1. Introduction

Fluid mixing is one of essential unit operation that appears in a variety of industrial processes to produce a homogeneous and specified concentration, temperature, and other properties in fluids. In this process, depending on usage environment and conditions, various mixers have been employed, e.g., propeller, turbine, paddle, anchor, helical screw, helical ribbon, etc. The range of application and suitable operating condition of commercially available mixer have been reviewed in several works in literature, e.g., (Holland and Chapman, 1966; Uhl and Gray, 1966; Nagata, 1975; Cheremisinoff, 2000; McCabe et al., 2005), as shown in Table 1. For a low viscosity fluid, propeller- and turbine-types mixers have been used with high rotational speed. On the other hand, for a high viscosity fluid, the helical screw- and ribbon-types mixer have been used with low rotational speed. Also, as a conventional bladeless mixer, jet mixers, which is driven with external pump, are used with advantages of low shear stress, high safety, wider mixing and relatively simple structure (Grenville and Nienow, 2004; Revill, 2007).

In this process, the fluid mixing mechanism for high viscous fluid in terms of the chaotic behavior in the dynamics system has been investigated by Spencer and Wiley (1951), Aref (1984) and Kusch and Ottino (1992). In order to clarify the mixing process of low viscosity fluid the Reynolds number effects have been studied with respect to powered consumption (Rushton et al., 1950; Rushton, 1952; Bates et al., 1963; Schwartzberg and Treybal, 1968), dimensionless blend time (Dickey and Fenic, 1976). Furthermore, the turbulent parameter such as intensity and energy spectrum of turbulence (Kim and Manning, 1964; Cutter, 1966; Mujumdar et al., 1970; Anandha Rao and Brodkey, 1972; Komasawa

Enhancement of rotating jet by spirally structured vortex tube in centrifugal bladeless mixer flow

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Abstract
The flow characteristics in a centrifugal bladeless mixer were investigated by using particle image velocimetry (PIV) and large eddy simulation (LES). The numerical result is compared with experimental one in terms of the phase-averaged velocities in radial and tangential directions. The result was analyzed by comparing with that of a conventional flat-blade mixer. A spirally structured vortex tube pair was observed around the centrifugal bladeless rotor. In a vertical cross-section of the spirally structured vortex tube pair, a zigzag street of counter-rotating vortices like a reverse von Kármán vortex street was formed. It was found that the rotating jet flow was enhanced by the reverse von Kármán vortex street of the spirally structured vortex tube pair. Furthermore, the sustained rotating jet flow constructed a couple of large toroidal structured vortex tube near the tank wall. The large toroidal structured vortex caused a wider circulation in the stirred tank, which was advantage to stir the fluids over the whole field.

Keywords: Spirally structured vortex tube, Reverse von Kármán vortex street, Rotating jet, Mixing, Particle image velocimetry, Large eddy simulation
et al., 1974; Van Der Molen and Van Maanen, 1978), transportation process of turbulent kinetic energy (Ducci and Yianneskis, 2006), and dissipation of turbulence kinetic energy (Zhou and Kresta, 1996; Baldi and Yianneskis, 2003) have been widely studied. According to these works, it was confirmed that the transportation and distribution of the turbulent kinetic energy were crucial parts of the mixing process for low viscosity fluid. According to the work of Yianneskis et al. (1987), Lee and Yianneskis (1998), Schäfer et al. (2000) and Sharp and Adrian (2001), it was indicated that there was a relationship between the turbulent kinetic energy and vortices, because the high turbulent kinetic energy was always located at the trailing vortex region. Furthermore, Van’t Riet and Smith (1975) and Van’t Riet et al. (1976) showed that the vortices influenced the flows near the mixer and played an important role in mixing process in stirred tank.

Table 1 Suitable operating condition for different types of mixer from (Holland and Chapman, 1966; Edwards and Baker, 1992; Doran, 2013).

| Viscosity [Pa s] | Low rotational speed | High rotational speed |
|-----------------|----------------------|----------------------|
| 10^{-3}~10      | Anchor               | Propellers, Turbines |
| 10^{-1}~10      | Helical screw, Helical ribbon | Paddles |
| > 10            |                      |                      |

Fig. 1 Schematics of centrifugal bladeless rotor. (a) Bird view of centrifugal bladeless rotor; (b) Fundamental flows generated by centrifugal bladeless rotor.

The present paper focuses on an invented centrifugal bladeless mixer (C-mix®, Aquatechs CO, LTD.), which is a bladeless mixer to generate a rotating jet flow without any additional input as an external pump. The present centrifugal bladeless rotor has eight L-shaped flow channels in a rotor as shown in Fig. 1 (a) and (b). A discharge flow (1) is achieved due to centrifugal force and simultaneously a suction flow (2) and secondary flow (3) appears as shown in Fig. 1 (b). In the previous research (Azam et al., 2019), we showed that for low viscosity fluid the centrifugal bladeless mixer effectively stirs the fluid in the wider tank with low rotational speed. However, the mechanism of generating a wider circulatory flow by the centrifugal bladeless rotor was not yet investigated clearly.

Now, the present paper aims to identify the flow characteristics and to clarify mechanism of generating a wider circulatory flow by the centrifugal bladeless rotor, by using a particle image velocimetry (PIV) in an experiment and a large eddy simulation (LES) in a numerical analysis. The result is analyzed by comparing with that of a conventional flat-blade mixer.

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| A      | Van-Driest wall-damping model coefficient |
| C_s    | Smagorinsky coefficient     |
| d      | Rotor diameter [m]          |
| D      | Tank diameter [m]           |
2. Experimental Method

Particle image velocimetry is a favorable experimental technique to investigate a complicated flow structure in a stirred tank, e.g., the previous papers (Sharp and Adrian, 2001; Escudie et al., 2004; Li et al., 2011, 2018) studied the velocity profile by using PIV measurement.

Fig. 2 Schematic diagram of experimental setup. (a) Side view; (b) Top view; (c) Mixer geometry.
As well as those experiments, the present study engaged 2D-PIV system in interrogation of the complex flow structure in the mixer. Figure 2 presents a schematic diagram of the experimental apparatus. Figures 2 (a) and (b) show the side and top views of the experimental setup, respectively. The experiment was carried out in an un baffled cylindrical tank of the diameter, $D = 0.6 \text{ m}$. The cylindrical tank was filled with tap water of the height, $H = D$. A transparent lid was set on the upper surface of water to restrain the surface fluctuation. The cylindrical tank was enclosed with a square tank and water was charged in the space between the tanks to attain a refractive matching as much. A centrifugal bladeless rotor (8 channels, channel height 0.0135m and width 0.009m) and a flat-blade rotor (3 blades, blade height 0.0135m) with the diameter, $d = D/10$, was tested in the present experiment as shown in Fig. 2(c). The rotor was installed at the height of $0.75H$, along the central axis of the cylindrical tank. The diameter of the driving shaft is $d/5$.

A dual head Nd: YAG laser system (Solo III, Spectra physics, 15 Hz) was used to illuminate the test section. The width of the light sheet is 1 mm with pulse energy 50 mJ, pulse duration 5 ns, and wavelength 532 nm. The laser light was delivered from the side horizontally as shown in Fig. 2 (b). The measurement section is rectangular as 0.09 m×0.07 m, indicated with the red rectangle in Fig. 2 (b).

A CMOS camera (IDT M5) 2288 × 1728 pixels in resolution, 8 bits in depth was used in the measurement. The horizontal flow images were acquired with a mirror as shown in Fig. 2 (a). The tracers is DIAION HP20 of 250 ± 25 µm of diameter and specific gravity 1.01, and dyed fluorescent red color, 620-750 nm with Acryl Gouache. For the observation, an orange sharp cut filter of transmittance threshold 580(±5) nm was used to eliminate the unnecessary noise.

In order to acquire the phase lock observation a laser sensor was used as a trigger to detect the shaft rotation as shown in Fig. 2 (a). The acquisition system was synchronized by using the trigger pulse through a signal conditioner and a timing hub with the camera. The time separation of the frame straddling is 300 µs for suitable observation. The 500 pairs of images were stored to obtain the phase-averaged data. A PIV software, ProVISION-XS, IDT was used to analyze the PIV data. The special resolution of image was 40.5 µm/pixel. FFT cross-correlation technique was adapted, in which the interrogation size was selected as 60 × 60 pixels.

The rotation speed of the rotor was fixed at 250 rpm through the present experiment. The Reynolds number is defined as

$$\text{Re} = \frac{\rho (\Omega d) D}{\mu},$$

where, $\rho$, $\mu$, and $\Omega$ represent water density, water viscosity, and the angular velocity, respectively. In the definition, as shown here, the circumferential velocity of rotor, $\Omega d/2$, and the tank diameter, $D$ are chosen as the representative velocity and length for this problem. Under the present condition, the Reynolds number Re is 4.7 x 10$^5$ for all results in this paper.

3. Numerical Method

The large eddy simulation (LES) was employed for this flow analysis as the most appropriate scheme which can provide the solution of the complex and unsteady flow field as reported in the previous relevant research on the stirred tank simulation (Eggels, 1996; Derksen and Van Den Akker, 1999; Yoon et al., 2003; Hartmann et al., 2004).

In the present simulation, a commercial software, Star-ccm+ Ver.11.04 was utilized. The governing equations are continuity and Navier-Stokes equations in incompressible fluid. The subgrid-scale was analyzed using the Smagorinsky model (Smagorinsky, 1963) and incorporated with the Smagorinsky coefficient, $C_s = 0.1$, von Kármán constant, $\kappa = 0.41$ and Van-Driest wall-damping model coefficient, $A = 25$. The scheme is based on the finite volume method (FVM) as well known, here, the volume mesh was constructed with polyhedral and prism cells. The central-difference scheme and the second-order implicit unsteady algorithm were used for convection term and time integration, respectively. The total number of cells was about 3.2 million. The preliminary calculations were carried out using the number of cells about 1.7 million and 3.2 million. The spirally structured vortex tube could be well simulated even in the results using the coarse mesh 1.70 million. The current paper focuses on the spirally structured vortex tube generated by the bladeless mixer. Therefore, the results using the number of cells 3.2 million is enough to discuss the dynamics and structure of the spirally structured vortex tube.

In the simulation, the rotor with driving shaft was introduced in the tank. Sliding mesh technique was used by introducing an interface between the rotating and stationary domains as shown in Fig. 3. A non-slip boundary condition
was applied at all of the wall boundaries. The ‘all $y^+$’ wall-function treatment was adopted on the near-wall mesh. This is suitable to calculate the velocity in the wide range of $y^+$.

The $y^+$ values on the rotor surface was lower than $8.0$. On considering the calculational time cost and time resolution, the time step $\frac{T}{240}$ was set. Here, $T$ is the rotation period of the rotor. All calculations were carried out until the phase-averaged values converge within a sufficient accuracy and the initial disturbances have been swept out. The convergence criteria was determined by

$$\frac{\|\bar{v}^{n+1} - \bar{v}^n\|}{\|\bar{v}^n\|} < \varepsilon.$$

Here, $\bar{v}^n$ denotes the phase-averaged velocity magnitude, and $\varepsilon$ means convergence value set as $1.0 \times 10^{-4}$. The superscript $n$ indicates the number of rotations, counting since initial disturbance swept out.

4. Results

4.1 Comparison of PIV and LES

First of all, in the experimental analysis, the phase-averaged radial and tangential velocities in the horizontal plane shown by the red rectangle in Fig. 2 will be compared between the PIV and LES.

(a) PIV

(b) LES

Fig. 4 Phase-averaged radial velocity component of flat-blade rotor.
Figure 4 presents the magnitude distribution of phase-averaged radial velocity for the flat-blade rotor, obtained from (a) PIV and (b) LES. The inspected position of the horizontal plane was chosen at the vertical middle section where the rotor was allocated. The coordinates are normalized with the radius of the rotor, $R$, and the velocities with the circumferential velocity of the rotor, $\Omega R$. In these figures, high and low velocity regions are observed near the blade tip. These regions are indicated with closed dashed areas as H, and L, respectively. In other regions, the radial velocity in the LES is lower than the PIV. This may be caused by grid quality and unavoidable experimental errors. We confirmed the difference of the phase averaged radial and tangential velocity distributions even in the 1mm vicinity of the vertical midpoint of the mixer. This suggests that the 1mm laser sheet in a large velocity gradient and a bit of the difference of the laser sheet location lead to significant experimental error in the 2D-PIV. Additionally, small shaft vibration was observed despite using two bearings.

![Fig. 4 Phase-averaged radial velocity component of flat-blade rotor](image)

Figure 5 presents the radial velocity component distributions for the bladeless mixer as well as Fig. 4. The distribution is quite different with the previous figure. In the case of flat-blade rotor, H and L are concentrated near the blade, however, in the case of bladeless rotor, we can see a wide H region and small L region. The high radial velocity region is observed at the trailing corner of the nozzle and spreads up to 1.8R. As shown in Fig. 5 (a) and (b), near the nozzle outlet, the radial velocity for the LES is slightly higher than that for the PIV.

![Fig. 5 Phase-averaged radial velocity component of bladeless rotor](image)

Figure 5
Phase-averaged radial velocity component of bladeless rotor.

![Fig. 6 Phase-averaged tangential velocity component of flat-blade rotor](image)

![Fig. 6 Phase-averaged tangential velocity component of flat-blade rotor](image)
Figures 6 and 7 present the comparison of phase-averaged tangential velocity distribution in the flat-blade and the bladeless rotors, respectively. In the case of the flat-blade rotor, the high tangential velocity region obtained from the PIV is observed near the rotor, as shown in Fig. 6 (a) and also in Fig. 6 (b). However, near the rotor, the tangential velocity for the LES is higher than that for the PIV. In the case of the bladeless rotor, the high tangential velocity region, $J$, is found behind each nozzle as shown in Figs. 7 (a) and (b). As shown in this figure, the jets induced by the rotor appears around the rotor. The jet structure contributes the important subordinate effects as mentioned later.

![Fig. 7 Phase-averaged tangential velocity component of bladeless rotor.](image)

Figure 8 shows the circumferentially-averaged radial velocity distributions in terms of the normalized radial position, $r/R$. The circumferentially-averaged radial velocity, $\bar{v}_r$ is measured by

$$\bar{v}_r(r) = \frac{\int_{-\Delta\theta/2}^{\Delta\theta/2} \bar{v}_r(r, \theta) r d\theta}{r \Delta\theta}.$$  \hspace{1cm} (3)

Here $\bar{v}_r$ is the phase-averaged radial velocity, $\Delta\theta = 2\pi/m$; $m$ is the number of nozzle (or blade) of the mixer. In the figure: open circle and square denote the PIV results for the flat-blade and the bladeless rotor, respectively. The dashed and solid lines represent the LES results for the flat-blade and bladeless rotor. Here, a simple flow prediction by a potential flow theory assuming a simple source at the origin is also indicated with asterisk. The simple source flow gives the radial velocity with

$$v_r(r) = \frac{\bar{V}_R}{r}.$$  \hspace{1cm} (4)

Where $\bar{V}_R$ is considered as the source radial velocity and measured from the LES data by taking the surface average of $\bar{v}_r$ over the nozzle exit surface.

![Fig. 8 Comparison of circumferentially-averaged radial velocity between the flat-blade and the bladeless rotors by PIV and LES.](image)
In this figure, for the blade-type mixer case, open circle is slightly increasing with $r/R$ up to 1.3, then decreasing rapidly up to 1.6. On the other hand, dotted line is almost constant up to 1.1 and then steeply decreases. This discrepancy between the PIV and LES may be caused by the three-dimensional flow influenced with a large velocity gradient in the axial direction. For the bladeless mixer case, comparing open square and solid line, both of them increase up to around 1.4 and then monotonically decrease with $r/R$. Namely, the acceleration regions are observed in $1.0 < r/R < 1.4$.

Here, the potential theory gives an appropriate reference in the consideration. Comparing the blade and bladeless type, the former is smaller than the potential flow prediction, but the latter larger. This fact suggests that the radial velocity produced not only by the source flow due to the centrifugal force effect by the rotor, but also implies the other contribution, which will be considered in the following section.

Fig. 9 Comparison of circumferentially-averaged tangential velocity between flat-blade and bladeless rotors obtained by PIV and LES.

Next, Fig. 9 shows the circumferentially-averaged tangential velocity distributions. All symbols, lines and experimental conditions are the same as Fig. 8. Both of the PIV and LES values decrease monotonically with $r/R$ increasing. Furthermore, the tangential velocity of the bladeless type is larger than that of the flat-blade.

As discussed in Figs. 4 to 9, the LES results seems to be reliable with respect to the flow field near the rotor. Therefore, the flow characteristics will be discussed with the reference based on the LES results hereafter.

### 4.2 Structure and Dynamics of Spirally Structured Vortex Tube

The vortices generated by the rotation of the rotor dominate the flow field in a stirred tank (Van’t Riet and Smith, 1973, 1975; Van’t Riet et al., 1976). In this section, the structures and dynamics of the vortices generated by the rotor will be discussed in detail.

![Fig. 10 Structures of vortices and core flow for (a) flat-blade and (b) bladeless rotors. The blue and red iso-surfaces are the vortex tube identified with $\lambda_2 = -100$ s$^{-2}$ and the white iso-surface shows the core flow structure visualized with $|\mathbf{v}|/\Omega R = 0.2$.](image-url)
Figures 10 (a) and (b) show the vortex and core flow structures for the flat-blade and the bladeless rotor, respectively. The vortex structures were identified using the $\lambda_2$ criteria, which was proposed by Jeong and Hussain (Jeong and Hussain, 1995). The vortex tubes are visualized with the iso-surfaces of $\lambda_2 = 100$ s$^{-2}$. The blue and red iso-surfaces indicate the vortex tubes accompanying the negative and positive tangential vorticities, respectively. Furthermore, the core flow structure which is induced by the rotor rotation is extracted with the iso-surface of $v_r/\Omega R = 0.2$ as white color. For the flat-blade case, the circularly structured vortex tube pair is observed in upper and lower sides as shown in Fig. 10 (a). On the other hand, as shown in Fig. 10 (b), spirally structured vortex tube pair is observed around the bladeless rotor. For both cases, the core and jet structures illustrated with the white iso-surface are found between the vortex tube pair. Comparing the two cases, the jet structure in the bladeless mixer is further extended downstream than the blade type.

![Diagram of vortex structure](image)

Figure 11 presents (a) a sketch of the vortex structure and (b) the distribution of the normalized tangential vorticity, $\omega_\theta/\Omega$, and (c) one of the normalized radial velocity, $v_r/\Omega R$, around the flat-blade rotor. Figures 11 (b) and (c) are presented in a vertical cross-section including the green line shown in Fig. 10 (a). As shown in Fig. 11 (a), the trailing vortices were continuously released from the blade, and flowed outward and formed a circular vortex tube by merging the trailing vortices which was generated from the adjacent blades. This phenomenon was also reported in the previous research (Van’t Riet and Smith, 1975; Yianneskis, 2007). As shown in Fig. 11 (b), the cores of the two circularly structured vortex tubes move outward and apart, and finally collapse. Bresler et. al. (Bresler et al., 1997), Lamberto et.al. (Lamberto et al., 1999) and Hashimoto et. al. (Hashimoto et al., 2009) visualized the circularly structured vortex tube at low Reynolds numbers for several blade-type and found that the circularly structured vortex tube was stable at low Reynolds numbers. On the other hand, the present research at the high Reynolds number, $Re = 4.7 \times 10^5$, shows that the circularly structured vortex tube is unstable and break down in a short time. Although this rapid dissipation of the circularly structured vortex generates intense turbulence around the flat-blade rotor and enhances the flow mixing near the rotor,
the high radial-velocity region quickly disappears as the two circular vortex cores are transported downstream with separating mutually, as shown in Fig. 11 (b) and (c).

![Diagram of the developing process of vortices](image)

Fig. 11 (a) Schematic diagram of the developing process of vortices, (b) $\omega_0/\Omega$ distribution and (c) $v_r/\Omega R$ distribution in bladeless mixer. Figures (b) and (c) are presented in the vertical cross-section involving the green line shown in Fig. 10 (b).

In the next, Fig. 12 illustrates (a) the schematic diagram of the developing process of vortices and (b) the distribution of $\omega_0/\Omega$ and (c) that $v_r/\Omega R$ around the bladeless rotor. The figures (b) and (c) was demonstrated on the cross-section as well as Fig. 11. Since, the centrifugal force ejects the channel fluid as a rotating jet flow outward, as shown in Fig. 12 (a), the shear layer between the rotating jet flow and the ambient fluid generates a pair of counter-rotating vortices near the nozzle exit (see nozzle N2). When the co-rotating vortex tubes which were produced from the different nozzles become closer, they start the twisting around each other due to the interaction as shown in Fig. 12 (a). According to Meunier (Meunier et al., 2005), the two co-rotating vortices are forced to get closer to each other in conserving the angular momentum and start the twisting and merging of vortices (Cerretelli and Williamson, 2003; Meunier et al., 2005; Leweke et al., 2016), and finally terminates in a single spiral vortex tube. As illustrated in the vertical cross-section, the zigzag street of counter-rotating vortices is appeared like a reverse von Kármán vortex street (Cerretelli and Williamson, 2003; Meunier et al., 2005; Leweke et al., 2016) and induces outward velocity in the flow field between them. Consequently, it is confirmed that the high radial-velocity region is allocated between the reverse von Kármán vortex street, as shown in Fig. 12 (c).

Figures 11 and 12 suggest that the circularly and spirally structured vortex tubes play an important role in the flow around the rotor.
The blade and hole geometries such as the number of blades and holes affect the vortex size and interaction between vortices. However, they do not significantly affect vortex generating mechanisms mainly focused on the present research.

### 4.3 Flow Pattern in Stirred Tank

In this section, we will discuss the flow pattern to understand the inherent difference between the two flows. Figure 13 demonstrates the streamlines in the $z$-$r$ plane around the flat-blade and the bladeless rotors. The streamline is calculated from the phase-averaged velocity vectors. In the flat-blade mixer, two pair of circulation ($I$, $II$) are observed near the rotor. One exists above the rotor as indicated with ($I$), and the other below the mixer as indicated with ($II$). The centers of both circulated flows are observed close to the rotor. Namely, the flat-blade generates a small but strong circulation near the rotor. Such disturbances cause prompt dissipation due to the quick break down of the circularly structured vortex, as mentioned in the section 4.2. On the other hand, for the bladeless case, although the two pair of circulations ($I$, $II$) are also observed, the centers of both circulations are located considerably far from the rotor. Furthermore, the streamlines are divided obviously into two directions, the straight upward and downward direction near the tank wall. It is attributed to the strong momentum transfer due to the interaction between spiral vortex and rotating jet flow. These flow patterns were confirmed in the previous research using particle tracer method (Azam et al., 2019).

![Fig.13 Streamlines in $(z, r)$ – plane along the rotating axis of the mixer. (a) Flat-blade mixer; (b) Bladeless mixer.](image1)

![Fig.14 Toroidal structure at $\lambda_2 = -0.1 \, \text{s}^{-2}$.](image2)
Figures 14 (a) and (b) show the vortex structure for the flat-blade and the bladeless rotor, respectively. The vortex tubes are visualized with the iso-surfaces of $\lambda_2 = -0.1 \, \text{s}^{-2}$. The blue and red iso-surfaces indicate the vortex tubes accompanying the negative and positive tangential vorticities, respectively. For the flat-blade case, a couple of large toroidal structured vortex tube continuously generates and disappears near the rotor, as shown in Fig. 14 (a). On the other hand, for the bladeless type, a couple of large toroidal structured vortex tube appears near the tank wall, which is caused by the sustained rotating jet flow. The large toroidal structured vortex tube pair causes a wider circular flow in the stirred tank. It was confirmed that the cores of the toroidal structured vortex tubes for both rotors correspond to the centers of the circulations as shown in Fig. 13 (a) and (b).

![Streamlines in a (r, θ) plane.](image)

**Fig. 15** Streamlines in a (r, θ) plane.

![Averaged flow angle in horizontal plane.](image)

**Fig. 16** Averaged flow angle in horizontal plane.

To understand the essential difference in the circulatory flows, the streamlines in the r-θ plane across the rotor is illustrated in Fig. 15. From these figures, we shall discuss the curvature or tangential angle of the streamlines to distinguish the essential flow pattern. Here, let’s consider the averaged flow angle variation as illustrated in Fig. 16. The inclination of the averaged flow, $\bar{\varphi}$, is defined in this paper as

$$\bar{\varphi} = \arctan \frac{\bar{v}_\theta}{\bar{v}_r}.$$  \hspace{1cm} (5)

Here, $\bar{v}_\theta$ and $\bar{v}_r$ are the circumferentially-averaged tangential and radial velocities, respectively. The large or small flow inclinations correspond to the streamline being circular or spiral, respectively. As shown in this figure, the dashed line that indicates that flow angle decreases up to $r/R < 2.5$ and flow inclination in the flat-blade mixer has the minimum at $r/R = 2.5$. This is attributed to the induced radial velocity by the counter-rotating vortices near the rotor, as shown in Fig. 11. In the far region $r/R > 2.5$, the flow angle proportionally increases with $r/R$ increasing. This profile is resulted from the quick dissipation of the circular vortex tube, as described in the section 4.2. In the case of
bladeless type, as indicated with the solid line, the profile also steeply decreases up to $r/R < 2.0$ and has the minimum at $r/R = 2.0$. This variation is influenced by the induced radial velocity due to the counter-rotating vortices near the rotor, as shown in Fig. 12. The minimum flow angle in the bladeless type is smaller than that of the flat-blade. When $r/R > 2.0$, the flow angle is almost the constant up to $r/R = 8.0$. In this region, it was confirmed that the decay rate for both radial and tangential velocities were almost inversely proportional to the radial distance. This means that the flow in this region obeys the assumption of the source and the free vortex in potential flow. This fact implies that the spirally structured vortex tube is sustained downstream, as described in the section 4.2. For $r/R > 8.0$ the flow angle increases due to the boundary effects of the tank wall.

4.4 Power Consumption

The shaft torque was calculated from the pressure and viscous forces on rotating surfaces using the LES. The shaft power between the flat-blade and bladeless mixers was compared. In the tested conditions, the shaft power of the flat-blade mixer is $9.3 \times 10^{-2}$ N m s$^{-1}$ and the shaft power of the bladeless mixer is $8.7 \times 10^{-2}$ N m s$^{-1}$. Namely, the power consumption of the bladeless mixer is 6% smaller than that of the blade-type mixer.

5 Conclusion

The flow characteristics in an invented conduct-type mixer is investigated using a particle image velocimetry (PIV) and a large eddy simulation (LES). The PIV and LES results are compared with respect to the phase-averaged field in the radial and tangential velocities.

In the bladeless mixer, the spirally structured vortex tube pair is found, and the high-speed rotating jet flow region is observed between it, which is caused by the induced outward velocity by a reverse von Kármán vortex street of the spirally structured vortex pair that is sustained downstream. Consequently, the rotating jet flow as well as the spirally structured vortex tube pair are sustained in far field. The sustained rotating jet flow generates a large toroidal structured vortex tube pair near the tank wall which causes a wider circulation over the whole field in the stirred tank. This wider circulation is advantageous for mixing process in the wider area.

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