PIV measurement and study on turbulence generator flow field of medium consistency pump

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Abstract. In order to study the flow characteristic in turbulence generator of medium consistency pump, a particle image velocimetry (PIV) test rig was established. 2D-plane flow field was acquired fast and effective by adjusting the angle and position of mirror. For investigating the effect of speed on flow field, velocity and turbulent kinetic energy were measured at speed 80r/min, 130r/min and 200r/min. Dimensionless method was adopted to analyze flow field by quantitative approach. The results showed that on vertical flow plane axial velocities decrease with radius increasing in the region of turbulence generator blade, and axial velocity direction was changed and increased with radius increasing outside the region of turbulence generator blade. Internal flow direction of turbulence generator was at opposite direction with outside flow. Fluid flows from inlet to outlet of turbulence generator blade and then go back to inlet, which forms a circle. On horizontal flow plane, circumferential velocity increase with radius increasing firstly, and then the maximum appears at outer diameter of turbulence generator, and last it decreases gradually. Turbulent kinetic energy increases with rotational speed increasing at inner of turbulence generator flow field, and high turbulent kinetic energy mainly concentrates near the blade inlet and external diameter of turbulence generator. Therefore, in order to achieve better turbulence effect, high turbulent kinetic energy can be obtained by changing the shape of blade inlet structure, increasing the blade outside diameter and improving rotational speed.

1. Introduction

Medium consistency technology is becoming increasingly popular with paper-making industry[1]. While the pulp concentration exceeds 7%, pulp suspension stops flowing. As a powerful and necessary tool, the turbulence generator was employed to obtain fluidization. Study on inner flow field is very useful for design and optimization of turbulence generator.

With the development of laser, computer and image processing technology, the particle image velocimetry (PIV) has been used for flow visualization in rotary machinery[2][3][4]. PIV is non-touch and instantaneous flow field testing technology. There exists hardly any literature devoted to inner flow field towards turbulence generator. Turbulence generator is similar to stirring vessel with twist blade. Compared with general stirring vessel, turbulence generator can agitate and obtain fluidization. PIV measurement technique and numerical method have been carried on the mechanical agitation tank flow field experimental study by An Zicheng[5], and the detailed information of flow field, vorticity
and turbulent kinetic energy (TKE) were discussed, and the effects of rotational speed and blade distance were investigated. Yang Xiaoling and Yan Jing[6] used particle image velocimetry measurement technique to obtain instantaneous vorticity distribution, and flow velocity under the influence of rotational speed was presented. PIV has been used for flow measurement in stirred tank with double three-blade hydrofoil impellers, as for experiment study (Guo Xin[7]; Liu Xinhong[8]; Nie Yiqiang[9]; Fan Jianhua[10]), and the effects of the spacing between the two impellers, the submergence of the upper impeller below the liquid surface, and the clearance of lower impeller above the base of vessel on the flow pattern were investigated. The flow fields of two Rushton turbines with different lengths of blades have been measured by using PIV under the same power input by Chen Xianming[11], and the effect of the blade length of the Rushton turbine on the velocity, turbulent kinetic energy and trailing vortices was investigated, and the effect of clearance between the impeller and tank bottom on the trailing vortices was also studied. Bugay[12] and Huchet[13] used PIV measurement technique for axially agitation tank inner flow field, and the dissipation rate of turbulent kinetic energy was obtained. Sharp[14] analyzed the flow information in blade region using PIV technique, and the small-scale flow structure was discussed. Three-dimensional PIV (3-D PIV) has been used to study the 3-D flow field in stirring tank by Chung[15], and the distribution of turbulent kinetic energy was investigated.

This paper concerned with the characterization of flow information in turbulence generator. A PIV experimental setup was established. The flow details, as for velocity and turbulent kinetic energy, on vertical and horizontal plane were measured. The investigation can provide design and optimization reference for turbulence generator.

2. Materials and methods

In order to measure and visualize the flow in turbulence generator and capture the velocity and turbulent kinetic energy distribution, the PIV experiment setup was established, as shown in figure 1. Turbulence generator and glass vessel were produced by using transparent poly (methylmethacrylate) (PMMA). For visual shooting, all the surfaces were polished.

For obtaining the details of vertical flow information, outer surface has 4 planes, and all non-transparent parts were painted in matt black to minimize laser reflection. The vertical flow field was captured directly and the horizontal flow information was obtained by mirror which setup below lifting platform, and flow field was acquired fast and effective by adjusting the angle and position of mirror.

The distance between turbulence generator and bottom of glass vessel was controlled by lifting platform. To realize different rotational speed, an inverter was employed to control, and the precise was 0.2%. The experimental PIV tracer particle composed of Na₂SiO₃, Na₂CO₃ and SiO₂.

![Figure 1. Schematic diagram of PIV test rig](image-url)
As shown in figure 2, the PIV system comprised of computer, double pulsed laser, light path system, particle, a frame-straddling CCD camera (TSI Inc., USA), synchronizer, Insight 3G software and Tecplot Focus 2008 post software.

![PIV system](image)

**Figure 2.** PIV system

### 3. Method and experimental apparatus

Turbulence generator of diameter $D=150\text{mm}$ located inside the glass vessel filled with distilled water. The hub of turbulence generator $d_h$ is $50\text{mm}$. The turbulence generator used was a 4 twist blades. The detailed parameters were shown in figure 3. Cylindrical coordinate system origin was setup in center of glass vessel bottom. Axial direction is in the $z$ direction, and radial direction is in the $r$ direction.

![Details of measurement](image)

**Figure 3.** Details of measurement

The interesting area of vertical flow field was setup as $B\times L=70\text{mm}\times 100\text{mm}$ for obtaining flow information in inlet blade of turbulence generator. Five divided width with $b=14\text{mm}$ separation were used, and 4 vertical lines (line14, line28, line42 and line56) were shown in figure 3. The distance $H$ between bottom of area and glass vessel was 0.3$D$. For obtaining tangential velocity and turbulent kinetic energy, three different planes which were setup in upstream, blade inlet and downstream were used. The distances, $h_1$, $h_2$ and $h_3$, between horizontal plane and bottom of glass tank were 0.27$D$, 0.6$D$ and 1.07$D$. The inlet diameter $d_1$ of turbulence generator was 0.53$D$. 

3.1. Vertical measurement

The interesting area $B \times L$ of vertical plane was shown in figure 3. The $90^\circ$ between laser and CCD camera was setup, and the laser planes was perpendicular to side of glass vessel, as shown in figure 4(a). The details flow information in turbulence generator were acquired and analyzed at 80r/min, 130r/min and 200r/min, respectively. For a minimize error, the flow field at same phase was shoot 100 images at a constant speed, and the velocity and turbulent kinetic energy in vertical line were obtained from mean value of images information.

3.2. Horizontal measurement

Calibration of the lens direction to perpendicular to turbulence generator shaft was carried out before horizontal flow field experiment. The movement of the seeding particles with horizontal plane was monitored from underneath the glass vessel by using a $45^\circ$ face reflecting mirror, as shown in figure 4(b). There were 3 horizontal planes, as $h_1$, $h_2$ and $h_3$, were employed to obtain the horizontal flow field. The mean value of images was also used.

![Figure 4. Equipment setup for (a) vertical 2-D PIV, and (b) horizontal 2-D PIV](image)

4. Results and discussion

Based on Tecplot Focus 2008, the post software, axial and tangential flow velocities were obtained from vertical and horizontal plane, respectively. As shown in figure 5, the vertical and horizontal flow fields were carried out.

![Figure 5. Velocity distribution at speed $n=80$ r/min](image)
For ease of comparison between different configurations, the impeller tip speed, \( v_t \), was employed to normalize velocity.

\[
C_w = \frac{w}{v_t}, \quad C_{\tan} = \frac{v_{\tan}}{v_t} \tag{1}
\]

Where the \( C_w \) and \( C_{\tan} \) were normalized axial velocity and tangential velocity. \( w \) and \( v_{\tan} \) were instantaneous velocity, \( v_{\tan}=(u^2+v^2)^{0.5} \), and \( v_t \) was the turbulence generator tip speed.

\[
v_t = \frac{\pi D n}{60} \tag{2}
\]

where \( n \) was turbulence generator speed, r/min.

In order to obtain the maximum shear velocity and fluidization, turbulent kinetic energy, \( k \), which was an important turbulent characteristic, was always employed to analyze the turbulence intensity. PIV system can take enough accuracy in flow field, as for example in the previous studies\[15\][17]. Turbulent kinetic energy, \( k \), takes the form of the half trace of the Reynolds stress tensor, i. e. ,

\[
k = \frac{1}{2}(u'^2+v'^2+w'^2) \tag{3}
\]

where \( u', v', w' \) were the square of the root means square (RMS) values of the instantaneous fluctuating velocity components which can be determined from PIV data.

The turbulent kinetic energy was also normalized by the turbulence generator tip speed.

\[
C_k = \frac{k}{v_t^2} \tag{4}
\]

4.1. Flow field in vertical plane

4.1.1. Effect of rotational speed on axial velocity. Effect of rotational speed on axial velocity is shown in figure 6. The normalized axial velocity, \( C_w \), distribution in line 14 and line 42 are shown in figure 6(a) and figure 6(b). The \( C_w \) decreases with radial position, \( 2r/D \), increasing. In the region around the turbulence generator inlet, \( 0.53<2r/D <0.93 \), \( C_w \) is substantially close to zero. With the rotational speed increasing, \( C_w \) is not notably decreases. As shown in figure 6(b), \( C_w \) is positive when \( 2r/D \) is less than 0.9, and \( C_w \) is negative when \( 2r/D \) is more than 0.9, so it should be pointed out that the axial flow direction is changed. The flow direction in turbulence generator is +z direction, however the external flow direction is -z direction. The liquid flows from the inlet of the turbulence generator to the upper movement and then returns to the inlet of turbulence generator blade.

![Figure 6. Effect of rotational speed on axial velocity](image-url)
4.1.2. Velocity distribution. Axial velocity distribution in different lines is shown in figure 7. The normalized axial velocity, $C_w$, distribution at speed 80r/min and 200r/min is shown in figure 7(a) and figure 7(b). In line 14, as shown in figure 7, with radial position, $2r/D$, increasing $C_w$ decreases firstly, then $C_w$ is close to zero, and axial velocity decreases at last. $C_w$ decreases with $2r/D$ increasing in line 28 and line 42. Since the flow was blocked by the turbulence generator hub, the flow direction changes and normalized axial velocity increases with $2r/D$ increasing firstly, and then decreases. There is a maximum velocity $C_w =0.47$ at $2r/D=0.61$.

![Velocity distribution](image)

(a) $n=80$ r/min (b) $n=200$ r/min

Figure 7. Axial velocity on transversal

4.1.3. Turbulent kinetic energy in vertical plane. PIV yields $u'^2$ and $w'^2$ in vertical plane. Assuming isotropy, the missing fluctuating velocity component in the $x$ direction, $u'^2$, can be estimated by a 2-D approximation,

$$\bar{u'^2} = \frac{1}{2}(\bar{v'^2} + \bar{w'^2}),$$

thus

$$k = \frac{3}{4}(\bar{v'^2} + \bar{w'^2})$$

So the normalized turbulent kinetic energy, $C_k$, in vertical plane was defined.

As shown in figure 8, effects of different speed on normalized turbulent kinetic energy in line 14, line 28, line 42 and line 56 were discussed. Figure 8(a) shows that $C_k$ in line 14 is notably greater than that in other lines, and with radial position, $2r/D$, increasing, $C_k$ increases firstly and then decreases, and it reveals that high $C_k$ is distributed in the inlet of turbulence generator blade since the maximum value, $C_k$, is in $0.56 < 2r/D < 1.04$, and $C_k$ increases with speed increasing. Figure 8(b), 8(c) and 8(d) show that the turbulent kinetic energy is uniformly distributed. In a word, the high turbulent kinetic energy is in the inlet of turbulence generator, however the low $C_k$ is in inner of turbulence generator, so high turbulent kinetic energy can be obtained by changing the shape of blade inlet structure.

![Turbulent kinetic energy](image)

(a) line 14 (b) line 28
4.2. Flow field on horizontal plane

4.2.1. Effect of rotational speed on tangential velocity. Effect of rotational speed on tangential velocity is shown in figure 9. The normalized tangential velocity, $C_{\text{tan}}$, distribution on plane $h_1$, $h_2$, $h_3$ are shown in figure 9(a), figure 9(b) and figure 9(c), and the dash-dot lines, $2r/D=0.33$ and $0.53$, represent turbulence generator hub and the inner diameter of extend blade shown in figure 9(b) and figure 9(c). As shown in figure 9, $C_{\text{tan}}$ decreases slowly with rotational speed increasing. With $2r/D$ increasing normalized tangential velocity increases gradually, and the maximum is at $2r/D=1.0$, and then $C_{\text{tan}}$ decreases sharply because fluid is lost the energy from turbulence generator blade. Figure 9(b) shows that the normalized tangential velocity, $C_{\text{tan}}$, rises slowly along with radial position, as shown in local enlarging figure, while the $2r/D$ is less than 0.53, because fluid velocity is induced by the extend blade of turbulence generator.

![Figure 9. Effect of rotational speed on tangential velocity](image)

![Figure 10. Tangential velocity distribution on cross section](image)
4.2.2. **Tangential velocity distribution.** Tangential velocity distribution in different plane is shown in figure 10. The normalized tangential velocity, $C_{tan}$, distribution at speed 80r/min, 130r/min and 200r/min are shown in figure 10(a), figure 10(b) and figure 10(c). Figure 10 shows that the $C_{tan}$ in plane $h_3$ is the maximum and 17.96%, 21.07% and 35.17% higher than $h_1$ at different speed, respectively. When the $2r/D$ is less than 0.24, $C_{tan}$ in plane $h_2$ is notably greater than that in pane $h_1$. Generally, the normalized tangential velocity in plane $h_1$, $h_2$ and $h_3$ are consistently distributed.

4.2.3. **Turbulent kinetic energy distribution.** 2-D PIV yields radial and tangential velocity fluctuation in horizontal plane. Assuming isotropy, as the same with chapter 3.1.3, thus

$$k = \frac{3}{4}(\overline{u'^2} + \overline{v'^2}) \tag{6}$$

Figure 11 shows the normalized turbulent kinetic energy on plane $h_1$, $h_2$ and $h_3$ was distributed at different speed. With radial position increasing, $2r/D >1.04$, $C_k$ on plane $h_3$ and $h_2$ is gradually higher than that on plane $h_1$, which reveals that the high turbulent kinetic energy is mainly distributed around outside of turbulence generator. Increasing the blade outside diameter can obtain high turbulent kinetic energy.

![Figure 11. Turbulent kinetic energy $C_k$ on cross section](image)

$C_k$ at different speed were compared, as shown in figure 12. With speed increasing, the fluctuation of turbulent kinetic energy is not obvious. $C_k$ on plane $h_1$ changes slightly with $2r/D$ increasing. On the plane $h_2$, two maximum exist when $2r/D$ is equal to 0.64 and 1.04. The intense velocity fluctuation is at inside and outside of extended blade of turbulence generator.

With $2r/D$ increasing, $C_k$ increases at first then decreases on the plane $h_3$. When $2r/D$ is equal to 1.04, $C_k$ approaches to 0.047, 0.0538 and 0.052 at 80r/min, 130r/min and 200r/min.

![Figure 12. Turbulent kinetic energy $C_k$ at different rotational speed](image)
5. Conclusions
For studying the flow characteristic in turbulence generator, this paper describes a particle image PIV test rig was established and velocity and turbulent kinetic energy were measured at different speed. Dimensionless method was adopted to analyze flow field by quantitative approach. Axial velocity decreases with $2r/D$ increasing. Internal flow direction of turbulence generator is at opposite direction with outside flow. Due to turbulence generator blade, tangential velocities on axial section increase with $2r/D$ increasing. With $2r/D$ increasing normalized tangential velocity increases gradually, and the maximum is at $2r/D=1.0$. Turbulent kinetic energy increases with rotational speed increasing, and high turbulent kinetic energy mainly concentrates near the blade inlet and external diameter of turbulence generator. High turbulent kinetic energy can be obtained by changing the shape of blade inlet structure, improving the blade outside diameter and improving rotational speed. Compared with pulp suspension, using distilled water in this research is not enough accurate, so transparent non-Newtonian fluid, such as sodium carboxymethyl cellulose (CMC), should be employed to do in further study.

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