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A New Model for Estimation of Just-Suspension Speed based on Lift Force for Solid-Liquid Suspension in a Stirred Tank

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A new model for estimation of just-suspension speed in a stirred tank is proposed based on the forces acting on a single stationary particle on a flat plate in the presence of a simple shear flow. We suggested that if the lift force acting on the particle is greater than the difference between gravitational force and buoyancy force, particle lifts off. However, if the lift force is smaller than the difference of these two forces, particle settles. In order to estimate the lift force component acting on the particle, a simple 3-dimensional of CFD model is generated. By simulated lift force component, the representative flow velocity subjected to the radius of the solid particle for just-suspension is determined. For estimation of the representative flow velocity, flow velocity distributions inside stirred tank is employed at the inlet of the CFD model as a customized boundary condition. The boundary condition is determined based on direct measurement of flow velocity close to the tank base using *L.D.V.* It is showed also that flow visualization close to the tank bottom using *P.T.V.* agrees well with the *L.D.V.* results.

The representative flow velocity obtained from the CFD model is verified and compared with the experimental value at just-suspension speed for a wide range of particle densities, $0.03 \leqq \Delta\rho/\rho_\ell \leqq 1.5$. The results showed that the calculated value agrees reasonably well with the experimental value within the error of ±15% at a given system using a 4 bladed pitched paddle impeller.

The determination of the effect of lift force acting on a solid particle for solid-liquid suspension in a stirred tank may overcome the limitation of the conventional experimental method by visual observation for characterizing the just-suspension speed. Moreover, the new proposed model also offers physical understanding in regards to explaining the mechanism of just-suspension which has not been reported by earlier workers.

Introduction

Solid-liquid mixing in a stirred tank is a common unit operation in chemical, mineral and other process industries. In many processes, such as dissolution, leaching, ion-exchange and adsorption, and solid-catalyzed reaction, the main objective is to provide maximum surface contact area of solid-liquid available for chemical reaction or transport processes. This can only be achieved by operating at complete suspension, where all particles are move freely inside stirred tank and no particle remains at rest longer for more than 1 or 2 seconds on the tank base (Zwietering, 1958).

Suspending solid particles in liquid requires the impeller to produce sufficient flow to lift settled particles on the tank base. In order to explain this, Wong *et al*. (2015) shows the sequence of areas on the tank base where particles concentrated before or just as suspension takes place. This was explained in terms of the fluid flow patterns and related to the overall suspension performance of the geometries used. They also stressed that an understanding of the flow behavior particularly close to the tank base is crucial in predicting the impeller speed and energy required to suspend solids in a stirred tank.

Since pioneering work by Zwietering (1958), there has been extensive work reported in literature pertaining to solids suspension. Empirical and semi-empirical correlations of the just-suspension speed, N_{js} are also been proposed. Many of the workers often followed Zwietering correlation or modified the Zwietering correlation by extending the range of variables including impeller design, impeller diameter, impeller clearance from the tank base, baffles or tank base design, and studied the effect of each variable independently (Nienow, 1968; Chapman *et al*., 1983; Raghava Rao *et al*., 1988; Armenante and Nagamine, 1998). Nevertheless the abundant work on this subject, Zwietering correlation still the most commonly referred. However, the method used by Zwietering for characterizing just-suspension speed does not offer substantial explanations on the mechanism on how the solid particles are lifted from the tank base although mentioned that the last point of just-suspension depends on the flow pattern in the lower part of the tank base and on the form of the tank base design. The 1-2s criterion method using visual technique to determine the just-suspension speed is very subjective which require careful and skilled observation (Jafari *et al*., 2012). Wong *et al*. (2015) also found that the 1-2s criterion was not applicable, however, to a very small percentage of particles which did not move, other than just vibrating at their respective locations even at very high impeller speeds. Moreover, the prediction of just-suspension speed using the proposed empirical correlation may not be as reliable if falls away from the range of parameters covered.

To overcome these limitations, some workers attempted further investigation to understand the just-suspension mechanism by proposed semi-theoretical models for determination of the just-suspension speed. Kolar (1960) presents theoretical analysis based on terminal velocity in a still fluid and derived relations from the experimental results to calculate just-suspension speed. However, the proposed correlation and experimental method are by means of homogeneous suspension. He found that at the just-suspension speed, the suspension condition in a stirred tank was not homogeneous. Consequently, the homogeneity of the solids suspension is achieved by increasing the impeller speed. This, in turns may leads to excessive prediction of impeller speed for just-suspension by using his proposed correlation. Baldi *et al*. (1977) proposed a model for determination of the just-suspension speed by means of the scale of turbulence. According to this model, they assumed that if the scale of turbulence have a scale of the order (or approximate) to the particle size, the energy transferred by these turbulence may able to lift off particles for just-suspension. Davies (1985) and Mersmann *et al*. (1998) also make an attempt to explain the Zwietering correlation in terms of basic turbulence theory, which has very similar concept to Baldi *et al*. (1977). However, according to Wichterle (1988), the concepts of Kolmogoroff's theory of homogeneous turbulence have its limitations, too. The energy is not dissipated uniformly throughout the stirred tank and there is no satisfactory knowledge of the dissipation intensity in the vicinity of the tank base. Hence, the validity of Kolmogoroff's theory in a stirred tank is still questionable. He suggested a theoretical model by considering that the just-suspension is determined by the ratio of the particle settling velocity to the characteristics velocity profiles around the particle at the tank base. He estimated the velocity profiles by determining the shear rates at the tank base in homogeneous liquid using electro diffusion method. The proposed model, however, may not be able to apply for large particle size of which does not lie inside the laminar boundary layer. Moreover, none of these entire models offer sufficient relevant physical meaning on the relationship between the force exerted by liquid flow and suspension of solid particles.

This work aims to propose a new model for estimation of just-suspension speed in a stirred tank based on the forces acting on a single stationary particle on a flat plate in the presence of a simple shear flow. Even though this model might not clarify the mechanism completely, importantly, it offers physical meaning to enhance further understanding on how solid particles lift off the tank base to achieve just-suspension. This model also relates the important parameter for just-suspension in a stirred tank, i.e. flow velocity with solid particles to ascertain just-suspension condition by direct measurement of fluid flow close to the tank base quantitatively and qualitatively. The forces that act on a single particle on a flat plate are studied and subsequently a new model to estimate just-suspension speed for solid-liquid suspension in a stirred tank is suggested.

1. A simple model based on lift force

We initially considered a single sphere particle in contact with a flat plate in the presence of a simple shear flow, as illustrated in Figure 1. Due to this fluid flow field, the flow velocity gradient around the particle, i.e. higher flow velocity above the particle compared with the flow below the particle results in pressure and viscous stress distributions around the particle and consequently exerts lift force on the particle. The lift force is an upward force, as well an upward force of buoyancy force and a downward force of gravitational force are also work on the particle. Therefore, we suggested that if the lift force acting on the particle is greater than the difference between gravitational force and buoyancy force, particle lifts off. However, if the lift force is smaller than the difference of these two forces, particle settles.

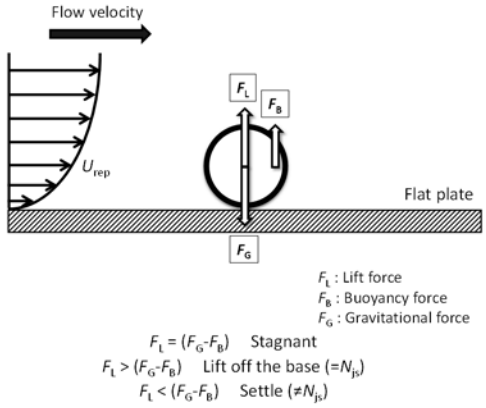


Fig. 1 Schematic diagram of forces acting on a single stationary particle on a flat plate in the presence of a simple shear flow

Based on this concept, we need to evaluate the lift force component based on the flow velocity distribution in regards to characterize flow close to the tank base. Since the objective is to evaluate the lift force component, a simple 3-dimensional model was generated with a single spherical solid particle is fixed and placed at the center of the flat plane using ANSYS Fluent, a commercial CFD software package, as shown in Figure 2 (a). This, significantly simplifies the complicated geometry of the stirred tank which inevitably requires powerful computer processor and extremely time consuming for solution. In CFD, the fluid flow field is solved; hence lift force can be determined by the hydrodynamic forces exerted around the surface of the particle, i.e. pressure force and viscous force which acts in perpendicular direction to the subjected horizontal shear flow.

Further, owing to the fact that fluid flow field determines the lift force action over the particle, it is required to measure flow velocity distribution inside stirred tank, particularly close to the tank base. This is to be applied at the inlet of CFD model as a customized boundary condition. Despite the chaotic nature and complexity of the fluid flow inside stirred tank even in a simple system, from a practical point of view, we focused in our analysis predominantly on the fluid flow which is responsible for carrying the particle towards the tank wall and originate them to lift off the tank base. This was done by directly measured fluid flow inside stirred tank quantitatively, particularly near the tank base using *L.D.V.* Furthermore, fluid flow pattern at the tank bottom was also analyzed qualitatively using *P.T.V.* in regards to relate the particle distribution on tank base and the last point where just-suspension took place.

2. 3D model and lift force calculation

A simple 3-dimensional model was generated with a single solid particle is in contact with a flat plane in the center was taken as a case study, as displays in Figure 2(a). The solid particle is spherical in shape and 1mm in diameter size. The length of the X, Y and Z planes are 50 mm, 25 mm, and 25 mm, respectively. An unstructured grid employing tetrahedral cells (tetra-mesh element number is 1.26×10^{6}) was employed to save set-up time and computational expense, as shown in Figure 2(b). The boundary conditions used are shown in Table 1. Since flow velocity gradient will affects the lift action over the particle, normalized flow distributions close to the tank bottom corresponding various values of tip velocity was employed in the inlet of the CFD model as a customized boundary condition, which in our case, it was determined experimentally by direct measurement using *L.D.V.* This flow was then specified using User Defined Functions (UDFs) using C programming language that can be loaded with the ANSYS Fluent solver. Navier Stokes equation for incompressible viscous flow is considered for our model. The general conservation of mass and momentum equations are as in following equations.

Conversation of mass

$$\nabla\cdot\vec{V}=0 \qquad (1)$$

Conversation of momentum

$$x:\ \rho\left(\frac{\partial u}{\partial t}+\vec{V}\cdot\nabla u\right)=-\frac{\partial p}{\partial x}+\mu\nabla^{2}u$$

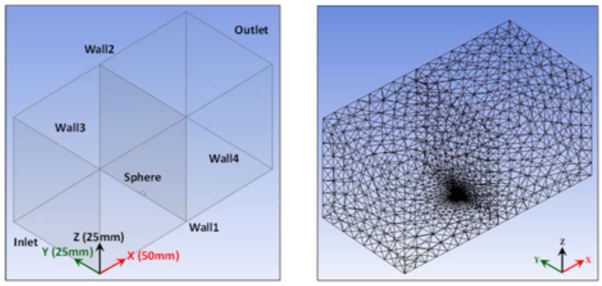
$$y:\ \rho\left(\frac{\partial v}{\partial t}+\vec{V}\cdot\nabla v\right)=-\frac{\partial p}{\partial y}+\mu\nabla^{2}v$$

$$z:\ \rho\left(\frac{\partial w}{\partial t}+\vec{V}\cdot\nabla w\right)=-\frac{\partial p}{\partial z}+\mu\nabla^{2}w-F_{g} \qquad (2)$$

The lift force acting on the particle can be determined by the pressure force and viscous force at a specified vector, which acts in perpendicular direction to the subjected horizontal shear flow, which in our case it is determined at *Z* direction.

Lift force

$$F_{a}=\vec{a}\cdot\vec{F_{p}}+\vec{a}\cdot\vec{F_{v}} \qquad (3)$$



(a) (b)

Fig. 2 3D model and unstructured grids

Table1 Boundary conditions

Inlet	:	Normalized flow distributions close to the tank bottom corresponding various values of tip velocity using User Define Functions
Outlet	:	Outflow
Sphere surface	:	No slip
Wall 1	:	No slip
Wall 2	:	Slip
Wall 3	:	Slip
Wall 4	:	Slip

The net force acting on a solid particle completely submerged in the liquid was calculated by subtracting the gravitational force with the buoyancy force using the following equation as follows.

Net force

$$F_{\text{net}}=(F_{G}-F_{B})=(\rho_{s}-\rho_{l})\left(\frac{\pi}{6}{d_{p}}^{3}\right)g \qquad (4)$$

3. Experimental

3.1 Measurement of just-suspension speed and particle distribution on tank base

A *D*=240 mm cylindrical, flat-based equipped with four standard baffles (*B*=0.1*D*) fully baffled Perspex tank was placed in a rectangular tank filled with water to allow for an undistorted view of the cylindrical tank content. The height of the liquid in the tank, *Z*, was kept equal to the tank diameter, *Z*=1.0*D*. The impeller used was a standard type of 4 bladed pitched paddle with ratio of impeller-to-tank diameter is *d*=0.5*D*. The impeller clearance from the tank base was set at one clearance, *C*/*d*=0.5. The details of the tank and impeller geometries are as shown in Figure 3. Since most of the earlier studies on solids suspension either used solid particles that were slightly denser or significantly denser with respect to the water, therefore, solid particles with a wide range of densities, $\Delta\rho/\rho_{\ell}=(\rho_{s}-\rho_{\ell})/\rho_{\ell}=0.03\sim1.5$ as shown in Table 2 were used in this study. Nevertheless, the density of the solid particles and their density difference with respect to the liquid phases is the most influential of the solid particles parameters on just-suspension speed, in that it has the highest exponent in Zwietering equation (Chapman, 1981). All the solid particles are spherical in shape with diameter, d_{p} is practically 1 mm (±5%). The particles size and shape were carefully chosen and confirmed by observation using a digital microscope KEYENCE VHX-500F. Meanwhile, tap water (ρ_{ℓ}=1000 kg/m^{3}) was used as a liquid phase.

The just-suspension speed, N_{js} and particle distribution on tank base were determined visually by watching directly at the side and bottom of the tank. The visual observation was additionally aided with the shine of halogen lamp and video was also captured during the experiments. N_{js} is the impeller speed at which particles are sufficiently lifted from being at rest on tank base and remain suspended in the stirred tank. At initial condition, solids particle of 0.0003% by weight of loading were all settled on tank base randomly. Impeller speed was increased gradually so that the sequence on tank base where the just-suspension took place can be determined. Then, impeller speed was increased further until all the particles are completely lifted and circulated in the tank. The reproducibility of the N_{js} measurement in this work was found to be within error of ±5%.

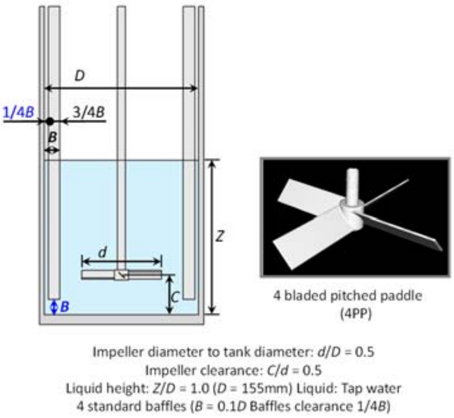


Fig. 3 Tank and impeller geometry

Table 2 Solid particles property

Solid particles	Polystyrene	Phenol	Acetate	Glass beads
Diameter size d_p [mm]	1			
Density ρ_s [kg/m^3]	1030	1250	1280	2500
Shape	Sphere			

3.2 Flow analysis inside stirred tank

Flow analysis inside stirred tank was carried out using the following methods according to the specific objectives. Flow inside stirred tank was measured qualitatively to observe the fluid flow patterns using Particle Tracking Velocimetry (*P.T.V.*). The objective of this measurement is to capture the fluid flow pattern at the bottom part of the stirred tank. This is to provide further understanding on how fluid flow pattern inside stirred tank can significantly effects on solid particles behaviour on the tank base before or just-suspension. Meanwhile, flow velocity close to the tank base was quantitatively measured using Laser Doppler Velocimetry (*L.D.V.*). The objective of this measurement is to characterize flow velocity profiles close to the tank base in a quantitative manner. By this, the fluid flow of which is sufficient to suspend solid particles for just-suspension could be directly imparted at the inlet velocity of the suggested CFD model as a customized boundary condition in order to evaluate the minimum lift force required for just-suspension.

The *P.T.V.* system and *L.D.V.* device for flow analysis inside stirred tank used in this study was exactly similar to that used by Kanamori *et al.* (2011). The *P.T.V.* measurements followed a procedure outline by Kanamori *et al*. (1990), Kobayashi (1991) and Kanamori *et al*. (2011). The stirred tank for this measurement was identical to that used for the N_{js} experiments. Since the objective here is to make qualitative observations of the fluid flow pattern, they were captured at impeller tip speed, V_{tip}=0.95 m·s^{-1}, at which stable flow patterns could be captured. Water was used as an experimental medium inside stirred tank. Particle tracers used were Nylon12 in micron order in spherical shapes. The density of this particle tracers are approximately similar with the water used. For the light sheet, an Argon ion laser was used. Each of these particle tracers was tracked using four time steps that later detected using the tracking algorithm. A high speed CCD camera (100 f/s) was used to record multiple images of the moving particles. The *P.T.V.* measurements were set at the bottom part of the tank: (120mm×90mm).

Meanwhile, the *L.D.V.* device (TSI, Inc.) was used to measure fluid flow velocity close to the tank base, quantitatively. The *L.D.V.* measurements were carried out in a stirred tank which is the impeller-to-tank geometry (d/D=0.5) is matched with N_{js} experiments and *P.T.V.* measurements. Particle tracers used were Expancel® (Japan Fillite) in micron order in spherical shapes. The density of this particle tracers are approximately similar with the water used. The green laser beams produced by Innova 70-C (Coherent, Inc.) was emitted in a horizontal XY plane to obtain radial and tangential velocities components, v_r and v_θ, respectively. The laser power was set to 0.70W. Since a slight change in the room temperature may reduce the power of the beams resulting in a reduction of the detected sample rate (number of counts per unit time), room temperature was kept constant during measurements. Measurements were made at a fixed impeller tip speed for all measurements at 10 different heights from the tank base, z=0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 mm and 8 radial positions, r/D=0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45, as shown in Figure 4. Fine adjustment of measurement points are viewed by detected output signal using an oscilloscope. The sampling time was set at 900 and 1800s, corresponding to approximately 5000 data points at each measurement position. Both the *P.T.V* and *L.D.V* measurements were carried out in between the baffles.

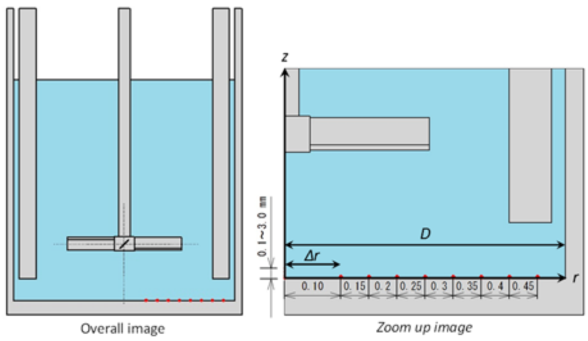


Fig. 4 Flow measurement points

4. Result and Discussions

4.1 Just-suspension speed

Figure 5 shows the just-suspension speed results for four different densities for a given d_p=1mm of solid particles. It is clearly shown that the just-suspension speed increases with an increase in the particle density. The increase in just-suspension speed from less dense particle, i.e. polystyrene particles to high dense particle, i.e. glass beads particles can be related to the increase in terminal velocity with an increase in particle density. Subsequently, higher impeller speed was required to lift denser particles from tank base for just-suspension. This finding was found evident to those reported by Drewer *et al.* (1998) and Ayranci *et al.* (2012). It can be noted also that the just-suspension speed does not linearly increased with an increase of particle density. This result may shows similar tendency to change in the lift force subjected to the effect of particle density with impeller speed.

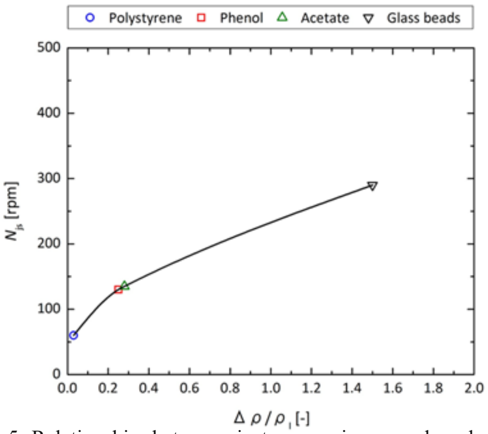


Fig. 5 Relationship between just-suspension speed and particle density difference relative to water

4.2 Particle distribution on tank base and fluid flow pattern

Particle distribution on tank base and the last point where just-suspension took place were determined visually during the determination of just-suspension speed experimentally. At initial condition, particles were randomly distributed stationary on tank base. As impeller speed is increased gradually, particles started to move and collected either in the center just below the impeller hub or in the annular region around the periphery. Some of the particles in the central region were lifted upwards before fall back again to the tank base or weakly moved to the annular region from the drag of the primary flow. Meanwhile, particles in the annular region moved weakly towards the impeller direction, some were seen lifted upwards by the primary flow before fall back again to the tank base. As the impeller speed is increased further, particles were mainly collected in the annular region around the periphery from which they are last suspended (r/D = 0.40). This can be very much expected with the fluid flow pattern given in Figure 6. In the figure, the blue color arrow shows the main discharged flow by the impeller, whereas the red color shows the secondary flows generated from the main discharged flow. It is clearly observed that the 4PP impeller discharges axial downward flow at the tank base. As the main outward flow hits the tank base, a weak secondary loop is induced towards the center just below the impeller hub. This agrees considerably well with bulk fluid flow pattern inside stirred tank for the 4PP reported by Wong *et al.* (2005). It is observed also that a weak secondary flow from the primary flow is also being induced inwards periphery to the tank wall. This result is also relevant with the observation made by Kresta and Wood (1993), who reported a counter-rotating secondary circulation loop forms close to the tank base at similar clearance using 4PP at a similar ratio of impeller-to-tank geometry used in this study. In addition, Ibrahim and Nienow (1999) also reported that the particle distribution in the annular region is related to the meeting of the main flow outwards and a secondary flow being induced inwards around the edge of the tank base.

The last point where the just-suspension takes place, however, may also depends on the size of the particles used (Nienow, 1968). Recent study by Wong *et al*. (2015) used three different sizes of very fine PMMA particles with diameter 18.0µm, 75.3µm and 195.5µm. At similar clearance, they reported that center as the last points of suspension for all particle sizes. In our study, at just-suspension speed, particles at the annular region vicinity to the baffles, approximately near r/D=0.40 were observed to be finally lifted, which if they fall back on tank base they were re-lifted instantaneously and circulated continuously in the tank.

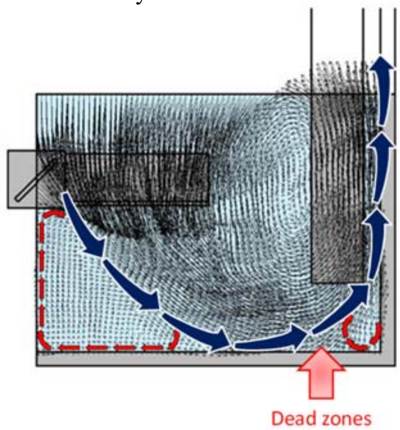


Fig. 6 Fluid flow pattern close to the tank bottom

4.3 Flow velocity close to the tank base

Figures 7 and 8 show quantitative measurement results of radial and tangential velocities profiles close to the tank base, respectively. The flow maps are color coded, with the highest (positive) velocity represented by red color and the lowest (negative) velocity with dark blue color. The direction convention for these figures is as follows: radial velocities are positive towards the tank wall and negative towards the tank center, tangential velocities are positive towards clockwise impeller rotating direction and negative opposing impeller rotating direction. It is observed that radial velocities, particularly in the region beneath the impeller (r/D=0.10～0.25) and vicinity to the tank wall (r/D=0.45) are negative, i.e. flow is directed towards to the tank center, most likely because the lower values of velocities due to the formation of weak secondary flows. Meanwhile, highest velocity is obtained at vicinity impeller tip (r/D=0.30, 0.35, 0.40) indicates that strong outward flow is produced by the impeller. These results are in very good agreement with fluid flow pattern close to the tank bottom in earlier section.

On the other hand, the tangential velocity profiles are relatively lowest at very close to the tank base, i.e. below 0.5mm from tank base, particularly in the region just beneath the impeller. Above 0.5mm from tank base, positive clockwise rotating direction is significantly increasing, and this is corresponding to the strongly directed outward flow in radial direction by the impeller. However, it should be noticed that tangential velocity is quite low also in the region vicinity to the tank wall (*r/D*=0.40). This is mainly because the primary flow cannot reach until the edge of the tank wall and secondary flow is also induced inward from the tank wall.

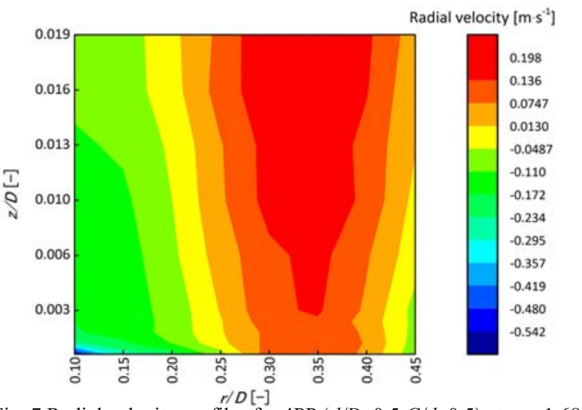


Fig. 7 Radial velocity profiles for 4PP (*d/D*=0.5 *C/d*=0.5) at v_{tip}=1.68 m·s^{-1}

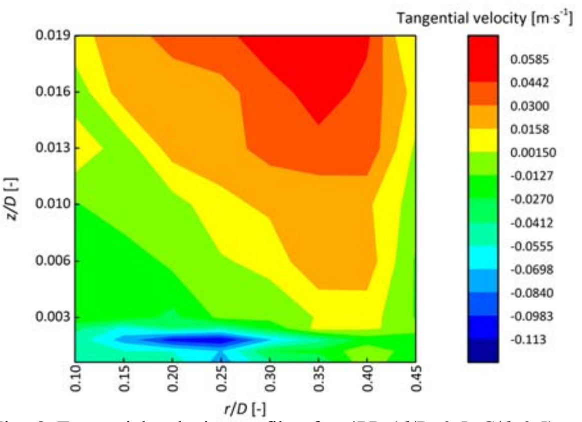


Fig. 8 Tangential velocity profiles for 4PP (*d/D*=0.5 *C/d*=0.5) at v_{tip}=1.68 m·s^{-1}

It is showed that the mechanism that results in lifting the particles for just-suspension are dependent on the fluid flow close to the bottom of the tank. Based on the results discussed above, we identified the fluid flow, which is responsible for carrying the particle towards the tank wall, originate them to lift off the tank base, and circulate them in the tank. It is observed that the positive value of radial velocities vicinity to the tip of the impeller (*r/D*=0.30, 0.35, 0.40) which are responsible to carry the particles towards the tank wall and originate them to lift off the tank base for just-suspension. Since the particles were moved in positive clockwise-rotating direction of the impeller, positive tangential velocities in these regions (*r/D*=0.30, 0.35, 0.40) are also considered. Subsequently, the mean of the positive value of radial and tangential velocities, $\overline{v_{r+}}$ and $\overline{v_{\theta+}}$ at *r/D*=0.30, 0.35, 0.40 are given consideration to be used as resultant velocities and normalized, using the following procedures.

Resultant velocity

$$v(z) = \sqrt{\overline{v_{r+}}^2 + \overline{v_{\theta+}}^2} \quad (5)$$

The resultant velocities were then normalized at v_{tip}=1.68 m·s^{-1} and referred to as "normalized velocity, $v_n(z)$" throughout the paper, as shown in the following equation.

Normalized velocity

$$v_n(z) = \frac{v(z)}{v_{\mathrm{tip}}} \quad (6)$$

This normalized velocities distribution are as shown in Figure 9.

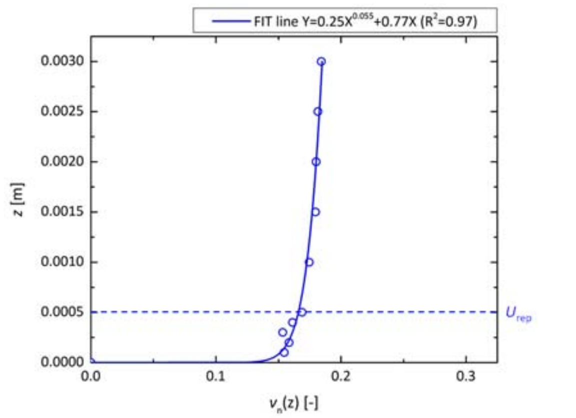


Fig. 9 Normalized flow velocities for the mean of positive values of radial and tangential velocities at *r/D*=0.30, 0.35, 0.40

Nouri *et al*. (1987) has shown that velocity profiles above and below the impeller stream scaled well with the impeller tip speed in the baffled system. This result is also supported with further work by Zhou and Kresta (1996) using several types of impellers. The experimental geometry design (ratio of impeller-to-tank diameter) and clearance used in this work falls within a range of clearances of those used by Kresta and Wood (1993) and Ayranci *et al*. (2012) whose applied similar scaling method in their work. Considering that the scaling method could be applied for the present results, the normalized velocity distribution was used in calculation of velocity distributions close to the bottom of the tank corresponding various values of v_{tip} by means of the following relationship.

$$v(z) = v_n(z) \times v_{\mathbf{tip}} \quad (7)$$

The calculated velocity distributions were employed as a customized boundary condition at the inlet of the CFD model.

4.4 Computation of the lift force

Figure 10 shows the plot of computed lift force. The blue circle plots show the computed lift force. Abscissa U_{rep} is a flow velocity subjected to the radius of solid particle, i.e. $z=d_p/2$ corresponding to the calculated lift force. It is chosen as a representative flow velocity at bottom part of the tank to correlate with the computed lift force to determine the minimum flow velocity required for the just-suspension. By the correlation between the lift force and U_{rep} using the following power law formula, $F_L=5.83\times10^{-5}\cdot(U_{rep})^{2.05}$, the representative flow velocity of each solid particle to ascertain just-suspension condition is determined. It is interesting to notice that, the lift force is almost proportional to the square of representative flow velocity for each particle regardless of the particle densities. According to our model, if the lift force is greater than the difference between buoyancy force and gravitational force, the particle lifts off the tank base. Consequently, by subtracting the buoyancy force from the gravitational force, the minimum lift force requires for just-suspension can be determined, as shown by the solid lines in the respective figure. Thus, from the corresponding correlation obtained, the representative flow velocity required for just-suspension can be determined for each solid particle, as shown by the dotted lines in the respective figure. Furthermore, the tip velocity corresponding the representative flow velocity is calculated by substituting U_{rep} to $v(z)$ in Equation (7).

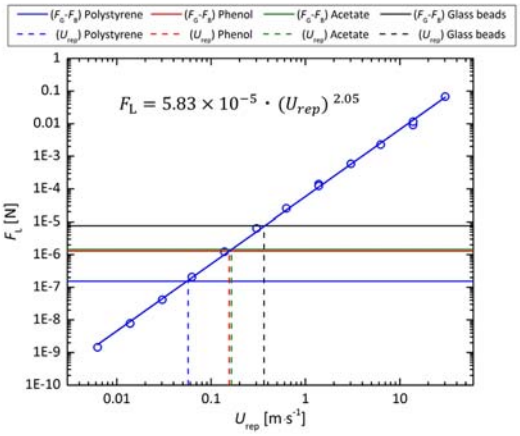


Fig. 10 Plot of computed lift force

Table 3 shows the values of tip velocity and impeller speed at just-suspension, N_{js} for each solid particle by the proposed model and experimental work. It should be remarked that flow close to the tank base is often fluctuates, meanwhile the imparted flow velocity in the CFD model is constant, and this may affect the lift action on the particles. Nevertheless, considering also that the experimental error involved in measuring just-suspension speed and flow velocity distribution, it is found that the calculated values based on the proposed model vary within ±15% from the experimental values.

Table 3 Calculated and experimental values of impeller speed and tip velocity at just-suspension

Solid particles	Polystyrene	Phenol	Acetate	Glass Beads
Density, $\Delta\rho/\rho_l$ [-]	0.03	0.25	0.28	1.5
N_{js} calc. [rpm]	55	147	155	343
$V_{tip\ (js)}$ calc. [m/s]	0.35	0.92	0.97	2.15
N_{js} exp. [rpm]	60	130	135	290
$V_{tip\ (js)}$ exp. [m/s]	0.38	0.82	0.85	1.82
Error (%)	-8	11	13	15

Further, the relationship between N_{js} and $\Delta\rho/\rho_\ell$ in Table 3 is presented in Figure 11. A linear regression analysis of calculated data based on the lift force for a wide range of particle densities in this work ($0.03 \leqslant \Delta\rho/\rho_\ell \leqslant 1.5$) gave an exponent of 0.47.

$$N_{js} \propto \left(\frac{\Delta\rho}{\rho_l}\right)^{0.47}$$

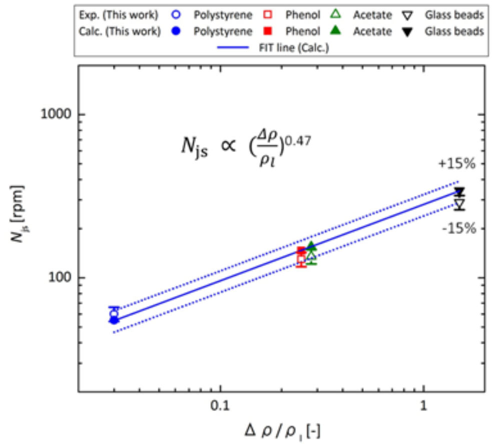


Fig. 11 Impeller speed at just-suspension by proposed model and experimental

4.5 Comparison with literature data

Table 4 shows the exponent of density obtained by different investigators. It can be clearly seen that the exponent obtained in this work using the proposed model was found to be almost similar to those reported by earlier investigators, and in particular to those presented by Zwietering (1958) and Myers *et al.* (1994), regardless of the size and shape of the solid particles, and the type of the impellers used. Moreover, the exponent also shows good agreement with those in the theoretical development based on turbulence model of Baldi *et al*. (1977).

Table 4 Comparison of exponent for density of solid particles found by in this work and various workers

Authors	Solid phase			Impeller	Exponent
	Size, d_p [mm]	Density, $\Delta\rho/\rho_l$ [-]	Shape		
This study	1.0	0.03 ~ 1.50	Spherical	4PP	**0.47**
Zwietering (1958)	0.125 ~ 0.85	0.35 ~ 2.29	Irregular	6FT	0.45
Nienow (1968)	0.15 ~ 0.60	0.53 ~ 1.48	Spherical	6FT	0.43
Chapman (1981)	0.3	0.05 ~ 1.90	Spherical, flat and irregular	6FT	0.40
Myers *et al.* (1994)	1.18	0.0060~ 1.91	Rectangular cylinders	4PP and Chemineer HE-3	0.45
Armenante *et al.* (1998)	0.12	0.375 ~ 1.50	Spherical	6PP	0.51

Figure 12 shows the predicted value of just-suspension speed by using Zwietering correlation and calculated value of just-suspension speed using our proposed model. Comparison was made by using S values reported by those literature data available for pitched paddle impeller by considering identical geometry configuration employed in this study, i.e. d/D=0.5 and C/d=0.5, for a range of particle densities covered. S value is a dimensionless parameter accounting in Zwietering correlation, varies with impeller design, impeller diameter-to-tank diameter, and impeller clearance-to-tank diameter. Due to the small amount of solid particles used in this work, only solid particles concentration is neglected in the calculation. However, this may less affect the prediction of the just-suspension speed since the exponent of the solids concentration is very small in the correlation, due to the very weak dependence of just-suspension speed on solids concentration (Chapman, 1981). The error limit given for predicted just-suspension speed to that of calculated just-suspension speed using our proposed model is as shown in the respective graph, ±15%. It is well observed that predicted just-suspension speed using *S* values calculated from data of Nienow and Miles (1978) and, Armenante and Nagamine (1997) agrees well with our calculated just-suspension speed, with all data falls within error limit. It also can be noted that the *S* value recommended by Chapman (1981) reflects an increase in just-suspension speed from our calculated value, although still within in their reported limit error (±14%). Ibrahim *et al*. (2015) in their recent works reported that the *S* factor does not only change with geometry, but vary significantly with changes in operating parameters. Hence, *S* value presented by Chapman (1981) may give slight variations from our calculated just-suspension and predicted just-suspension by other workers. Nevertheless, in overall, it was demonstrated that the just-suspension speed calculated by our proposed model agrees reasonably well with earlier workers, whose used the visual observation to predict the just-suspension speed.

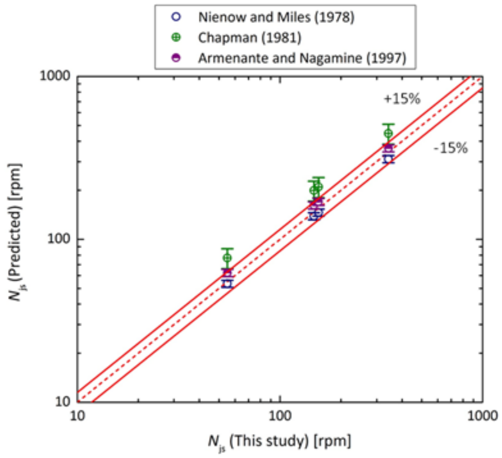


Fig. 12 Just-suspension speed by proposed model and Zwietering correlation

Conclusions

In attempt to further understand the mechanism of just-suspension theoretically, a model has been proposed by studied the force balance applies on a single stationary particle. The model suggested that, if the lift force acting on the particle is greater than the difference between gravitational force and buoyancy force, the particle lifts off. However, if the lift force is smaller than the difference of these two forces, particle settles. The lift force was calculated by generated a 3D model, with a single spherical particle stationary on a flat plate is taken as a case study. The flow velocity profile in regards to determine the lift force was quantitatively measured using *L.D.V.* and normalized. By the simulated lift component, the representative flow velocity required to initiate particle to lift off the tank base and suspended in the tank was determined. A comparison with experimental values shows fairly good agreement with the calculated values for a range of particle densities studied.

This method, even though simple, importantly, it offers physical meaning on how solid particles achieve just-suspension. By understanding the effect of lift force for just-suspension; this may overcome the limitation of visual observation which is very subjective. Further, this work can be extended to variations of particle sizes, impeller designs and geometries and particle-particle interaction effect so that a new correlation can be proposed.

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Nomenclature

ρ_s	= solid particle density	[kg/m³]
ρ_l	= liquid density	[kg/m³]
$\Delta\rho$	= $(\rho_s$-$\rho_l)$	[kg/m³]
p	= pressure	[N/m²]
g	= gravitational acceleration	[m/s²]
d_p	= solid particle diameter	[m]
m	= mass	[kg]
V_l	= liquid volume	[m³]
F_a	= total force at a direction	[N]
F_p	= pressure force	[N]
F_v	= viscosity force	[N]
F_G	= gravitational force	[N]
F_B	= buoyancy force	[N]
F_L	= lift force	[N]
$v(z)$	= resultant velocity	[m/s]
v_{tip}	= impeller tip speed	[m/s]
v_r	= radial velocity	[m/s]
v_θ	= tangential velocity	[m/s]
$v_n(z)$	= normalized velocity	[-]
N_{js}	= impeller speed at just-suspension speed	[rpm]
U_{rep}	= representative flow velocity corresponds to the velocity at radius particle	[m/s]
N	= impeller speed	[rpm]
C	= impeller clearance from tank base	[m]
D	= impeller diameter	[m]
d	= tank diameter	[m]
B	= baffle diameter	[m]
Z	= liquid height	[m]
r	= position from tank center towards tank wall	[m]
z	= position from tank base	[m]
F_x, F_y, F_z	= total force of respective location x, y, z	[N]
u, v, w	= functions of location x, y, z	
∇	= del operator	
CFD	Computational Fluid Dynamics	
UDF	User Define Function	
P.T.V.	Particle Tracking Velocimetry	
L.D.V.	Laser Doppler Velocimetry	
4PP	4 bladed pitched paddle impeller	

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