Study of critical suspension speed of impeller in two paddles stirred kettle

Yingwu Chen, Hong Xu*, Peng Xu, Yanlun Ren
School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai, China
hxu@ecust.edu.cn

Abstract. Experiments and numerical simulations were used to study the two-layer paddle stirring system. Glass bead particles and aqueous polyvinyl alcohol solution were used as the solid-liquid phases, and the variation of the critical suspension speed of impeller $N_{js}$ under different parameters was analyzed by testing the parameters of liquid phase viscosity, solid phase particle size, and solid-phase mass fraction. The results showed that the main resistance (surface viscous resistance) increased with the increase of liquid-phase viscosity at particle size $d=0.3$ and $d=0.5$ mm, and this factor inhibited the solid-phase diffusion, resulting in an increasing trend of $N_{js}$ with the increase of liquid-phase viscosity. At particle size $d=0.8$ and $d=1$ mm, the main resistance (gravity) is not related to the liquid phase viscosity, and the intensity of turbulent pulsation in the kettle is enhanced with the increase of liquid phase viscosity, which is favorable to the solid phase diffusion, and $N_{js}$ decreases with the increase of liquid phase viscosity. The increase in solid-phase volume fraction increases $N_{js}$.

1. Introduction
A solid-liquid suspension is a typical unit of operation in the process industry, where the solid particles are stirred at a uniform speed to maintain a homogeneous distribution in the liquid phase, thus enhancing the mass transfer efficiency between the solid and liquid phases. The current academic research on solid-liquid suspension has been extensively conducted, focusing on two main directions, one of which is to achieve controllable solid-liquid suspension through specific parameter optimization. The second is the optimization of the suspension performance in ensuring that the solid particles in the stirred vessel maintain a high degree of uniformity of distribution over some time and the lowest possible power consumption[1]. Thus, researchers have systematically investigated the relationship between the structural parameters of the stirred vessel and the operating conditions of the stirring process and the suspension performance, as well as analyzing the influence of liquid phase physical parameters and solid-phase physical parameters on the suspension performance[2]. In this paper, glass bead particles and aqueous polyvinyl alcohol solution are used as solid and liquid phases in a double-layer paddle stirring system. The effects of liquid phase viscosity, solid phase particle size, and solid-phase mass fraction on the critical suspension speed of impeller $N_{js}$ within the system are investigated. The above formation patterns are explored in terms of the main body flow and turbulent pulsation theory.
2. Experiment

2.1. Equipment
The experimental setup consists of a stirring system and a parameter measurement system (Figure 1). The stirring system includes the electric motor, coupling, shaft, stirring paddle, stirring kettle, etc. The parameter measurement system consists of pressure sensors etc. The stirring kettle is a flat-bottomed cylindrical vessel made of transparent acrylic glass with a diameter of $T=300$ mm and a liquid level of $H=300$ mm at rest, and the bottom of the kettle is perforated for the installation of a pressure sensor to measure the pressure at the bottom of the kettle. The paddle is a down-pumping pitched blade turbine paddle with outer diameter $D=120$ mm, width $d=30$ mm, and thickness $w=2$ mm. The bottom of the lower blade is at a height of $S_1=50$ mm from the bottom and the distance between the two blade layers is $S_2=120$ mm.

![Figure 1. Stirring Equipment](image)

2.2. Material system
The experimental liquid phase was an aqueous polyvinyl alcohol solution. Polyvinyl alcohol powder and pure water were prepared in aqueous solution at a certain concentration and dissolved at 90°C temperature to prepare. The experimental liquid phase viscosity was selected as 60cp, 103cp, 164cp, and 224cp, and pure water was selected as the control group. The experimental solid phase was glass bead particles with the specific composition of $\text{SiO}_2$, $\rho=2500$kg/m³. The particle size was divided into $d=0.3$mm, $d=0.5$mm, $d=0.8$mm, and $d=1$mm. The different influencing factors corresponding to the solid phase masses in the experiments are shown in Table 1.

| No. | Solid phase particle size (mm) | Solid phase volume fraction (%) | Solid phase mass (kg) |
|-----|-------------------------------|--------------------------------|----------------------|
| 1#  | 0.3                           | 8%                             | 4.24                 |
| 2#  | 0.3                           | 15%                            | 7.95                 |
| 3#  | 0.5                           | 8%                             | 4.24                 |
| 4#  | 0.5                           | 15%                            | 7.95                 |
| 5#  | 0.8                           | 8%                             | 4.24                 |
| 6#  | 0.8                           | 15%                            | 7.95                 |
| 7#  | 1.0                           | 8%                             | 4.24                 |
| 8#  | 1.0                           | 15%                            | 7.95                 |
2.3. Parametric measurements

2.3.1. Critical suspension speed of the impeller. The bottom pressure method is used to measure $N_{js}$. To avoid the measurement error caused by the direct impact of particles on the sensor, two nuts are used to fix the sensor at the bottom of the stirring kettle, and the nut is partially screwed into the kettle to leave a gap, and a fine wire mesh is welded on to prevent particles from passing through.

The bottom of the kettle is subjected to a combination of hydrostatic and dynamic pressures, where the hydrostatic pressure is related to the suspension condition of the solid phase particles by the following equation[3]:

$$\Delta P_{\text{static}} = \frac{M_s(1-\rho_l/\rho_s)g}{A}$$  \hspace{1cm} (1)

The dynamic pressure is mainly related to the stirring motion of the liquid phase by the following equation[3]:

$$\Delta P_{\text{dynamic}} = aN^2, \quad N \gg N_{js}$$  \hspace{1cm} (2)

The total pressure equation is as follows:

$$\Delta P = \Delta P_{\text{static}} + \Delta P_{\text{dynamic}}$$  \hspace{1cm} (3)

Equation: $M_s$ is the mass of the suspended solid phase, kg. $\rho_s$ is the density of the solid phase, $\rho_l$ is the density of the liquid phase, kg/m$^3$. $A$ is the total area of the bottom of the vessel, m$^2$. $a$ is the coefficient of dynamic effect.

According to equations (1) to (3), when the speed $n$ reaches $N_{js}$, the static pressure no longer increases, but the dynamic pressure continues to increase. Calculate the static pressure value when $n> N_{js}$ substitute into equation (3) to separate the $\Delta P_{\text{dynamic}}$ curve, and fit to calculate $a$. Recalculate the fitted $\Delta P_{\text{dynamic}}$ value and substitute into equation (3) to separate the $\Delta P_{\text{static}}$ curve, where the $\Delta P_{\text{static}}$ value is constant is $N_{js}$.

2.3.2. Numerical simulation of flow field distribution and turbulent pulsation intensity. In this paper, the intensity of turbulent pulsations and the distribution of the flow field in the kettle are obtained utilizing numerical simulations at various locations in the kettle. The physical model parameters for the numerical calculation are shown in Figure 1 for the structure of the stirred kettle. The liquid phase is an aqueous polyvinyl alcohol solution, the solid phase is glass bead particles, and the physical parameters are set the same as the experimental measurements. According to the physical structure and symmetry of the flow, 1/4 of the kettle body was selected as the calculation domain. The MRF method is used to calculate the flow field, and the computational domain is divided into the dynamic zone (paddle region) and the static zone (outside the paddle region). The dynamic zone uses an unstructured tetrahedral mesh and the static zone uses a structured hexahedral mesh. At the same time, to improve the calculation accuracy, the mesh is encrypted for the paddle, the intersection of dynamic and static regions, the near-wall region, and the stirring shaft. Based on this, the number of meshes in the computational domain is determined to be 319205 by the grid independence test, and the specific grid division is shown in Figure 2.
The free liquid surface in the system is defined as a symmetry condition, the two planes at the boundary of the computational domain are defined as a periodic condition, the paddle speed is set to 500 r/min, the paddle and the stirring shaft are set as rotating wall conditions, and the wall of the stirred kettle is set as stationary wall conditions. The standard k-ε model is used to simulate the turbulent flow, and the calculation of the near-wall region is handled by the standard wall function method. The Euler-Euler two-fluid model is used for the multi-phase flow model. The solid-phase particles are treated as a proposed fluid that can interpenetrate with the liquid-phase fluid, and the set of control equations for each phase is solved separately. Gidaspow model is used for the drag force action.

3. Results and discussion

3.1. Model validation
In this paper, the experimental data of Spidla et al[4] were used to verify the accuracy of the model calculations. The structural and operational parameters of the stirring kettle in the calculations are consistent with the literature: solid-phase particle size 0.35 mm, solid volume fraction 10 %, and liquid-phase is water. From Figure 4, \( \frac{C_V}{C_{V_{avg}}} = 1.25 \) at \( \frac{h}{H} < 0.6 \) (\( C_V/C_{V_{avg}} \) is the ratio of the concentration at the sampling point to the average concentration). When \( \frac{h}{H} > 0.6 \), \( C_V/C_{V_{avg}} \) decreases rapidly as \( \frac{h}{H} \) increases. When \( \frac{h}{H} = 0.9 \) there are almost no glass bead particles. The simulation results are consistent with the changing trend of experimental data, which proves that the model used in this paper is accurate and reliable, and can well predict the flow field and turbulent pulsation intensity distribution in the kettle.
3.2. Model validation

Figure 5 shows the changes in particle suspension in the kettle when the stirring speed n increased for the four particle sizes in the control group experiment. The experimental results showed that for the four particle sizes, the particles did not appear to be suspended at \( n=50 \text{r/min}-350 \text{r/min} \). When \( n>350 \text{r/min} \), the particles were suspended in the kettle, and the suspended particles increased with \( n \), but until \( n=600 \text{r/min} \), the solid-liquid two-phase stratification in the kettle was serious. \( d=0.3 \text{mm} \) particles were suspended at \( 0.6H \), \( d=0.5 \text{mm} \) particles were suspended at \( 0.5H \), \( d=0.8 \text{mm} \) particles were suspended at \( 0.4H \), \( d=1 \text{mm} \) particles were suspended at \( 0.3H \). From this, it can be concluded that the liquid phase with low viscosity cannot make the solid phase achieve complete off-bottom suspension under the system of water as the solvent.

![Figure 3. Normalized solid concentration at \( r/R=0.6 \)]({})

This phenomenon can be explained by the variation of forces on the particles in the flow field: during rotational mixing of the paddles, the particles are mainly subjected to gravity and buoyancy \( (F_{gv}) \), viscous drag on the particle surface by the main body flow \( (F_d) \) and other forces \( (F_o) \), which can suspend the particles when the following equation is satisfied:

\[
F_{gv} = F_d + F_o
\]

\[
F_{gv} = \frac{1}{6} \pi d^3 g (\rho_s - \rho_l)
\]
Equation: \( F_d = C_D \frac{\pi d^2 \rho v^2}{2} \)  

Figure 5(a) shows the velocity vector diagram of the bottom of the kettle obtained by numerical simulation under different liquid phases. Compared with the liquid phase of polyethylene aqueous solution, when the liquid phase is pure water, the flow field at the bottom of the kettle is thin, which indicates that the velocity of the fluid at the bottom of the kettle is smaller and the viscous drag force of the fluid on the particles is smaller. The force on the bottom of the kettle \((F_d+F_o)\) is smaller than its own \(F_g\), and the upward motion of the particle leaving the bottom of the kettle is blocked. The particle’s own \(F_g\) increases with the increase of particle size, which further leads to the decrease of suspension height.

Figure 5. Flow field and turbulence intensity distribution at the bottom of the stirred kettle

3.3. The impact of the main factors on \(N_{js}\)

The experimental results are shown in Figure 6, where an increase in the solid phase volume fraction results in an overall larger \(N_{js}\) at a liquid phase viscosity of 60cp to 224 cp. At \(d=0.3\) mm, \(d=0.5\) mm particle size, \(N_{js}\) increases with increasing liquid phase viscosity, and the overall increasing trend is the same as the Zwietering’s correlation equation[4]. At \(d=0.8\) mm, \(d=1\) mm particle size, \(N_{js}\) decreases with increasing liquid phase viscosity, and the overall decreasing trend is the same as the Tamburini’s correlation equation[5].
The main reason: the presence of the surface viscous resistance $F'_d$ of the fluid to the particles during their upward movement, with the same expression as in equation (6) ($v_i$ is the velocity of the particles). At $d=0.3$ mm and $d=0.5$ mm, $F'_{pv}/F'_d<1$, the surface viscous resistance is the main resistance to particle diffusion, which is positively correlated with the liquid phase viscosity and inhibits particle diffusion, resulting in the increase of $N_{js}$ with the increase of liquid phase viscosity at $d=0.3$, $d=0.5$ mm particle size. At $d=0.8$ mm and $d=1$ mm, $F'_{pv}/F'_d>1$, gravity is the main resistance to the upward movement of particles, while the turbulent pulsation intensity at the bottom of the kettle is shown in Figure 5(b), which becomes stronger with the increase of liquid phase viscosity, which is favorable to the diffusion of solid-phase particles, thus making the $N_{js}$ at $d=0.8$ mm and $d=1$ mm particle size increase with the increase of liquid phase viscosity and the opposite trend.

4. Results and discussion
At particle size $d=0.3$ mm and $d=0.5$ mm, the particle surface viscous resistance is the main resistance to the diffusion of solid-phase particles in the kettle, while it is shown that the viscous force resistance increases with the increase of liquid phase viscosity, inhibiting the diffusion of particles in the kettle, resulting in an increase of $N_{js}$ with the increase of liquid phase viscosity. At particle size $d=0.8$ mm and $d=1$ mm, the particles’ gravity is the main resistance to the diffusion of solid-phase particles in the kettle. The intensity of turbulent pulsation in the kettle strengthens as the viscosity of the liquid phase increases, which facilitates the diffusion of particles in the kettle, and $N_{js}$ decreases as the viscosity of the liquid phase increases. An increase in the volume fraction of the solid phase leads to an overall increase in $N_{js}$.

References
[1] Ochieng, A., Onyango, M.S. (2010) CFD simulation of solids suspension in stirred tanks: review. Hem. Ind., 64(5): 365-374.
[2] Shamlou, P.A. (2016) Processing of Solid-Liquid Suspensions. Butterworth-Heinemann Ltd., Boston UK
[3] Micale, G., Grisafi, F., Brucato, A. (2002) Assessment of Particle Suspension Conditions in Stirred Vessels by Means of Pressure Gauge Technique. Chemical Engineering Research & Design, 80(8): 893-902.
[4] Spidla, M., Sinevic, V., Jahoda, M., et al. (2005) Experimental Assessment and CFD Simulations of Local Solid Concentration Profiles in a Pilot-Scale Stirred Tank. Chemical. Papers. 59(6): 386-393.
[5] Zwietering, T.N. (1958) Suspending of solid particles in liquid by agitators. Chemical Engineering
Science, 8(3-4):244-253.
[6] Tamburini, A., Brucato, A., Buseglio, A., et al. (2014) Solid–Liquid Suspensions in Top-Covered Unbaffled Vessels: Influence of Particle Size, Liquid Viscosity, Impeller Size, and Clearance. Industrial & Engineering Chemistry Research, 53(23):9587–9599.