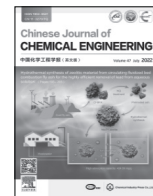




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Full Length Article

Study on the solid–liquid suspension behavior in a tank stirred by the long-short blades impeller

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ABSTRACT

We investigated the solid–liquid suspension characteristics in the tank with a liquid height/tank diameter ratio of 1.5 stirred by a novel long-short blades (LSB) impeller by the Euler granular flow model coupled with the standard $k-\varepsilon$ turbulence model. After validation of the local solid holdup by experiments, numerical predictions have been successfully used to explain the influences of impeller rotating speed, particle density, particle size, liquid viscosity and initial solid loading on the solid suspension behavior, i.e. smaller particles with lower density are more likely to be suspended evenly in the liquid with higher liquid viscosity. At a low impeller rotating speed (N), increase in N leads to an obvious improvement in the solid distribution homogeneity. Moreover, the proposed LSB impeller has obvious advantages in the uniform distribution of the solid particles compared with single Rushton turbine (RT), dual RT impellers or CBY hydrofoil impeller under the same power consumption.

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1. Introduction

Solid–liquid mixing is an important unit operation and has been widely used in the fields of industrial sewage treatment, sediment transportation, catalytic reaction and crystallization reaction [1–3]. The purpose of solid–liquid suspension operation is to increase the contact area in the reactor, reduce the mass transfer resistance of liquid film on the surface of the solid particles, thus, improving reaction efficiency and production capacity of the process. In a stirred tank for solid–liquid system, the impeller plays an important role in the uniform distribution of solid particles in the liquid phase, therefore, designing an appropriate impeller system for a particular solid–liquid system becomes an attractive issue in the chemical engineering process.

Solid–liquid flow characteristics in the stirred tank equipped with many kinds of impellers have been studied extensively in the past decades. An ideal solid–liquid flow is that all solid particles could be suspended uniformly in the liquid phase, the surface of solid particles could be fully covered by the liquid [4,5]. However, in practice, the suspension behavior of solid particles in the tank is in a chaotic state due to significant density difference

between two phases. To achieve a high-quality suspension of the solid particles, many improvements in the shape of the traditional impellers have been made. For example, Zhao *et al.* [6] proposed an improved Intermig impeller and found that higher solid particles suspension quality could be achieved at a 20% reduction in power consumption due to the strong axial circulation capacity compared with the standard Intermig impeller. Jirout *et al.* [7] compared the solid–liquid mixing efficiency of 11 kinds of impellers and found that the pitched three-blade impeller with diagonally folded blades had lower energy consumption in the suspension process than other impellers. Gu *et al.* [8] found that the fractal impeller could improve the suspension performance of solid particles at the same power consumption with respect to the sawtooth impeller. Gu *et al.* [9] compared the agitation state of rigid impeller and rigid flexible impeller, and found the perforated rigid flexible impeller could achieve higher suspension efficiency of the solid particles. Recently, our group has proposed a novel long-short blades (LSB) impeller. Previous studies [10,11] show that large mass transfer coefficients could be achieved due to the uniform distribution of the bubbles in the liquid. This should be attributed to the combined configuration of the long blades and the short blades. Velocity field analysis demonstrates [12] that the short blades of the LSB impeller generate a strong axial up-flow in the center, which interacts with the dominant radial motion of the long blades, leading to effective mass exchange and momentum transfer in the whole stir-

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red tank. These flow characteristics are particularly helpful for improving the distribution uniformity of a second phase (gas or solid). The obvious mass transfer intensification of the gas–liquid two phase flow stimulates us to investigate its potential application in the solid–liquid two phase flow.

The solid–liquid suspension process is mainly regulated by two phase hydrodynamics, which in turn depend on the configuration and operation parameters of the impeller. In order to obtain a good-quality solid–liquid suspension state, it is necessary to understand the hydrodynamic characteristics of two phases in the stirred tank. Besides experimental investigations, the development of computational fluid dynamics (CFD) has brought more convenient theoretical methods for the study of solid–liquid two phase flow. Currently, Euler–Euler method and Euler–Lagrange method are mainly used for the numerical simulation of solid–liquid two-phase. The Euler–Lagrange method [13–16] takes the fluid as a continuous medium, assumes that the liquid phase affects the particle motion and is not affected by the particle motion, then solves separate equations for the particles, bubbles and droplets in the fluid. In the solution process, three-dimensional motion trajectory of the particles is obtained by integrating the forces acting on the particles, and the influence of turbulence on the trajectory is taken into account in the way of random motion. The Euler–Euler method, also known as two-fluid model is widely adopted due to its less computation amounts and reliable results [17–20]. For example, Kasat *et al.* [21] simulated solid–liquid two-phase turbulence in a stirred reactor using a two-fluid model and a standard $k-\varepsilon$ model. Fan *et al.* [22] used an improved inner–outer iterative method and a two-fluid model to simulate the solid–liquid two-phase turbulent flow of fine particles in a standard Rushton turbine (RT) stirred tank. The simulation results are in good agreement with the PIV experimental results, which verifies the reliability of the simulation model. However, in the traditional Euler–Euler approach, the solid phase is completely treated as a fluid phase, which does not endow the properties of particles and might lead to a large prediction discrepancy, in particular in a dense solid–liquid suspension system. For example, Sardeshpande *et al.* [23] studied the influences of different drag models on solid–liquid suspension and found that the drag model proposed by Brucato *et al.* [24] overestimate the slip velocity near the blades when the solid holdup reaches 7% (volume). In recent years, the kinetic theory of granular flow (KTGF), which considers the collision and friction of particles by calculating the solid pressure and viscosity, has been coupled into Euler–Euler model (known as Euler granular model) to obtain more accurate predictions of solid–liquid two phase flow. Ochieng *et al.* [25] compared the predictions by the Brucato model [24] and the Gidaspow model [26] (which consider the particle–particle interactions through solid pressure), and found that the predictions were consistent with the results of the work by Sardeshpande *et al.* [23] when the solid holdup is low, whereas Gidaspow model [26] could predict the distribution of particles more accurately at high solid holdup. Xie *et al.* [27] used a modified KTGF model to study particle–particle interactions in dense solid–liquid suspensions. The results show that the particle–particle interactions can be ignored for small particle size and low solid holdup, while for large particle size and high solid holdup, the particle–particle interactions may affect the suspension characteristics. Wang *et al.* [28] also used the Euler granular model to study the flow characteristics of solid–liquid two-phase particles in a stirred tank, and found the prediction agree well with the experimental data measured by Pianko-Oprych *et al.* [29].

The objective of this work is to study the solid–liquid hydrodynamics in a stirred tank equipped with the novel LSB impeller experimentally and numerically. Solid suspension performance in the tank equipped with standard RT, dual RT impellers, and CBY impeller were also investigated for comparison. Standard $k-\varepsilon$ tur-

bulence model and Euler granular model were adopted to predict the solid–liquid suspension process. The influences of impeller type, particle diameter and density, liquid viscosity and impeller rotating speed on the solid–liquid suspension performance were then discussed.

2. Experimental

The experimental system includes a flat-bottomed cylindrical tank with inner diameter (T) of 0.2 m, equipped with four baffles of 0.1 T in width. The liquid height, H , is equal to 1.5 T . Fig. 1 shows a schematic representation of the tank and LSB impeller. The LSB impeller consists of a fixer, three long blades (LBs), six short blades (SBs) and two fixed rings. Six SBs (height $\times$ width = 35 mm $\times$ 30 mm) are fixed to the connecting ring. The characteristic diameter (D) of the LSB impeller is 0.5 T . The off-bottom clearance, C , keeps a constant value of $C/T = 0.25$. Two sets of the LBs with 100 and 150 mm in length (L_{lb}), were investigated to study the effect of the LSB impeller submergence ($S = 50$ and 100 mm, respectively).

The experimental setup is shown in Fig. 2. Local solid holdup is measured by the sampling method [30,31]. Glass bead with density of $\rho_s = 2500 \text{ kg}\cdot\text{m}^{-3}$ and diameter of $d_s = 0.2 \text{ mm}$ are used as solid particles and water ($\rho_L = 1000 \text{ kg}\cdot\text{m}^{-3}$) is used as the liquid phase. The sampling tube is a glass tube with an inner diameter of 5 mm installed in two radial positions ($r/R = 0.7, 0.9$), and can be moved freely in different axial positions ($z/T = 0-1$). A peristaltic pump was used to draw the sample with a volume of approximately 20 ml at 6 axial positions ($z/T = 0.225, 0.45, 0.675, 0.90, 1.125, 1.35$, respectively). The samples (water and glass beads) were then dried in an oven and weighed to obtain the local solid holdup. After each drying and weighing, the corresponding water and glass beads were added back to the tank to keep constant solid and liquid loading. Each measurement was repeated three times to obtain the mean value. The mean relative error of all the measurements is 2.1%.

3. Numerical Approach

3.1. Model equations

Euler granular model was adopted to describe the flow behavior of each phase, in which the continuous and dispersed phases are regarded as interacting interpenetrating continua with each other in the system. The properties of the solid phase are described by kinetic theory of granular flow. The standard $k-\varepsilon$ mixture turbulence model [32–34] was adopted in the simulation, where the continuous and dispersed phases are assumed to share the same turbulent kinetic energy (k) and turbulent energy dissipation rate (ε). The momentum equations for each phase are listed in Tables 1 and 2, respectively.

3.2. Drag model

The forces affecting the inter-phase momentum transfer mainly includes drag, Basset, lift and virtual mass forces. Basset force involves a history integral which is time-consuming to evaluate and, in most cases, is much smaller than the inter-phase drag forces [21]. Moreover, the lift and virtual mass forces were estimated to be smaller compared to the dominant drag force, especially for a particle to liquid density ratio larger than 2 [17,35]. Therefore, only the drag model is considered in this paper, which has also been widely adopted in the literatures [17,21,22,32,36,37]. The Gidaspow model [26,38] is adopted to calculate the drag forces, which is a combination of Wen–Yu model

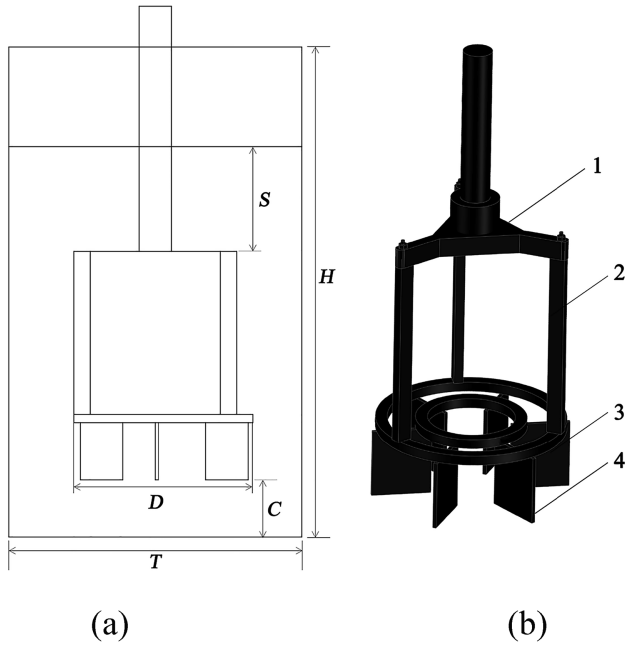


Fig. 1. Geometric structure diagram of (a) the stirred tank and (b) the LSB impeller. (1) Fixer; (2) Long blades; (3) Connection rings; (4) Short blades.

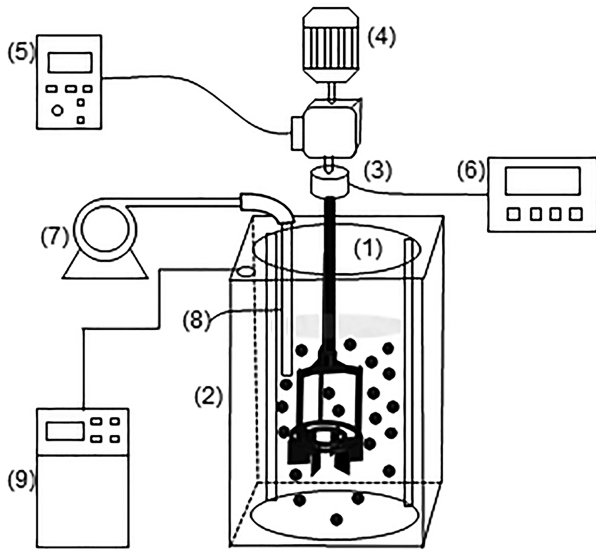


Fig. 2. Schematic diagram of the experimental apparatus. (1) LSB impeller; (2) Stirred tank; (3) Torque meter; (4) Motor; (5) Speed controller; (6) Torque recorder; (7) Peristaltic pump; (8) Sampling pipe; (9) Thermostat water system.

and Ergun equation. The liquid–solid exchange coefficient, K_{SL} , can be given as follows:

$$K_{SL} = \frac{3}{4} C_D \frac{\alpha_S \alpha_L \rho_L |U_S - U_L|}{d_S} \alpha_L^{-2.65} \quad (1)$$

where

$$C_D = \frac{24}{\alpha_L Re_S} \left[1 + 0.15 (\alpha_L Re_S)^{0.687} \right] \quad (2)$$

Table 1
Euler–Euler two-fluid model equations

Description	Model equations
Mass equation	$\frac{\partial}{\partial t} (\alpha_L \rho_L) + \nabla \cdot (\alpha_L \rho_L U_L) = 0$ $\frac{\partial}{\partial t} (\alpha_S \rho_S) + \nabla \cdot (\alpha_S \rho_S U_S) = 0, \alpha_L + \alpha_S = 1$
Momentum equation	$\frac{\partial}{\partial t} (\alpha_L \rho_L U_L) + \nabla \cdot (\alpha_L \rho_L U_L U_L) = -\alpha_L \nabla p + \nabla \cdot \tau_L$ $+ \alpha_L \rho_L g + F_{S,L}$ $\frac{\partial}{\partial t} (\alpha_S \rho_S U_S) + \nabla \cdot (\alpha_S \rho_S U_S U_S) = -\alpha_S \nabla p - \nabla p_S$ $+ \nabla \cdot \tau_S + \alpha_S \rho_S g + F_{S,L}$
Stress tensor	$\tau_S = \alpha_S \mu_S (\nabla U_S + \nabla U_S^T) + \alpha_S (\lambda_S - \frac{2}{3} \mu_S) \nabla \cdot U_S I$
Turbulence model	$\frac{\partial}{\partial t} (\rho_m k) + \nabla \cdot (\rho_m U_m k) = \nabla \cdot \left(\frac{\mu_m}{\sigma_k} \nabla k \right) + G_{k,m} - \rho_m \epsilon$ $\frac{\partial}{\partial t} (\rho_m \epsilon) + \nabla \cdot (\rho_m U_m \epsilon) = \nabla \cdot \left(\frac{\mu_m}{\sigma_\epsilon} \nabla \epsilon \right) + \frac{\epsilon}{k} (C_{1\epsilon} G_{k,m} - C_{2\epsilon} \rho_m \epsilon)$

$$Re_S = \frac{\rho_L d_S |U_S - U_L|}{\mu_L} \quad (3)$$

If $\alpha_L \leq 0.8$,

$$K_{SL} = 150 \frac{\alpha_S (1 - \alpha_L) \mu_L}{\alpha_L d_S^2} + 1.75 \frac{\rho_L \alpha_S |U_S - U_L|}{d_S} \quad (4)$$

3.3. Simulation details and boundary conditions

In the description of the impeller rotation, the multiple reference frame (MRF) approach can be adopted for unsteady-state simulations in a pseudo-steady-state manner [39,40], yielding satisfactory prediction results [16,27,39–44]. Moreover, compared with the sliding mesh approach, the MRF approach has a significant reduction in computational resources. Thus, it was adopted to simulate the impeller rotation in this work. The stirred tank was divided into the inner rotating zone and the non-rotating zone. The interface between the rotating and non-rotating zones was treated as an internal boundary condition (interior). The free liquid level above the stirred tank was defined as symmetry. All geometric models were constructed by SCDM and the mesh was divided by fluent meshing. The region around the impeller rotating region was refined to ensure the prediction accuracy. The stirred tank with LSB impeller ($L_{lb} = 100$ mm) was selected for grid independence verification. The predicted profiles of axial velocity, radial velocity, turbulent kinetic energy and turbulent dissipation rate with 320000, 720000, 1030000 and 1680000 elements are compared in Fig. 3. It can be seen that the differences using different grid resolution are very small. In the following simulation, the grid number of the LSB impeller ($L_{lb} = 100$ mm) was 320000. The grid numbers of single RT impeller stirred tank, LSB impeller ($L_{lb} = 150$ -mm) stirred tank, dual RT impellers stirred tank, and CBY impeller stirred tank were 330000, 500000, 470000, 410000, respectively.

The standard wall function was employed on the solid walls. Phase Coupled SIMPLE algorithm was used for pressure–velocity coupling. The second order upwind scheme was used to discretize the convection term. The QUICK scheme was used to discretize the volume fraction. In the initial simulation, all particles were patched at the bottom of the tank with the volume fraction of 0.6. The time step is 0.001 s and the relative residual is 1×10^{-4} . The commercial CFD software, FLUENT 17.0 was used to calculate the transient numerical simulations of the solid–liquid suspension. After reaching a quasi-steady state, fluid flow data including local solid holdup and velocity were collected and the time-averaged values were obtained by statistical analysis. Meanwhile, the torques generated on the impeller were monitored continuously to calculate the corresponding power consumption.

Table 2
Kinetic theory of granular flow model equations

Description	Model equations
Granular kinetic energy equation	$\frac{3}{2} \left[\frac{\partial}{\partial t} (\rho_s \alpha_s \theta_s) + \nabla \cdot (\rho_s \alpha_s U_s \theta_s) \right] = (-p_s I + \tau_s) \cdot \nabla U_s + \nabla \cdot (k_{\theta_s} \nabla \theta_s) - \gamma \theta_s + \varphi_{LS}$
Solid pressure	$p_s = \alpha_s \rho_s \theta_s + 2 \rho_s (1 + e_{ss}) \alpha_s^2 g_{0,ss} \theta_s$
Solid bulk viscosity	$\lambda_s = \frac{4}{3} \alpha_s^2 \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\theta_s}{\pi} \right)^{1/2}$
Solid shear viscosity	$\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr}$
Collision viscosity	$\mu_{s,col} = \frac{4}{5} \alpha_s^2 \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\theta_s}{\pi} \right)^{1/2}$
Kinetic viscosity	$\mu_{s,kin} = \frac{\alpha_s \rho_s d_s \sqrt{\theta_s \pi}}{6(3 - e_{ss})} \left[1 + \frac{2}{5} (1 + e_{ss}) (3e_{ss} - 1) \alpha_s g_{0,ss} \right]$
Radial distribution function	$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,max}} \right)^{\frac{1}{2}} \right]^{-1}$
Energy diffusion coefficient	$k_{\theta_s} = \frac{15 d_s \rho_s \alpha_s \sqrt{\theta_s \pi}}{4(41 - 33\eta)} \left[1 + \frac{12}{5} \eta^2 (4\eta - 3) \alpha_s g_{0,ss} + \frac{16}{15\pi} (41 - 33\eta) \eta \alpha_s g_{0,ss} \right]$
	$\eta = \frac{1}{2} (1 + e_{ss})$
Collision energy dissipation	$\gamma \theta_s = \frac{12(1 - e_{ss}^2) g_{0,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \theta_s^{3/2}$

4. Results and Discussion

4.1. Prediction accuracy validation

To validate the CFD model, predicted axial distributions of the local solid holdup at two selected radial positions ($r/R = 0.7$ and 0.9) in the tank equipped with the LSB impeller were firstly compared with the experimental results, as shown in Fig. 4. Initial solid holdup (C_{avg}) of the particles ($d_s = 0.2$ mm, $\rho_s = 2500$ kg·m⁻³) is fixed at $C_{avg} = 4\%$ (volume) while the rotating speed is changed.

It is seen that the predicted profiles at three selected rotating speed levels ($N = 240, 350$ and 450 r·min⁻¹) are in good agreement with the experimental results. In addition, at a low rotating speed, e.g. $N = 240$ r·min⁻¹, there are few particles above the liquid level of $z/T = 1.0$. When the impeller rotating speed increases, the number of accumulated particles at the bottom of the tank decreases, and more particles reach the top of the stirred tank. Further increase in the impeller rotating speed, e.g. when it reaches 550 and 600 r·min⁻¹, no obvious improvement of the particle distribution in the tank could be made compared with the case of $N = 450$ r·min⁻¹.

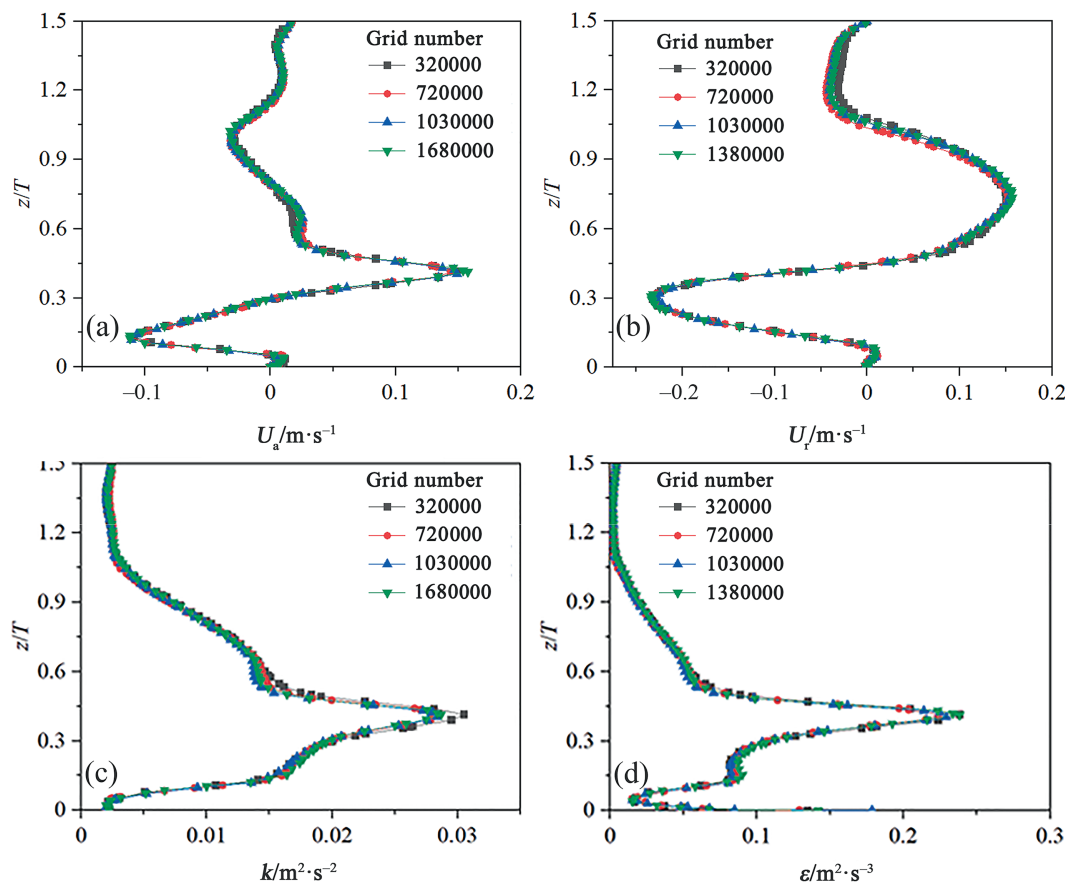


Fig. 3. Distribution of axial velocity, radial velocity, turbulent kinetic energy and turbulent dissipation rate at a selected radial position of $r/R = 0.9$ with different grid resolution: (a) axial velocity; (b) radial velocity; (c) turbulent kinetic energy; (d) turbulent dissipation rate. $N = 150$ r·min⁻¹, $d_s = 0.2$ mm, $\rho_s = 2500$ kg·m⁻³, $C_{avg} = 4\%$ (volume).

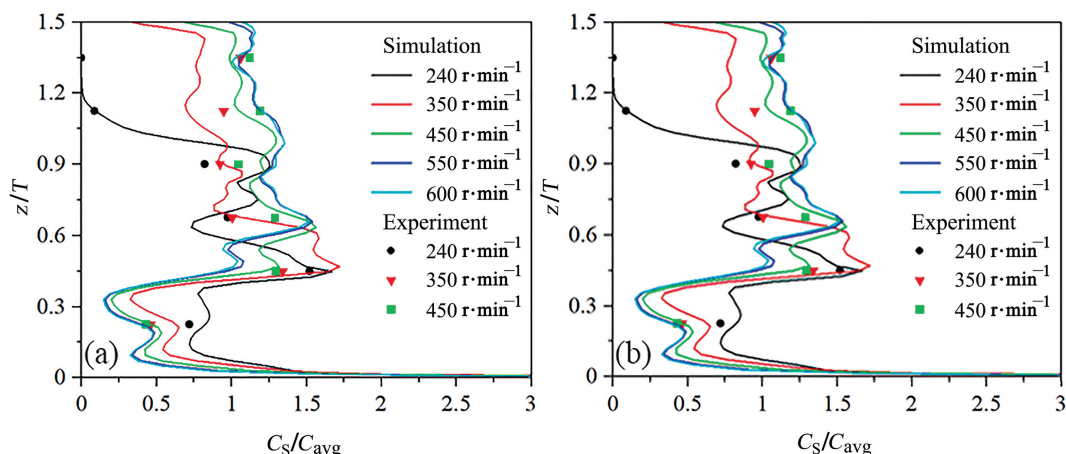


Fig. 4. Comparison of predicted solid holdup profiles with experimental results: (a) $r/R = 0.7$ and (b) $r/R = 0.9$. $d_s = 0.2$ mm, $\rho_s = 2500$ kg·m⁻³, $C/T = 0.25$, $L_{lb} = 100$ mm, $C_{avg} = 4\%$ (volume).

4.2. Flow patterns

To have an overview of the liquid flow characteristics, the velocity vectors in the stirred tank equipped with the LSB impeller, single RT impeller, or dual RT impeller are firstly compared in Fig. 5. It is found that although the vortices from the bottom of the tank with the LSB impeller are similar in shape to those with the single RT impeller, the flow patterns are completely different. For the RT impeller, due to the existence of the disc, the vortices below and above the disc are separated and the mass exchange only occurs in the discharge area of the blades (Fig. 5(b)). On the contrary, for the LSB impeller, due to the absence of the disc, the liquid discharged by the SBs mainly returns to the bottom, and then go upwards through the hollow connecting ring by strong collision into each other, forming a strong axial up-flow in the center (Fig. 5(a) and (c)). Moreover, obvious radial motions are observed in the upper part of the tank due to the radial pumping of the LBs, whereas the axial motions dominate the flow up the disc for the RT impeller. In addition, near the upper edges of the long blades, two vortices are generated and a down-flow is observed in the center of the top half. Direct impingement of the axial up-flow and down flow results in an obvious radial flow in the middle of the tank. Such flow characteristics are conducive to the mass exchange, energy loading and dispersion of the second phase (gas or solid phase).

4.3. Effect of particle density and diameter

According to kinetic theory of granular flow, the viscosity of solid phase is closely related to the particle size and density. Fig. 6 shows contour plots of the local solid holdup on two typical horizontal cross-section planes of $z/T = 0$ (bottom) and $z/T = 0.75$ (middle). It is seen that with the increase of particle density, the number of particles accumulated at the bottom of the tank increases significantly, resulting in a worse solid suspension quality. One can also see that on the middle cross-sectional plane ($z/T = 0.75$), solid particles are more evenly distributed in the case of lower particle density, e.g. $\rho_s = 1600$ kg·m⁻³, while more particles accumulate in the middle of the cross-sectional plane in the case of $\rho_s = 2500$ kg·m⁻³. This should be attributed to the particle lifting by the axial up-flow and the collision between the up-flow and the down-flow, as shown in Fig. 5. One can see that there exists a relative stagnant region in the middle cross-sectional plane of the tank. When the particle density increases, the particles cannot be completely transported out of the stagnant region by the radial pumping of the fluid, leading to obvious particle accumulation in the center region with the local solid holdup larger than 0.15 (see Fig. 6(d)).

To explore the effect of the particle diameter, we changed the particle size from 0.1 to 0.3 mm and plotted the local solid holdup profiles along the axial direction at two radial positions ($r/R = 0.7$

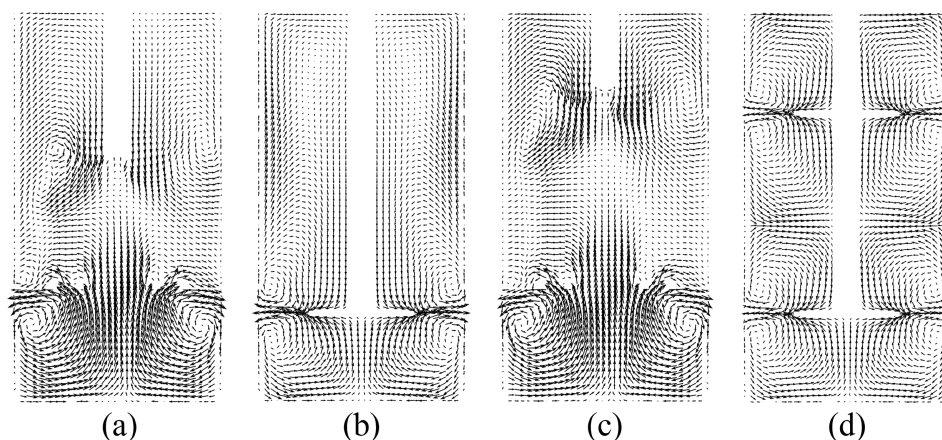


Fig. 5. Velocity vectors in the tank with the LSB impeller, single RT impeller or dual RT impellers on the x - z plane: (a) LSB, $S/T = 0.5$; (b) single RT; (c) LSB, $S/T = 0.25$; (d) dual RTs.

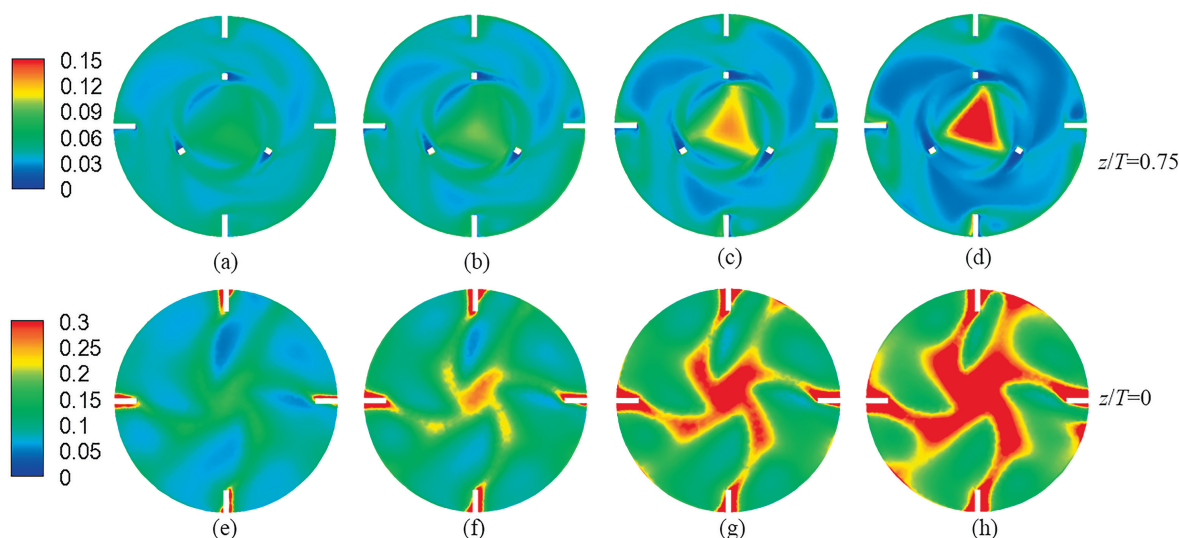


Fig. 6. Contour plots of local solid holdup on the cross-sectional planes at different axial locations: (a, e) $\rho_s = 1600 \text{ kg}\cdot\text{m}^{-3}$; (b, f) $\rho_s = 1900 \text{ kg}\cdot\text{m}^{-3}$; (c, g) $\rho_s = 2200 \text{ kg}\cdot\text{m}^{-3}$; (d, h) $\rho_s = 2500 \text{ kg}\cdot\text{m}^{-3}$. $N = 350 \text{ r}\cdot\text{min}^{-1}$, $d_s = 0.2 \text{ mm}$, $C_{\text{avg}} = 4\%$ (volume).

and $r/R = 0.9$), as shown in Fig. 7. It is seen that large particles of $d_s = 0.3 \text{ mm}$ can hardly reach the upper region in the tank, in particular above the plane of $z/T = 1$, whereas the axial distribution of the solid holdup becomes more uniform in the whole tank when small particles of $d_s = 0.1 \text{ mm}$ or $d_s = 0.2 \text{ mm}$ are used. This is consistent with the drag model, in which smaller particles are more likely to be suspended. Moreover, according to kinetic theory of granular flow, both shear viscosity and volume viscosity decrease when the particle diameter or density decreases, which account for the experimental results satisfactorily. In addition, these results can also be explained by free settling velocity (V_t) for spherical particle, as described by Eq. (5),

$$V_t = \left[\frac{4}{3} \frac{gd_s(\rho_s - \rho_L)}{C_D \rho_L} \right]^{0.5} \quad (5)$$

In the same case, particles with large diameter or density have a large value of free settling velocity, which makes them more difficult to suspend.

4.4. Effect of liquid viscosity

Liquid viscosity (μ_L) is another factor affecting the suspension of the particles. Here, we changed μ_L from $1 \times 10^{-3} \text{ Pa}\cdot\text{s}$ to $20 \times 10^{-3} \text{ Pa}\cdot\text{s}$ and compared the axial distributions of the local solid holdup in Fig. 8. One can see that the axial distributions in the case of $\mu_L = 20 \times 10^{-3} \text{ Pa}\cdot\text{s}$ are more uniform than that of $\mu_L = 1 \times 10^{-3} \text{ Pa}\cdot\text{s}$, which implies that the liquid viscosity effect is significant. When the solid particles are suspended in a viscous liquid, the viscous drag force will increase when μ_L increases, leading to a lower sedimentation speed of the particles. Thus, it is more difficult for the particles to return back to the bottom after its successful suspension. Drag force model equations give a direct explanation of this effect, *i.e.* the exchange coefficient of the solid–liquid phase is positively related to the liquid viscosity, higher liquid viscosity leads to larger drag force between the solid and liquid phases, which is conducive to momentum transfer between the two phases. In addition, the particle response time, t_s , which is defined as the time when the particle reaches 63% of the free flow velocity (Eq. (6)), can give a quantitative analysis of the liquid viscosity effect, *i.e.*

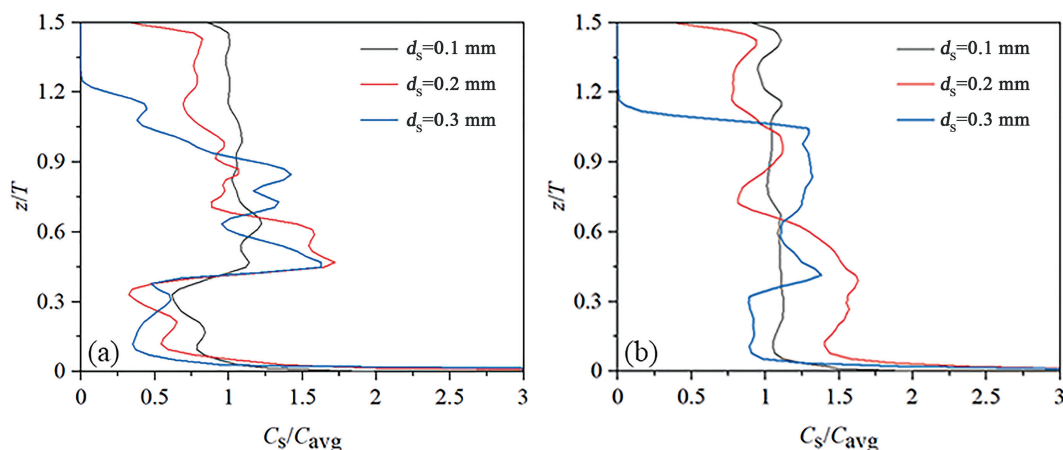


Fig. 7. Influence of particle diameter on the axial distributions of the local solid holdup: (a) $r/R = 0.7$ and (b) $r/R = 0.9$. $N = 350 \text{ r}\cdot\text{min}^{-1}$, $\rho_s = 2500 \text{ kg}\cdot\text{m}^{-3}$, $C_{\text{avg}} = 4\%$ (volume).

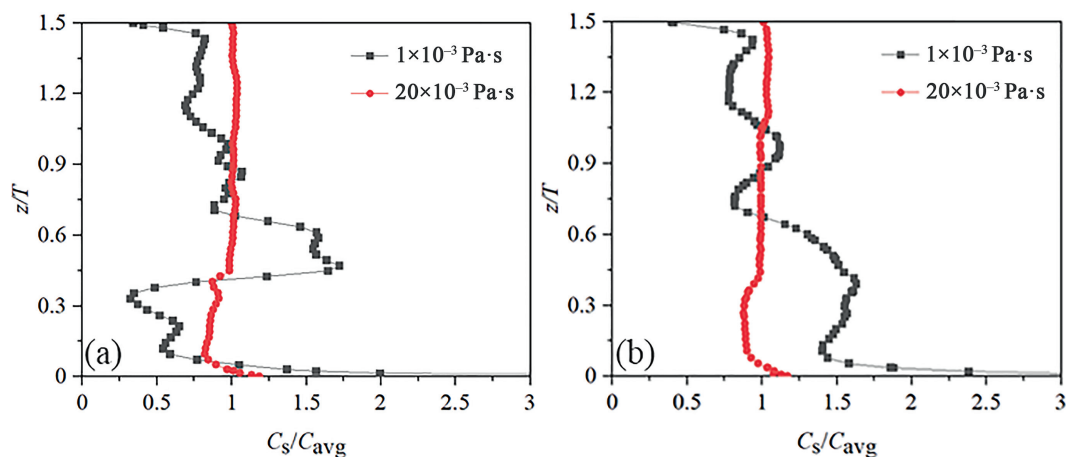


Fig. 8. Influence of liquid viscosity on the axial distributions of the local solid holdup: (a) $r/R = 0.7$ and (b) $r/R = 0.9$. $N = 600 \text{ r}\cdot\text{min}^{-1}$, $d_s = 0.2 \text{ mm}$, $\rho_s = 2500 \text{ kg}\cdot\text{m}^{-3}$, $C_{\text{avg}} = 4\%$ (volume).

$$t_s = \frac{\rho_s d_s^2}{18\mu_L} \quad (6)$$

From Eq. (6) one can see that the particle response time is only one half when the liquid viscosity is doubled. Thus, higher liquid viscosity is beneficial to the uniform distribution of solid particles.

4.5. Effect of solid loading

According to the Euler granular model, the pressure and viscosity of the solid phase is related to the solid particle concentration. In this work, initial solid phase height patched at the bottom of the tank are changed from 0.02 to 0.03 and 0.04 m, and the corresponding mean solid volume holdups (C_{avg}) are 4%, 6% and 8%, respectively. Many studies [45,46] have shown that the initial solid holdup has an obvious effect on the just suspended speed (N_{js}), which is always measured by the tank bottom observation method. The measured values at three solid loadings are 286, 296 and 309 $\text{r}\cdot\text{min}^{-1}$, respectively, indicating that increase in C_{avg} leads to a slight increase in N_{js} for the LSB impeller. Moreover, the N_{js} can be predicted by tangent-intersection analysis method, which has been reported by Hosseini *et al.* [47]. The predicted N_{js} value in the selected case of $C_{\text{avg}} = 4\%$ (volume) is 278 $\text{r}\cdot\text{min}^{-1}$, which agrees well with the experimental result. Fig. 9 illustrates the effect of C_{avg} on the predicted axial and radial distributions of the local solid holdup at a fixed impeller rotating speed of $N = 350 \text{ r}\cdot\text{min}^{-1}$. It is

seen that the uniformity of axial distribution becomes worse when the solid loading increases, in particular in the zone of $z/T > 1.2$. While the radial distribution of the local solid holdup is similar, except that the solid holdup increases when the solid loading increases.

4.6. Comparative study

To reveal whether the proposed LSB impeller has advantages in solid–liquid mixing, we compared the solid suspension behavior in the tank stirred by the LSB impeller with those stirred by single RT impeller, dual RT impellers, and CBY impeller under the same power consumption. Here, the characteristic diameter and off-bottom clearance of RT impellers and CBY impeller are the same as that of LSB impeller. The blades size (height $\times$ width = 35 mm $\times$ 30 mm) of RT impeller is also the same as that of the SBs. The impeller distance of the dual RT impellers system is 0.775 T . In our previous study [12], the predicted power consumption agrees well with the experimental results by torque measurement. In this work, the impeller rotating speed is varied to calculate the power numbers of LSB impeller ($S/T = 0.5$), single RT impeller, LSB impeller ($S/T = 0.25$), dual RT impellers and CBY impeller. The values are 7.00, 6.55, 8.51, 16.23, 0.80, respectively, corresponding to the same power consumption of $P/V = 3.1 \text{ kW}\cdot\text{m}^{-3}$. Fig. 10 shows the comparison of solid holdup iso-surfaces with different values for

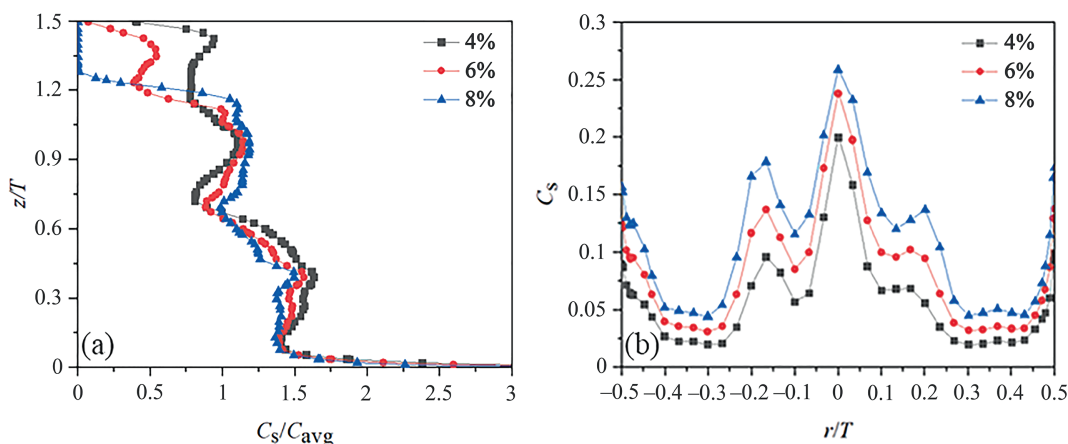


Fig. 9. Influence of initial solid holdup on the axial and radial distributions of the local solid holdup: (a) axial distributions ($r/R = 0.9$) and (b) radial distributions ($z/T = 0.15$). $N = 350 \text{ r}\cdot\text{min}^{-1}$, $d_s = 0.2 \text{ mm}$, $\rho_s = 2500 \text{ kg}\cdot\text{m}^{-3}$.

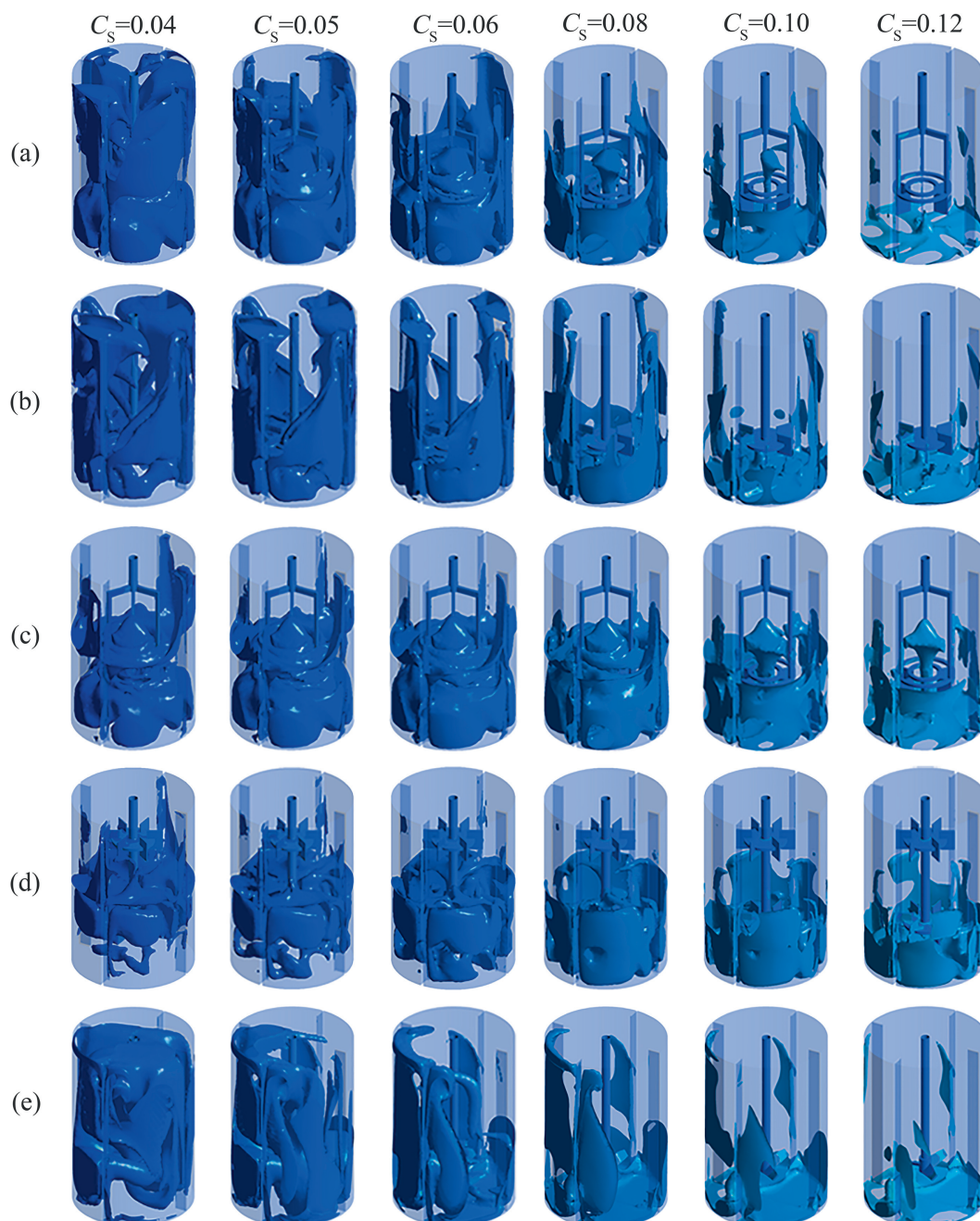


Fig. 10. Solid holdup iso-surfaces under the power consumption of $P/V = 3.1 \text{ kW} \cdot \text{m}^{-3}$: (a) LSB, $N = 450 \text{ r} \cdot \text{min}^{-1}$, $S/T = 0.5$; (b) single RT, $N = 460 \text{ r} \cdot \text{min}^{-1}$; (c) LSB, $N = 425 \text{ r} \cdot \text{min}^{-1}$, $S/T = 0.25$; (d) dual RTs, $N = 340 \text{ r} \cdot \text{min}^{-1}$; (e) CBY, $N = 925 \text{ r} \cdot \text{min}^{-1}$. $d_s = 0.2 \text{ mm}$, $\rho_s = 2500 \text{ kg} \cdot \text{m}^{-3}$, $C_{\text{avg}} = 4\%$ (volume).

different impellers. Firstly, we studied the effect of the submergence depth of LSB impeller (S/T) on the solid suspension behavior. When the submergence depth decreases from $S/T = 0.5$ (Fig. 10(a)) to $S/T = 0.25$ (Fig. 10(c)), the particle distribution in the whole tank becomes worse. One can see that more particles accumulated at the bottom of the tank when $S/T = 0.5$ ($C_s = 0.10, 0.12$), while more particles reach the upper part of the tank ($C_s = 0.04–0.06$) compared with the case of $S/T = 0.25$. This implies the submergence depth has a significant effect on the solid distribution for the LSB impeller.

Moreover, the particles in the tank with the LSB impeller (Fig. 10(a)) are also more evenly distributed than those with single RT impeller (Fig. 10(b)) or dual RT impellers (Fig. 10(d)). Although solid holdup iso-surface of $C_s = 0.04$ in the tank with single RT impeller (Fig. 10(b)) reaches a height similar to that of the LSB impeller

(Fig. 10(a)), there are few particles above the impeller in the middle of the tank due to the existence of the disc for the RT impeller. As can be seen from iso-surface of $C_s = 0.12$, more particles accumulated at the bottom of the single RT impeller (Fig. 10(b)) and dual RT impellers (Fig. 10(d)). In addition, for a typical axial flow CBY impeller which is always used for solid suspension, we can see that the particles are still unevenly distributed, although more particles have reached the upper region of the tank (Fig. 10(e)).

To have a quantitative comparison of the uniformity of the particle distribution in the tank with different impellers, the variation coefficient in the whole tank, σ , is defined as

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{C_s}{C_{\text{avg}}} - 1 \right)^2} \quad (7)$$

In this work, the solid holdup at each position in the stirred tank are used to calculate variation coefficient. The calculated values of the variation coefficient for the LSB impeller ($S/T = 0.5$), single RT impeller, LSB impeller ($S/T = 0.25$), dual RT impellers and CBY impeller are 0.76, 0.97, 0.86, 1.34 and 1.08, respectively. This indicates that the LSB impeller can obtain the best particle distribution uniformity compared with RT impeller and CBY impeller under the same power consumption. This significant improvement of the solid distribution for the LSB impeller should be attributed the impeller configuration design. From Fig. 4(d) one can see that the down-flow and up-flow also meet in the middle of the tank for the dual RT impeller. However, two radial streams prefer to flow in a segregated manner, resulting in the worst solid distribution uniformity with $\sigma = 1.34$ among the four investigated cases.

5. Conclusions

To evaluate the potential application of our recently proposed long-short blades (LSB) impeller in the solid–liquid two phase flow, we studied the solid suspension behavior in a tank of $H/T = 1.5$ stirred by the LSB impeller both experimentally and numerically. The Euler granular flow model, which incorporates kinetic theory of granular flow into the traditional Euler–Euler two-fluid model, has been successfully used to predict the solid suspension behavior after validation by the measured local solid holdup. The standard $k-\varepsilon$ model was adopted as the turbulence model.

It is found that the granular flow model is an advanced model with high prediction accuracy for solid–liquid two phase flow modeling. The influences of impeller rotating speed, particle density, particle size, liquid viscosity and initial solid loading on the solid suspension behavior have been successfully explained, which is consistent with the basic understanding of solid–liquid system. For example, those smaller particles with lower density are more likely to be suspended evenly in the liquid with higher liquid viscosity. At a low impeller rotating speed (N), increase in N leads to an obvious improvement in the solid distribution homogeneity. However, a further increase in N does not improve the suspension quality any more. Initial solid loading has a significant effect on the axial distributions of the local solid holdup, whereas it has little effect on the radial distribution patterns except that the solid holdup increases when the initial solid loading increases.

The solid suspension behavior in the tank stirred by the LSB impeller are also compared with those by the traditional Rushton turbine (RT) impeller (single RT or dual RT impellers) and CBY impeller under the same power consumption. Results demonstrate that the particles are more evenly distributed in the tank with the LSB impeller, which should be attributed to the effective mass exchange and momentum transfer between the axial and radial flows. In addition, the submergence depth of the LSB impeller has a significant effect on the solid distribution, thus, an appropriate submergence depth should be well considered when it is used for even distribution of the particles in the liquid.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

C	off bottom clearance, mm
C_{avg}	mean volume fraction of solid phase
C_D	drag force
C_S	solid volume fraction
$C_{1\varepsilon}, C_{2\varepsilon}$	coefficient of $k-\varepsilon$ model
D	diameter of the impeller, mm
d_s	particle diameter, mm
g	gravitational acceleration, $m \cdot s^{-2}$
g_0	radial distribution function
H	liquid height, mm
K_{SL}	solid–liquid exchange coefficient
k	turbulent kinetic energy, $m^2 \cdot s^{-2}$
L_{lb}	the length of the long blades, mm
L_{sb}	the length of the short blades, mm
N	rotational speed, $r \cdot min^{-1}$
N_{js}	just suspended speed, $r \cdot min^{-1}$
N_p	power number
P	power, W
p	pressure, Pa
R	radial of the tank, mm
Re	Reynolds number
r	radial coordinate, mm
S	impeller submergence, mm
T	diameter of the tank, mm
t_s	particle response time, s
U	velocity, $m \cdot s^{-1}$
V_t	settling velocity, $m \cdot s^{-1}$
W_{lb}	the width of the long blades, mm
W_{sb}	the width of the short blades, mm
z	axial coordinate, mm
α	volume fraction
ε	turbulent dissipation rate, $m^2 \cdot s^{-3}$
θ_s	granular temperature, $m^2 \cdot s^{-2}$
λ_s	bulk viscosity, Pa·s
μ	viscosity, Pa·s
μ_s	shear viscosity, Pa·s
ρ	density, $kg \cdot m^{-3}$
σ_k	turbulent Prandtl number
τ	stress tensor, Pa

Subscripts

a	axial
L	liquid phase
S	solid phase
r	radial

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