entirely filled with the liquid and it was closed on top for avoiding air entrainment.

**The two-phase PIV technique**

The ensemble-averaged turbulent velocity fields of the continuous and the dispersed phases were measured in a portion of the vertical plane placed midway between two consecutive baffles using the PIV set-up whose main elements are shown in Figure 2, that is similar to that already applied to the investigation of gas-liquid and liquid-liquid stirred tanks by Montante et al. (2008) and Laurenzi et al. (2009), respectively.

![The PIV set-up.](image)

The technique allows to simultaneously and separately measure the mean and root-mean-square (r.m.s.) velocities of the two phases by a pulsed Nd:YAG laser and two cameras provided with appropriate light filters. In particular a New-Wave Solo Nd:YAG laser, emitting light at 532 nm with a maximum frequency of 15 Hz and two identical HiSense MK II, 1344×1024 pixels CCD cameras were adopted. The continuous phase was seeded by polymeric particles coated with fluorescent Rhodamin B emitting light at the wavelength of $\lambda=590$ nm, while the glass particles have the same emission wavelength of the laser light, thus allowing phase separation by light filters. The time interval between two laser pulses was calculated as the ratio between the required particle displacement, that has to be equal to a few pixels, and the impeller tip speed ($V_{\text{tip}} = \pi ND$) and it was finally fixed equal to 200 $\mu$s. For the liquid phase measurements, the interrogation area was set at $32 \times 32$ pixel, corresponding to about $5 \text{mm} \times 5 \text{mm}$, and the cross-correlation of the image pairs was performed on a rectangular grid with 50% overlap between adjacent cells. As a result, a velocity vectors were located on a grid of $2.5 \text{mm} \times 2.5 \text{mm}$. Afterwards, the instantaneous vectors obtained via cross-correlation were submitted to validation algorithms based on the evaluation of the peak heights in the correlation plane and on the check of velocity magnitude. The vectors that did not satisfy the selected validation criteria were discarded. Preliminary tests were conducted to set a suitable amount of seeding particles, number of image pairs and camera aperture in order to minimize the possible errors. A critical dependency of the r.m.s. velocities on the image number
was found and 2000 image pairs for each run were finally collected. It is worth observing that 2000 image pairs are sufficient to obtain sample-independent velocity fluctuations only if a very high percentage of valid vectors is obtained after the post-processing of the cross-correlation results, that is at least 1500 of the 2000 vectors have to pass the validation step and have to effectively contribute to the calculation of the r.m.s. velocity values.

The optical attenuation of the laser sheet across the measurement plane was acceptable up to 0.1 and 0.2 vol. % for the smaller and bigger particles, respectively; therefore, the application of this technique to solid-liquid systems is limited to very dilute conditions, although higher upper concentration limit might be obtained by adopting a more powerful laser light source. Moreover, since the percentage of validated vectors decreases moving from the vessel wall towards the centre due to progressive laser light attenuation, only the r.m.s. velocities collected in the plane portion closer to the vessel wall, that is identified by the green rectangle in Figure 1, were found to be quantitatively accurate.

In the following only the results relevant to the liquid phase in either single phase and two-phase conditions will be considered. The origin of the coordinates system is located at the centre of the vessel bottom and z, r are the axial and radial coordinates, respectively. The mean axial velocity, \(U\), is positive if directed upwards and the mean radial velocity, \(V\), is positive if directed towards the vessel wall. The axial and radial r.m.s. velocity will be named \(u'\) and \(v'\), respectively. The mean and r.m.s. velocities are normalized by the impeller tip speed and the axial and radial coordinate by the vessel diameter.

3. Results and Discussion

The liquid phase mean velocity in the two phase systems did not change appreciably with respect to the single phase flow with both particle sizes, as can be observed in Figure 3, where the color maps and the vector plots of the liquid mean velocity magnitude relevant to single phase and two selected solid-liquid systems are shown. Very small differences can be appreciated between the maps reported in Figure 3 (b) and (c), relevant to continuous phase flow without particles and with particles of diameter \(d_p=774\ \mu m\), respectively, while almost coincident velocity magnitudes were obtained with the smaller particles at all the investigated concentrations.

![Fig. 3 Maps of liquid mean velocity magnitude [m s\(^{-1}\)] and vector plots. (a) \(d_p=115\ \mu m\) 0.2 vol %; (b) single-phase; (c) \(d_p=774\ \mu m\) 0.2 vol %.

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In order to perform a more detailed quantitative comparison of the results, the mean axial and radial velocity profiles at a fixed radial location ($r/T=0.44$) obtained at various solid concentrations are compared in Figure 4: as can be observed, both the velocity components almost coincide in the single and two phase systems with the smaller particles, while a less negligible difference is apparent in the axial component only with bigger particles at the higher concentration of 0.14 vol %, which effect is to slightly decrease the axial velocity magnitude.

![Figure 4 Mean velocity profiles at r/T=0.44.](image)

Overall, this result is in agreement with Unadkat et al. (2009), who found negligible variations of the mean liquid flow field due to the solids (glass particles of $d_p=1000\mu m$ suspended in water at particle volumetric concentration up to 0.5%) in a stirred vessel equipped with a four bladed pitched-blade turbine.

A different behaviour is observed for the turbulence levels. Indeed, the maps of the axial and radial r.m.s. velocities shown in Figure 5 and 6, respectively, indicate that the particles affect the turbulence levels of the continuous phase even at the very low concentrations considered in this work.

![Figure 5 Axial liquid r.m.s. velocity maps.](image)

(a) $d_p=115\mu m$, $C_{vol}=0.05\%$; (b) $d_p=115\mu m$, $C_{vol}=0.1\%$; (c) single-phase; (d) $d_p=774\mu m$, $C_{vol}=0.05\%$; (e) $d_p=774\mu m$, $C_{vol}=0.1\%$;
Although the effect of turbulence modulation is modest as the system is very dilute, for both the r.m.s. velocity components it exhibits a clear trend for both particle sizes and at increasing particle volumetric fraction: the smaller particles produce turbulence damping relative to single phase conditions, while the bigger particles augment the fluctuating velocity components. Moreover, even for the very limited variations of particle concentration investigated, the results clearly indicate that the turbulence modulation is more pronounced, the higher the particle concentration is.

The velocity fluctuation profiles shown in Figure 7 and 8, relevant to the fixed radial location of \( r/T = 0.48 \) and 0.44, allow to better appreciate the extent of changes produced by the particles.

Overall, the radial and axial velocity fluctuations of the continuous phase in single phase flow are of the same order of magnitude, although the maximum value of the radial component is slightly higher than that of the axial component, as expected due to the radial flow generated by impeller. As can be observed, at any location the water r.m.s. values obtained with the smaller particles are lower than that of the single phase flow while the values obtained with the bigger particles are higher. It is also worth observing that the data scatter is negligible for almost all the investigated
conditions apart from that of the bigger particles at the higher concentration. The variation in turbulence fluctuations with respect to single phase flow at particle concentration of 0.1 vol. % and at r/T=0.48 is on average about 20 % (decrease) for the smaller particles and of about 25 % (increase) for the bigger particles.

![Fig. 8 Profiles of liquid radial and axial r.m.s. velocity at r/T=0.44.](image)

For interpreting the results, the dependency of turbulence modulation on the ratio between the particle diameter, $d_p$, and the integral length scale of turbulence, $\Lambda$, has been considered, following Gore and Crowe (1989, 1991). Based on several experimental results obtained mainly in gas-solid flows in pipes and free jets, these authors suggested that the value of $d_p / \Lambda$ allows to identify the condition of turbulence dampening ($d_p / \Lambda < 0.1$) or enhancement ($d_p / \Lambda > 0.1$).

In the case of stirred tanks, the applicability of Gore and Crowe’s criterion is uncertain since contradictory results have been found so far in similar systems. In particular, Unadkan et al. (2009) found that their data show turbulence suppression for $d_p / \Lambda = 0.285$, while Virdung and Rasmuson (1998) obtained in a stirred tank of standard geometry were considered: at the turbine level, the integral length scale was found to vary from 0.1 D/4 close to the blade tip to 0.3 D/4 going towards the wall. Therefore, in our case $\Lambda$ should range from 1.97 and 5.90 mm and, consequently, $d_p / \Lambda$ is always lower than 0.1 for the smaller particles and always higher than 0.1 with the bigger ones. As a results, our findings confirm the interpretation of Gore and Crowe.

### 4. Conclusions

The influence of diameter and concentration of a dispersed glass phase on water turbulence modulation in very dilute stirred suspensions has been experimentally investigated by PIV measurements. While the mean liquid flow field was found to be negligibly affected by the solids, the liquid r.m.s. velocity fluctuations were found to be attenuated or augmented depending on the particle size and the Gore and Crowe criterion based on the ratio of particle diameter and turbulent length scale was confirmed. Although the upper limit of the investigated particle concentrations did not exceed the value of 0.2 vol. %, the turbulence level variations were found to be more pronounced at increasing solid content.

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References

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