Numerical simulation of solid-liquid suspension characteristics induced by three-bent-bladed turbine in stirred tank

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Abstract: The software of CFD FLUENT was used to simulate the strengthening characteristics of three-bent-bladed turbine in solid-liquid suspension system. Diameter of stirred tank is $T = 100mm$. Four baffles are evenly distributed in the tank and two-phase material selection of glass ball-water system. Particle diameter is $25\mu m$ and solid volume fraction is 15%. The standard dual equation model is adopted in the liquid turbulence model. The Euler multiphase flow model is applied to simulate the suspension process. The strengthening effect of the impeller's upturned angle is discussed on solid suspension, and the radial velocity and solid volume concentration distribution of solid particles are analyzed, respectively. The results showed that, compared with 30 degrees of upturned angle of three-bent-bladed turbine (30° UA-3BT), the axial velocity of solid particles did not increase significantly with 20 degrees of upturned angle of three-bent-bladed turbine (20° UA-3BT) in the stirred tank. But distribution of solid volume concentration was more uniform, which reduced the accumulation of solid particles at the bottom of tank and the clean area of the top of stirred tank. 20° UA-3BT is beneficial to the full mixing of solid and liquid. Therefore, the turbine has a good application prospect.

1. Introduction
The mixing system of many industrial processes involves the suspension of solid particles in the liquid phase [1-3], and the effect of suspension will directly affect the final quality of the product. In order to obtain the desired mixing effect, it is necessary to know the flow field structure inside the mixing device, which is a key component that directly influences the circulation and mixing ability of the stirring medium. In recent years, Computational fluid dynamics (CFD) has been the hotspot of research on agitated reactor. Many numerical simulations have been carried out on the characteristics of flow field in solid-liquid suspension. Among them, Prakash et al. [4] simulated the suspension of solid particles in the liquid phase. Ochieng et al. [5-6] analyzed the influence of the solid concentration distribution and the critical suspension speed. Zhong Li et al. [7] simulated the solids volume flow rate of 5% of solid-liquid flow and off-bottom suspension speed. And Zhang et al. [8] conducted a simulation study on the flow characteristics of a high solids flow field. In addition, there was also a great deal of research working on particle height, residence time, mass transfer characteristics and velocity distribution [9-14], but the type of impeller was generally the rushton impeller or axial flow impeller. The form of impeller has not seen the relevant reports.

Currently, three-bent-bladed turbine was widely used in the FCC catalyst into the gel and suspension polymerization process, the stirring performance of the product quality and equipment had a direct
impact on energy saving. Therefore, the numerical simulation was used to study the solid-liquid suspension characteristics of the clover swept mixer in this paper. The distribution of the velocity field and the concentration field was analyzed. It was discussed that the change of upturned angle has effect on the concentration distribution and power consumption. It provides some theoretical basis for the design optimization of turbine and the selection of turbine.

2. STIRRED TANK STRUCTURE AND MESHING

Stirred tank uses flat-bottomed cylindrical that is diameter $T = 300 \text{mm}$ and uniform four baffles, shown in Fig. 1. It had loading height $H = T$, baffle width $w = T/10$ and wall thickness $t = T/30$. Impeller of three-bent-bladed turbine was diameter $D = 0.5T$, blade width $0.25D$, and distance from the bottom is $c = T/3$. After the bend angle $\theta$ was 50°, The flow field characteristics of upward angle $\alpha$ was 20° and 30° that was simulated respectively.

The system was an aluminum-water solid-liquid two-phase system with particle diameter $75 \mu \text{m}$, density $2600 \text{ kg/m}^3$, solid volume fraction 10% and agitator speed 360 rpm which was higher than the critical speed calculated by Zwietering's formula [19]. Particles could be suspended completely.

The calculation used an unstructured tetrahedron grid with a total number of grids of about 765,700, as shown in Fig. 2. It made use of $2 \times 3$ of grid distribution on the blade.

3. FLUID MECHANICS MODEL

At present, there were Eulerian-Lagrangian and Eulerian-Eulerian methods for the study of multiphase flow. According to the characterization of the system studied, Euler-Euler model was adopted for solid-liquid two-phase flow simulation in this paper. The model considered the multiphase flow as a continuous medium that permeated each other. The momentum equations were solved separately during the simulation for each phase. The interaction was modeled by the momentum exchange term between the phases and the drag force acting on the dispersed phase continuously [20]. The calculation assumed no mass transfer that made use of the Wen-Yu model [21-22] for the momentum exchange coefficient $K_{sl}$ between solid and liquid phases.

Continuity equation:

$$\frac{\partial}{\partial t}(\alpha \rho_i) + \nabla \cdot (\alpha \rho_i u_i) = 0$$

Liquid phase momentum equation:

$$\frac{\partial}{\partial t}(\alpha \rho_i u_i) + \nabla \cdot (\alpha \rho_i u_i u_i) = -\alpha_i \nabla p + \nabla \cdot \tau_i + \alpha_i \rho_i g + K_{sl}(u_i - u_i)$$

(2)
Suspension phase momentum equation:
\[
\frac{\partial}{\partial t}(\alpha \rho, u_i) + \nabla \cdot (\alpha \rho, u_i u_j) = -\alpha \nabla p - \nabla p_s + \nabla \cdot \tau_s + \alpha \rho \gamma + K_\alpha (u_i - u_s)
\]

(3)

Solid-liquid two-phase momentum exchange coefficient:
\[
K_\alpha = \frac{3}{4} C_\alpha \frac{\alpha_i \rho_i |u_i - u_s|}{\alpha_s} \alpha_i^{-2.65}
\]

(4)

Drag coefficient:
\[
C_D = \frac{24}{\alpha_i \text{Re}_i} \left[ 1 + 0.15 (\alpha_i \text{Re}_i)^{0.687} \right]
\]

(5)

The corresponding Reynolds number:
\[
\text{Re}_i = \frac{\rho_i d_{i} |u_s - u_s|}{\mu_i}
\]

(6)

4. CALCULATION METHOD

The two-phase system was calculated using the Multiple Reference Frame (MRF) method in FLUENT of CFD software. In this method, the computational domain was divided into two parts that one part contains the inner sub-region of the moving impeller and the other part contains the static sub-region of the tank and the baffle. The two part meshes were independent from each other, rotating together. The external grid was stationary, and the two grids were interpolated through the sliding interface [6, 7]. The calculation of the flow near the wall used the standard wall function method. And the liquid turbulence model used the standard \( k-\varepsilon \) two-equation model that acted in concert with the Mixture model of the multi-phase \( k-\varepsilon \) turbulence model. The Phase Coupled SIMPLE algorithm was used for pressure-velocity coupling. The differential format used the first-order windward format, and the convergence residual was \( 1 \times 10^{-4} \). The calculation domain selected the entire tank.

5. RESULTS AND ANALYSIS

5.1. Liquid flow field distribution

Fig.3 Velocity vector plots within axial lengthwise section of stirred tank

Fig. 3 is a vectorial flow velocity diagram formed by 20°UA-3BT. It could be seen that impeller of 3BT belongs to the radial type impeller, and the flow field showed a typical double vortex ring symmetrical structure from Fig. 3. The flow field in the vicinity of the impeller formed a high velocity zone. The velocity of the fluid in the impeller zone was reduced in a gradient direction, and the formation was wide
where the circulation area axial coverage was. In the tank it formed a good body flow that made full mixing driven by the external sub-flow field.

5.2. *Solid phase concentration distribution*

![Contour plots of solid concentration of 3BT](image.png)

Fig. 4 shows the solid content distribution in the YZ plane of the stirred tank respectively that is at the same speed for 20° UA-3BT and 30° UA-3BT. It could be seen that the concentration of solid particles is relatively large in the bottom of the stirred tank, and the concentration of solid particles was small in the top of the stirred tank. The solid-phase concentration distribution was not uniform in the stirred tank of 30° UA-3BT. A large concentration of sediment layer existed at the bottom of the stirred tank and a liquid cleaning layer appeared at the top of the stirred tank. In contrast, the stirred tank with 20° UA-3BT had a more uniform solid-phase concentration distribution, a lower bottom sediment concentration, and no top-cleaning zone existed. This was due to 20° UA-3BT greater suction and lifting force that was conducive to fluid mixing. In addition, as can be seen from Fig. 4, region with a lower solid-phase concentration appears near the stirring shaft due to the centrifugal force generated during rotation of the impeller.

5.3. *Axial velocity distribution of solid particles*

As can be seen from Fig. 5, the axial velocity distribution is at z/H=0.1, z/H=0.5 and z/H=0.75, respectively. The axial velocity of 20° UA-3BT is in the range of -0.03-0.13 m/s, as shown in Fig. 5(a) in the position of z/H=0.1. The absolute maximum axial velocity was 0.13 m/s. And axial velocity of 30° UA-3BT was -0.05-0.15 m/s range, the maximum axial velocity of the absolute value was 0.15 m/s increasing of 15.38%. The position was at z/H=0.5 where the axial speed of 20° UA-3BT was within the range of -0.65-0.21 m/s. The axial speed of 30° UA-3BT was between -0.7-0.2 m/s and the absolute maximum axial velocity increased by 7.69%. The position was z/H=0.75 where the axial speed of 20° UA-3BT is within the range of -0.23-0.15 m/s. But the axial speed of 30° UA-3BT was between -0.2-0.1 m/s, the absolute maximum axial velocity was reduced by 13.04%. At z/H=0.1 and z/H=0.5, the maximum absolute value of 30° UA-3BT was greater than that of 20° UA-3BT. However, the axial velocity for the solid particles of 20° UA-3BT was more uniform than that of 30° UA-3BT above the XY surface, which was beneficial to the thorough mixing of the solid-liquid phase and increased the solid particle suspension in the stirred tank.
5.4. Distribution of solid phase volume concentration

It can be seen from Fig. 6 that the solid phase volume concentration scoops at the $z/H=0.1$, $z/H=0.5$ and $z/H=0.75$ where the ranges are 0.975 - 1.050, 0.960 - 1.010 and 0.980 - 1.020 with differences of 0.075, 0.05 and 0.04. Solid-phase volume concentration of 30\degree UA-3BT was that range was 0.975 - 1.325, 0.930 - 1.050 and 0.900 - 1.010. And the difference was 0.35, 0.12 and 0.11. They are 4.667, 2.400 and 2.750 times higher than that of 20\degree UA-3BT respectively. Obviously, the solid phase volumetric concentration of 20\degree UA-3BT was more uniform and the mixing effect was better than that of 30\degree UA-3BT.

Fig. 7 shows the axial solid-phase volume concentration distribution for two impeller at $x = 100$. It was evident that the distribution of solid phase volume concentration was in the range of 1.00 - 1.25 along the axial direction at 20\degree UA-3BT, while 30\degree UA-3BT was 0.70 - 3.10 from Fig. 7. Compared to 30\degree UA-3BT, 20\degree UA-3BT had uniform volume concentration in the axial solid phase and solid phase suspension.
6. Summary

(1) Its macroscopic flow field of 20°UA-3BT showed that was a typical double-vortex ring symmetry structure because of its symmetrical impeller structure by analyzing the macro-flow field. The flow field near the blade formed a high velocity zone, forming a good body flow in the stirred tank and driving the mixing of the external subfield flow field.

(2) There was a large bottom sediment layer and a top cleaning layer of 30°UA-3BT and the solid concentration distribution was not uniform in the stirred tank. While the bottom sediment layer was small and there was no top clean area in the stirred tank of 20°UA-3BT.

(3) The maximum absolute value of the axial velocity of 30°UA-3BT was greater than that of 20°UA-3BT in the flow field formed by the two impellers, increased by 15.38% and 7.69% at z/H=0.1 and z/H=0.5 at the same rotational speed of 360 rpm, respectively. While the maximum absolute value of axial velocity was less than 20°UA-3BT, a reduction of 13.04% at z/H=0.75. The uniform axial velocity of 20°UA-3BT facilitated the thorough mixing of solid and liquid phases in the stirred tank and improved the suspension of solid particles. Compared with 30°UA-3BT, 20°UA-3BT had more uniform distribution and uniform solid phase suspension regardless of the solid-phase concentration distribution along the radial direction or the axial direction. It agitated what solid-liquid suspension was better.

NOMENCLATURE

\( b \) blade width, mm
\( C \) off-bottom clearance, mm
\( C_d \) Drag coefficient
\( D \) impeller diameter, mm
\( H \) fluid height, mm
\( K_{sl} \) Solid - liquid two-phase momentum exchange coefficient
\( N \) impeller speed, rpm
\( p \) Phase pressure
\( T \) tank diameter, mm
\( t \) time, s
\( u_i \) i-phase average speed, m/s
\( w \) flat baffles width, mm
\( \alpha_i \) Phase i phase content
\( i \) i phase, and I for the liquid phase, s for the solid phase
\( \theta \) backswept angle, °
\( \mu \) viscosity, Pa·s
\( \rho \) density, kg·m\(^{-3}\)
\( \rho_i \) i-phase density, kg·m\(^{-3}\)
\( \tau \) time delay
\( Re_s \) Reynolds number

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