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Mechanisms for drawdown of floating particles in a laminar stirred tank flow

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HIGHLIGHTS

- Floating particles distribution and liquid velocity were simultaneously measured.
- The simulated liquid and particle characteristics agree well with experimental data.
- Tangential velocity and particle collision trigger the drawdown of floating particles.

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ABSTRACT

Particle image velocimetry (PIV) experiments on a laminar stirred tank flow with floating particles at just drawdown conditions were performed. Careful refractive index matching of the two phases allowed to resolve the flow around the particles. The maximum solids volume fraction was 4%. The impeller was a pitched blade turbine with upward and downward pumping modes and with different off-bottom clearances, and the impeller-based Reynolds number ranged from about 50 to 120. Computational fluid dynamics (CFD) coupled to a discrete phase model (DPM) and discrete element method (DEM) was used to predict the flow field, with an emphasis on the tangential velocity component. The liquid velocity profiles predicted by the CFD simulations are in good agreement with the PIV experimental data. The drawdown process and local particle accumulation simulated by the DPM-DEM model agrees with the experimental phenomena as well. Tangential velocity and particles collisions around the shaft trigger the onset of the drawdown of the floating particles.

1. Introduction

Solid-liquid stirred tanks with floating particles (their densities are less than that of liquid) are commonly used in a variety of industrial processes, such as the production processes of coatings, cosmetics and lubricating oil [1]. While the suspension of solids that are heavier than the surrounding liquid has received extensive attention, limited information is available in the literature on the drawdown of floating particles in stirred tanks, which justifies investigating the mechanisms of particle drawdown in stirred tanks.

Since the first work regarding floating particles by Joosten et al. [2], researchers have focused on the macroscopic parameters including the just-drawdown speed N_{jd} [3–10]. N_{jd} is usually defined as the minimum impeller speed where all particles could be drawn down from the surface of the tank within 1–2 s, and it characterizes the performance of the mixing system. With this criterion, the effect of the physical properties of liquid and solids as well as solids loading on the N_{jd} have been considered, and several N_{jd} correlations were obtained for a variety of mixing configurations [3–5]. Paglianti et al. [11] used an electrical resistance tomography technique to measure solids concentration distributions of floating particles and proposed a new method for estimating the mixing time. Some researchers extended their work to the suspension of floating particles in gas–solid-liquid systems because many mixing systems are aerated in the process industries. In gas–solid-liquid systems, N_{jd} sometimes decreases as the gas rate increases, or N_{jd} increases early as the gas rate increases and then decreases after it reaches a maximum value [12,13]. Bao et al. [14,15] investigated the effect of the concentrations of floating particles on the N_{jd} in a three phases stirred tank.

Laser-based optical measurement techniques such as particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) have been used in experiments to investigate single-phase flows or dilute two-phase

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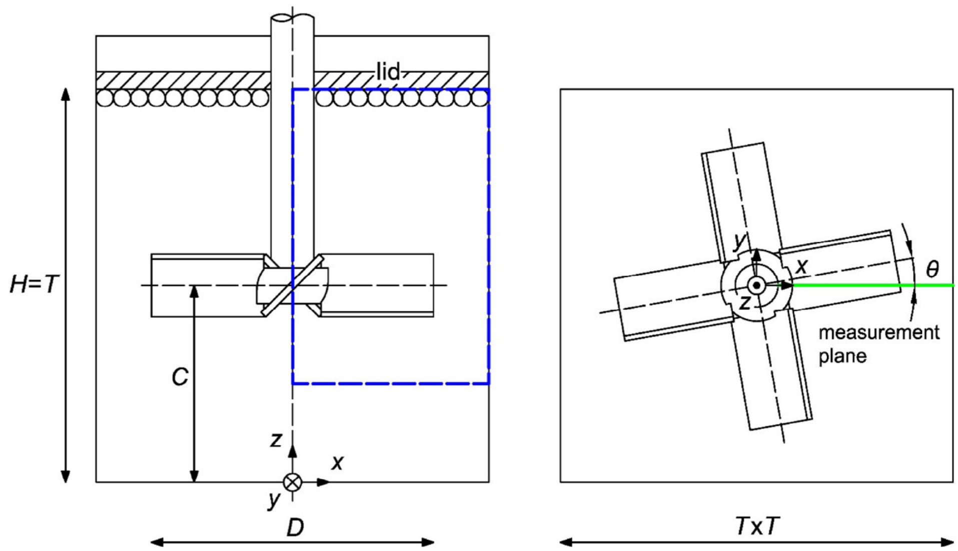

Fig. 1. Stirred tank geometry, (x, y, z) coordinate system, PIV measurement region shown by the blue rectangle, and impeller angle θ between the measured blade and the measurement plane for downward pumping model. The impeller in the right panel rotates counterclockwise.

flows. Solid-liquid flows present a challenging environment for the application of these optical imaging techniques; the presence of solids makes the two-phase flow opaque and not directly suitable for PIV and LDV measurements. Thus, the maximum solids concentration is usually limited to 1% by volume. At higher solids loadings, the laser light will more and more likely be obstructed and scattered by the solids. To overcome this problem, many researchers employed refractive index matching (RIM) in experiments [16–19]. Wiederseiner et al. [20] summarized currently available RIM methods. However, the RIM method was rarely reported in a solid–liquid system with floating particles. Based on our previous research on settling particles [21], we propose a new solid–liquid system to achieve RIM in this work. The solids are Polymethyl methacrylate particles, and the liquid is a mixture of sucrose and sodium chloride aqueous solution.

As for the flow field of solid–liquid systems, most published researches focus on settling particles. In our group we measured the overall flow pattern in the presence of floating particles, however, without matching the refractive indices [22,23]. Flat cylindrical shape polyethylene particles (Φ3.6 × 2.1 mm) were used as the floating solid material and the results of the PIV experiments show that the mean flow velocity decreases with an increase of particles concentration from 0% to 1% by volume [23]. The flow field near the liquid surface where floating particles are actually drawn down and the flow characteristics around particles were not considered in [23]. To facilitate a detailed analysis in drawdown mechanisms, in the current study, we simplify the flow system by placing a lid on top of the liquid surface and by decreasing the Reynolds number to make the flow laminar. In addition, to resolve the flow characteristics in the drawdown process of floating particles by using PIV, much larger spherical particles with diameter d_p = 9.6 mm were used to enhance resolution and the RIM technique was used to allow for an increase of the particle concentration. Details of our experimental setup will be discussed in the next section.

Computational fluid dynamics (CFD) has been used extensively to predict solids suspension in stirred tanks with the solids denser than the liquid (settling solids). However, only a limited set of CFD studies on floating particles in stirred tanks is available [24–29]. The Eulerian-Eulerian multiphase model along with the standard k-ε mixture turbulence model were usually used in these simulations and macroscopic parameters, such as flow pattern, power number, and solid concentration, have been investigated. Based on experimental and simulated results, some controlling factors, including surface vortex formation, turbulent fluctuations, and mean drag, have been identified [26–29]. However, particle collision was always neglected in these simulations. Recently, Li et al. [30] found that particle collision has a significant effect on the solid–liquid flow even when solids volume fractions are very small (about $O(10^{-4})$). At present, research on simulations of floating particle characteristics in stirred tanks by considering particle collision has not been reported.

The aim of this paper is in the first place to show the feasibility of particle-resolved PIV experiments with floating particles in a laminar flow. We constructed this base-case so as to address some fundamental mechanisms for the drawdown of floating particles and will gradually add complexity such as turbulent flow in the future. The tank-averaged solids volume fraction is up to 4%. Local accumulation phenomena of the solids around the top of the shaft can be observed. In the second place, by comparing experimental and simulated flow fields near the impeller and the shaft, we validate our simulation results with the DPM-DEM model and assess their accuracy. The effects of impeller pumping modes, off-bottom clearances, and solids concentrations on the flow dynamics are discussed as well. In the third place, based on analyses of the tangential velocity and pressure distributions and the just drawdown process simulated with collision models, we can draw conclusions regarding the mechanism of the drawdown of floating particles.

The paper is organized as follows: in the next section, the experimental setup is discussed, including the flow system, PIV experiments and image analysis. Then, the numerical approaches are briefly summarized with references to the relevant literature. In the subsequent *Results* section we first present the phenomena of the just drawdown of floating particles from the surface. Secondly, we discuss the effects of impeller pumping mode, off-bottom clearance, and overall solids loading on the liquid flow field. Thirdly, we compare the simulation results with the PIV experimental data, and identify the just drawdown conditions. The final section provides a summary and conclusions.

2. Experimental setup

2.1. Flow system

A schematic view of the flow geometry is shown in Fig. 1. A cuboid glass stirred tank with a flat square base (TxT = 0.22 × 0.22 m^2) was used and the liquid height H is equal to T. In order to construct a simplified drawdown of floating particles, a lid was placed on the top of the liquid, thus, the floating particles are entirely wetted without trapped air in the drawdown and the free surface is replaced by a no-