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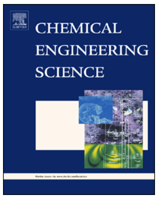

Investigation of turbulent fluid flows in stirred tanks using a non-intrusive particle tracking technique

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HIGHLIGHTS

- Turbulent fluid flow in a tank agitated by RT and PBT RPT impellers is studied by RPT.
- The RPT data are compared to LDA data and simulation results.
- Both Eulerian and Lagrangian descriptions of turbulent fluid flow are discussed.
- A novel method to measure the mixing time in stirred tanks is presented.

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ABSTRACT

Fully turbulent fluid flows in a laboratory-scale stirred tank (ST) equipped with a radial flow impeller (Rushton turbine; RT) or an axial flow impeller (pitched blade turbine; PBT) were analyzed using the radioactive particle tracking (RPT) technique. The present study covered the Eulerian and Lagrangian descriptions of fluid motions. The RPT measurement of the turbulent flow field in a tank agitated by an RT was benchmarked with CFD simulations of RANS-based turbulence models and laser-based measurements. There was good agreement between all the methods for the measured and predicted 3D mean velocity profiles at all locations in the ST. The RPT technique was used to measure the turbulent flow field in a tank agitated by a PBT for the first time. The behavior of the wall jet was investigated. There was close agreement between our results and those of previous studies for both systems. Lagrangian mixing measurements showed that particle trajectories can be used to generate Poincaré maps, which in turn can be used as a tool to visualize the 3D flow structure inside mixing systems. Two mixing indices, one based on the concept of stochastic independence and the other on the statistical concept of memory loss in mixing processes, were used to measure mixing times using RPT results. The present study showed that the RPT technique holds great promise for investigating turbulent flows and the mixing characteristics of STs, and for assessing the adequacy of numerical models.

1. Introduction

Stirred tanks (STs) are widely used for polymerization, oxidation, chlorination, fermentation, waste water treatment, cyanidation and other processes due to their good mixing performance, which ensures efficient contact between phases and a higher mass transfer rate. It has been estimated that approximately 50% of all chemical production processes worldwide by value, worth some US $1290 billion a year, use STs (Butcher and Eagles, 2002). Note that this value has increased significantly in recent years, owing to an increase in the production of added-value materials such as biopharmaceutical specialty products (e.g. proteins). For instance, the global market of biopharmaceutical products only is estimated at US $239 billion in 2015 (Pangarkar, 2014).

Despite being used as a basic unit operation by most chemical processing industries, ST designs are mainly based on global correlations involving for instance the power number, flow number, and Froude number. This can result in a number of uncertainties as such designs cannot provide detailed information on the local flow phenomena that govern the desired process result. Designs based on global correlations cannot take into account the non-uniform and complex 3D flow in an ST. An alternate design approach is thus required to ensure sustainable development, by reducing negative environmental impacts and increasing the process

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profitability (improving the yield). Such an alternative approach should also provide a better understanding of the fluid dynamics in STs, including information about internal flow structures (Sommerfeld and Decker, 2004).

The availability of increasingly powerful computers has transformed computational fluid dynamics (CFD) into a practical tool for understanding fluid dynamics and, as a result, designing efficient processes (Norton and Sun, 2008; Sommerfeld and Decker, 2004; Joshi and Ranade, 2003). The accuracy of CFD simulations is also improving due to the availability of better physical models, including evolved LES models for the prediction of turbulent flows. However, experimental validation is still required, even for the most accurate CFD models (Boyer et al., 2002). CFD analyses can also complement experimental work by reducing the cost and effort of acquiring experimental results.

CFD is increasingly being used to simulate STs. However, quantitative assessments of the accuracy of CFD analyses repose mainly on a comparison of the flows close to the impeller (Ng et al., 1998; Hartmann et al., 2004; Coroneo et al., 2011; Bashiri et al., 2014), due to limitations in acquiring whole tank experimental results. Turbulent flow fields in baffled STs are complex and chaotic, and exhibit 3D structures. The velocity fluctuations caused by the periodic passage of the impeller blades make the turbulent structure of the flow fields even more complex, especially in the region close to the impeller. These complexities make flow measurements in STs time consuming and labor intensive.

Many techniques have been developed in recent years to measure fluid flows in different process tanks and devices, including STs (Boyer et al., 2002; Chaouki et al., 1997; Mavros, 2001). Fluid flow measurement techniques can be divided into two general categories: invasive and non-invasive. The pitot tube (Wolf and Manning, 1966) and hot-wire anemometry (Cooper and Wolf, 1968) invasive fluid flow measurement techniques are inefficient due to the intrusive nature of the probe, which may cause local changes in the fluid flow. Laser doppler anemometry (LDA) (Wu and Patterson, 1989; Kresta and Wood, 1993; Zhou and Kresta, 1996; Rutherford et al., 1996; Lee and Yianneskis, 1998; Aubin et al., 2001; Ducci and Yianneskis, 2005; Murthy and Joshi, 2008) and particle image velocimetry (PIV) (Sheng et al., 2000; Sharp and Adrian, 2001; Baldi and Yianneskis, 2003; Escudie and Line, 2003; Baldi and Yianneskis, 2004; Aubin et al., 2004; Gabriele et al., 2009; Roy et al., 2010; Delafosse et al., 2011; Fontaine et al., 2015) are laser-based non-invasive fluid flow measurement techniques that are used to study the velocities, turbulent dissipation rates, and kinetic energies in STs, especially in the vicinity of the impeller. However, their use is restricted to transparent flows and transparent tank walls, due to the inherent use of a laser. In addition, measuring the whole flow fields with these techniques is cumbersome. Furthermore, these optical techniques only provide Eulerian data, while mixing is intuitively a Lagrangian process. To determine the Lagrangian motion of a fluid parcel, post-processing, with its intrinsic uncertainties, is required (Heniche and Tanguy, 2006).

Radioactive particle tracking (RPT) and positron emission particle tracking (PEPT) are also non-invasive techniques. While PEPT has been used to study fluid flows in STs (Fishwick et al., 2005; Pianko-Oprych et al., 2009), it is limited to tanks that are small enough to be placed in the PEPT camera. Furthermore, Chiti et al. (2011) have reported that the time resolution of the PEPT technique is relatively low (typically 40–60 ms), meaning that the radial velocities measured in the vicinity of the RT impeller are often significantly lower than the values reported in the literature by less than 50%. PEPT is also not very efficient for reconstructing tracer particle positions close to the edge of the system (Guida et al., 2012).

The RPT technique tracks the motion of a single γ-ray-emitting particle using several sodium iodide (NaI) scintillation detectors strategically placed around the system. This method was initially used to study single-phase flows in an ST equipped with an RT (Rammohan et al., 2001a,b). Despite using a relatively large tracer ($\sim$2.4 mm) in those studies, they showed that the RPT measurement technique can accurately measure the velocity of the flow in STs. While the results indicated that RPT is a promising approach for investigating fluid flows in STs, the authors used a not so high impeller Reynolds number ($Re = 12,345$) for which the fluid flow could barely be considered to be fully turbulent ($Re \geq 20,000$) (Machado et al., 2013). In addition, comparisons of velocity profiles with previously published results were limited to the region close to the impeller. RPT has also been used to study gas/liquid (Khopkar et al., 2005) and solid/liquid (Guha et al., 2007) flows in RT mixing systems.

Measuring the quality of mixing in STs is just as important as investigating flow patterns. Process industries are always on the lookout for ways to improve mixing operations, either by switching to more efficient impellers or by fine-tuning operating conditions. Therefore, quantitative approaches are needed in order to measure the mixing characteristics of impellers (Nienow, 1997). Mixedness can be assessed by measuring the concentration of a colored (Melton et al., 2002; Cabaret et al., 2007), fluorescence (Distelhoff et al., 1997; Guillard et al., 2000) or conductivity (Rewatkar and Joshi, 1991; Zhang et al., 2009) tracer at various locations in the tank, to determine how fast the variance of the tracer concentrations decreases to an expected value over time. Since some of these methods use probes, their main intuitive drawback is the alteration in fluid flow. While other methods do not use probes, they are of limited use in opaque systems (colorimetric methods, for example). However, techniques such as RPT, which are based on particle trajectories, do not have these limitations.

We have used RPT extensively to characterize solid flows in fluidized beds (Kiared et al., 1999; Mostoufi and Chaouki, 2004, 2001; Bashiri et al., 2010), spouted beds (Djeridane et al., 1998; Cassanello et al., 1999; Roy et al., 1994), cylindrical tumblers (Alizadeh, 2015) and V-blenders (Doucet et al., 2008). In the present study, we used RPT to study the hydrodynamics of an ST in the fully turbulent flow regime using axial (pitched blade turbine (PBT)) and radial (Rushtone turbine (RT)) impellers. Since these impellers are commonly used in process industries, there is an abundance of published data that can be compared with our experimental results.

Our goal was to assess the capacity of RPT to measure the Lagrangian and Eulerian fluid flow features of an ST in a fully turbulent regime ($Re = 2.2 \times 10^4$). In Section 2, we describe the experimental set-up design and configuration, revisit the basic principles of the RPT technique, and introduce the adopted CFD modeling approach for simulations of mixing systems. In the first part of Section 3, we compare the Eulerian fluid flow results of the RPT experiment to those of Murthy and Joshi (2008), which were obtained by LDA and CFD simulations for an RT mixing system. The comparison covers the bulk of the tank. To our knowledge, this is the first time that such a comprehensive comparison has been performed for a turbulent fluid mixing system using the RPT technique. We then present the 3D flow fields generated in the ST by the PBT impeller using RPT, an impeller widely used in industry but which has not been investigated as thoroughly as the RT. We also describe the ability of RPT to reveal the self-similar behavior of the wall jets generated by the PBT and RT impellers. In the second part of Section 3, we present the results of our Lagrangian study of turbulent fluid flows using Poincaré maps as well as the distribution of velocity magnitudes inside the tank. Lastly, we provide a detailed discussion of the results of mixing times