

Improvement of Mixing Efficiencies of Conventional Impeller with Unsteady Speed in an Impeller Revolution

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Abstract

An unsteady mixing speed was applied to laminar mixing in a vessel containing a conventional impeller. Three non-circle cams were combined to generate the unsteady speed in an impeller revolution. The mixing performances of the unsteady speed impeller were compared with those of a conventional impeller operated under a steady speed. The mixing time and the flow pattern were measured by flow visualization using the discoloration method in which sodium thiosulfate reacts with an iodine solution. Because the unsteady motion moved the center of the vortices, the doughnut rings above and below the impeller disappeared when unsteady mixing was employed.

Key words

Mixing, Agitation, Unsteady Speed Impeller, Mixing Time

Introduction

It is well known that doughnut-shaped non-mixing regions are generated both above and below steady speed turbine impellers in vessels with low Reynolds numbers. Both experimental (Metzner and Taylor, 1960; Dong *et al.*, 1994) and numerical (Desouza and Pike, 1972; Kuncewicz, 1992) studies have verified the existence of doughnut rings for Reynolds numbers less than 500. Many kinds of wide paddle type impellers have been developed, including Maxblend[®] (Sumitomo Heavy Industries Co., Ltd.), Fullzone[®] (Sinko Pantec Co., Ltd.), MR-205[®] (SATAKE Chemical Equipment Mfg., Ltd.), Hi-F Mixer[®] (Soken Chemical & Engineering Co., Ltd.) and Sammler[®] (Mitsubishi Heavy Industries, Ltd.). When these impellers are used, the doughnut rings easily become unmanageable. Lamberto *et al.* (1996), on the other hand, reported the effects of time-dependent revolution of an impeller on the enhancement of mixing in a stirred vessel. Nomura *et al.* (1997) reported the effects of unsteady agitation carried out by counter rotation and Ogawa *et al.* (1996) investigated the effects agitating a vessel by periodically reversing the revolution direction when mixing water with aeration. Yao *et al.* (1998) reported the effects of unsteady agitation generated by the co-reverse periodic rotation and time-periodic fluctuation of the rotational speed. Tanaka *et al.* (1988) reported that a forward-reverse mixing method gave polymer particles a more uniform size and Yoshida *et al.* (1996) reported that a forward-reverse mixing method applied to a gas liquid system can obtain large gas hold-up and volumetric oxygen transfer coefficients. Tanguy *et al.* (1999) numerically and experimentally demonstrated that a double planetary mixer generates good radial dispersion capabilities. Alvarez *et al.* (2002a, 2002b) and Zalc *et al.* (2002) observed the laminar flow structure and mixing patterns of doughnut rings in stirred tanks. They discovered that an eccentric system destroyed the laminar flow structure and improved liquid mixing. As mentioned above, unsteady mixing methods have shown a great potential for improving mixing performance.

In this study, an unsteady mixing speed is employed to eliminate the doughnut rings efficiently instead of modifying the impeller geometry and the rotational direction.

1. Experimental Methods

Figure 1 shows the impeller speed variation profiles used to produce the unsteady mixing. Three non-circle cams were combined to generate the unsteady speed in an impeller revolution. Two types of unsteady speed mixing method were used;

Type 1: The maximum speed was 1.45 times as fast as the mean speed and the minimum speed was 0.7 times as fast as the mean speed.

Type 2: The maximum speed was 2 times as fast as the mean speed and the minimum speed was 0.5 times as fast as the mean speed.

The experimental apparatus consisted of a transparent cylindrical glass vessel ($D=12.4$ cm, $H=8.3$ cm) without baffles. The vessel was filled with a starch syrup solution. A turbine impeller ($d=7.0$ cm, $b=1.4$ cm), which was used as the conventional impeller, was installed at the center of the vessel ($c/H=0.5$). In order to reduce light refraction, the cylindrical vessel was placed into a square acrylic resin vessel filled with water.

The mixing time and the mixing process were measured using flow visualization. The discoloration method, in which a sodium thiosulfate and an iodine solution react, was employed. Sodium thiosulfate was dissolved in starch syrup to obtain the same viscosity as the liquid. The ratio of the iodine solution to the sodium thiosulfate solution was 1 to 1.4, which allowed for the discoloration to be determined easily (Takahashi *et al.*, 1985).

A tracer method was used to visualize the flow patterns. The nylon particles, whose average diameter was 200 μm , moved in the vessel and were illuminated by an Ar-Laser slit beam. Photographs were taken with an exposure time of one second.

2. Results and Discussion

Figure 2 shows the relationship between the power number and Re number. The average power number for the unsteady speed impeller under laminar flow was the almost same as that of the steady speed impeller.

Figure 3 shows photographs of the unsteady and steady speed mixing processes, respectively. The mean rotational speed was 2 s^{-1} . Therefore, the minimum rotational speed was (a) 1.4 s^{-1} (b) 1 s^{-1} and the maximum rotational speed was (a) 2.9 s^{-1} (b) 4 s^{-1} for the unsteady speed motion. Doughnut-shaped colored regions were generated both above and below the steady speed impeller in the vessel. However, once unsteady speed mixing commenced, the center of these vortices soon disappeared. Therefore, the unsteady speed in an impeller revolution improved the mixing performance.

In order to investigate the reason why the doughnut ring dissipated when the unsteady speed in an impeller revolution was used, a tracer method was used to visualize the flow. As shown in **Figure 4**, the centers of a pair of vortices which were observed both above and below the impeller periodically moved closer and then farther away from each other. This phenomenon was not observed in the case of the steady speed impeller.

In order to compare the steady speed and the unsteady speed mixing performance, the relationship between the dimensionless mixing time $N \cdot t_m$ and the Reynolds number Re was investigated. **Figure 5** shows the results of experiments operated under steady, unsteady and co-reverse periodic rotations (Yao *et al.*, 1998) and time-periodic fluctuation of rotational speed (Yao *et. al.*, 1998). The impeller's rotation direction was changed for the co-reverse periodic rotation. The flow was altered in the time-periodic fluctuation of the rotational speed.

The dimensionless mixing time of the unsteady speed in an impeller revolution was two-orders smaller than that of the steady speed for $Re < 100$. Because the doughnut rings were present for several hours for the steady speed setup, complete mixing was controlled by the diffusive mechanisms between the doughnut rings and the active regions. Co-reverse periodic rotation and the time-periodic fluctuation of rotational speed was found to be slightly more effective than unsteady speed mixing for $Re < 40$ and these methods with an unsteady speed only slightly influenced the mixing time for $Re > 40$. The dimensionless mixing time of the unsteady speed mixing was found to be the same as that for steady speed mixing for $Re > 400$.

Conclusions

The mixing performance of unsteady speed in an impeller revolution was investigated. Because the unsteady motion varied the location of the centers of the vortices in the vessel, non-mixing regions like doughnut rings disappeared and the mixing time drastically decreased. Unsteady speed mixing was found to be much more effective than steady speed mixing when a conventional impeller is used under laminar flow.

Nomenclature

b	= height of an impeller blade	[m]
c	= bottom clearance of an impeller	[m]
D	= diameter of a cylindrical vessel	[m]
d	= impeller diameter	[m]
H	= liquid depth	[m]
N_P	= power number	[-]
N	= mean rotational speed of impeller	[s ⁻¹]
$N \cdot t_m$	= dimensionless mixing time	[-]
Re	= Reynolds number ($= d^2 N \rho / \mu$)	[-]
t_m	= mixing time	[s]
μ	= liquid viscosity	[Pa·s]
ρ	= liquid density	[kg/m ³]

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Figure Caption

Fig. 1 Unsteady speed in an impeller revolution

(a) Type1: $N_{\max}=1.45 N$, $N_{\min}=0.7 N$, (b) Type 2: $N_{\max}=2 N$, $N_{\min}=0.5 N$

Fig. 2 Power number of (Type 2) unsteady speed turbine impeller: ●, steady speed:○

Fig.3 Mixing process and mixing time using the turbine impeller at $N=2 \text{ s}^{-1}$, $Re=30$

(a) Unsteady speed mixing (Type 1), (b) Unsteady speed mixing (Type 2), (c) Steady speed mixing

Fig. 4 Visualized flow pattern of unsteady speed impeller (Type 1) at $N=2 \text{ s}^{-1}$, $Re=30$

Fig. 5 Relationship between dimensionless mixing time and Reynolds number

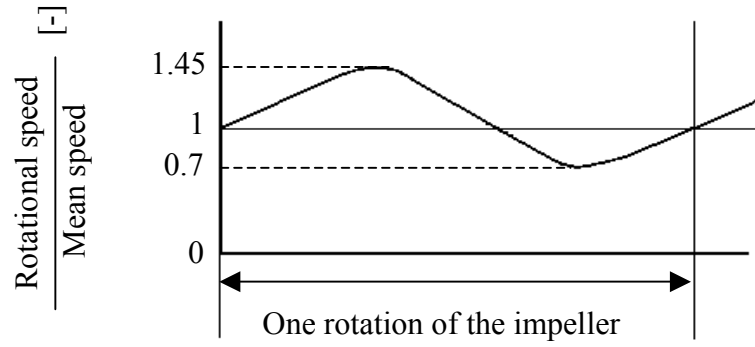
Unsteady speed mixing(Type1):●

Unsteady speed mixing (Type2): ■

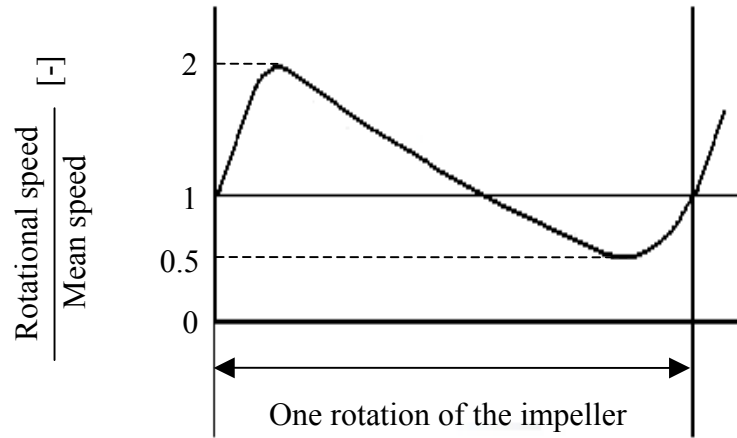
Co-reverse periodic rotation (Yao *et al.*, 1998): △

Time-periodic fluctuation of rotational speed (Yao *et al.*, 1998):▽

Steady speed mixing: ○



(a) Type1



(b) Type2

Fig. 1 Unsteady speed in an impeller revolution

(a) Type 1: $N_{\max}=1.45N$, $N_{\min}=0.7N$, (b) Type 2: $N_{\max}=2N$, $N_{\min}=0.5N$

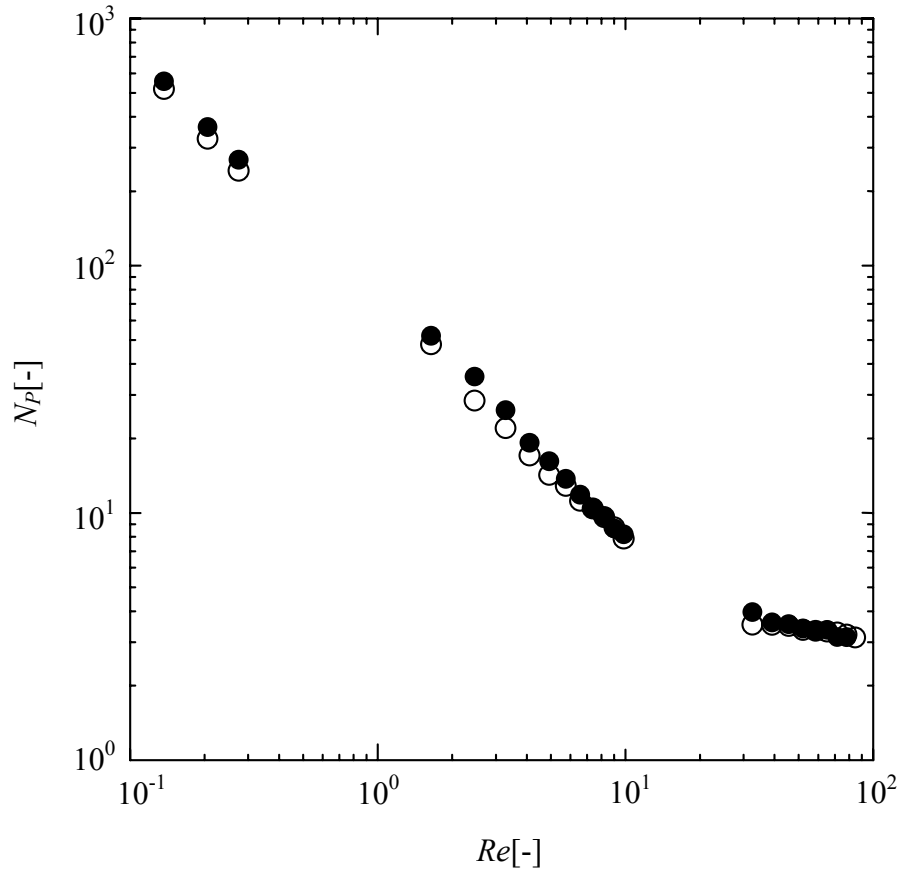
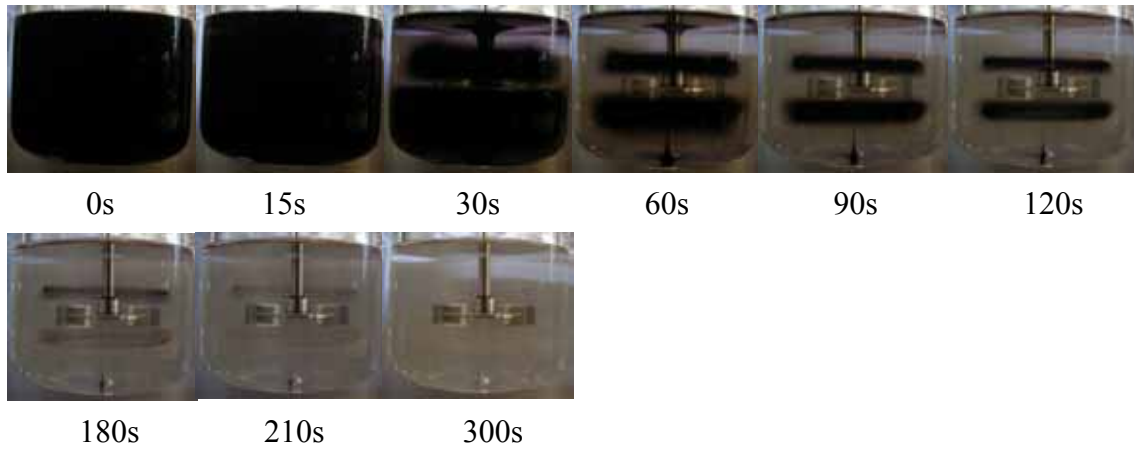
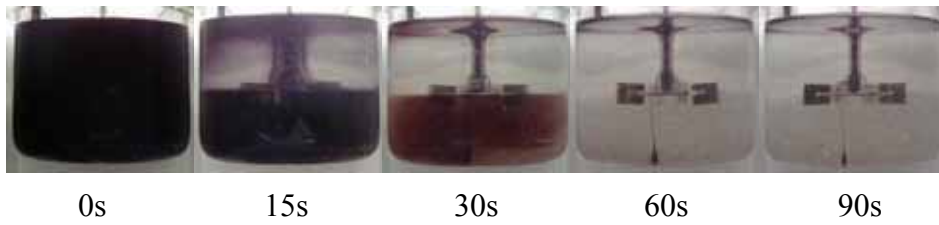


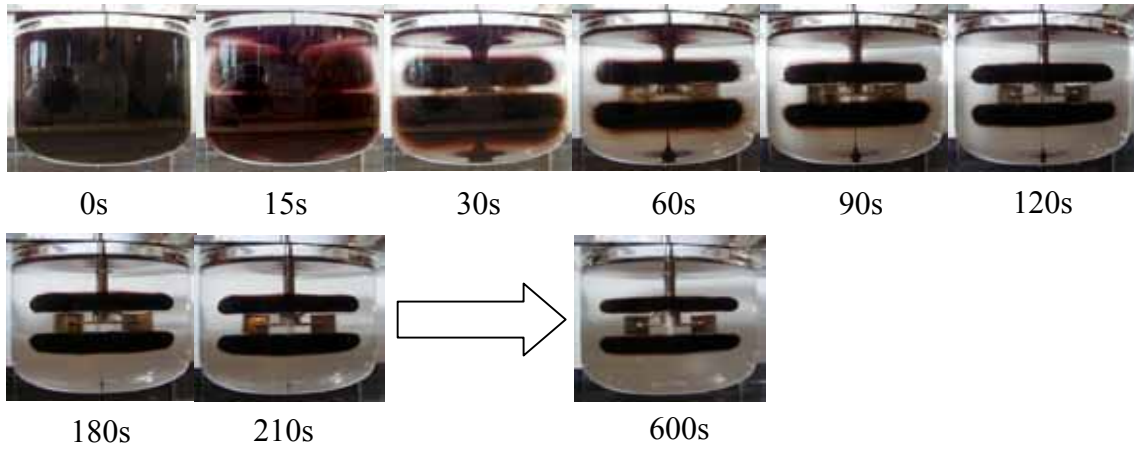
Fig. 2 Power number of turbine impeller unsteady speed (Type 2) : ●, steady speed:○



(a) Unsteady speed mixing (Type 1)



(b) Unsteady speed mixing (Type 2)



(c) Steady speed mixing

Fig.3 Mixing process and mixing time using the turbine impeller at $N=2s^{-1}$, $Re=30$
 (a) Unsteady speed mixing (Type 1), (b) Unsteady speed mixing (Type 2), (c) Steady speed mixing

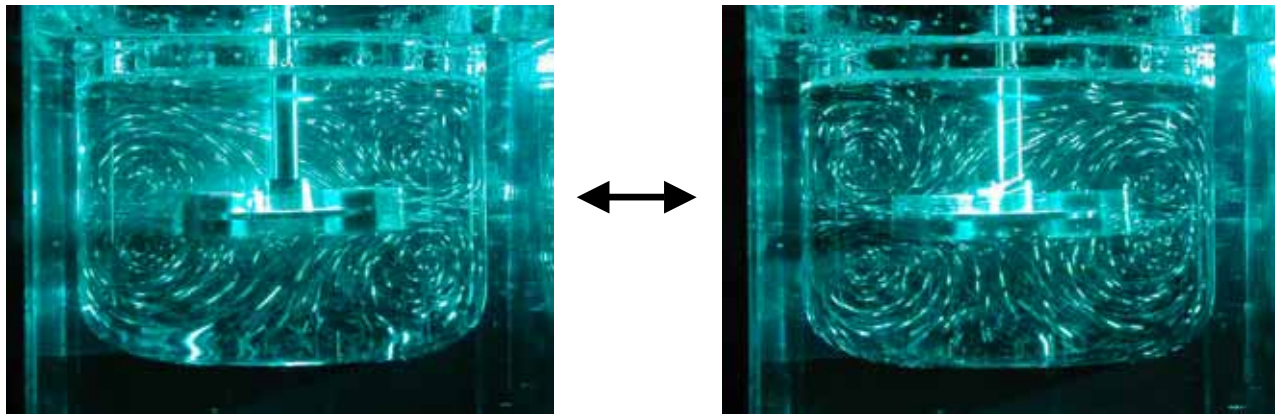


Fig.4 Visualized flow pattern of unsteady speed impeller (Type 1) at $N=2s^{-1}$, $Re=30$

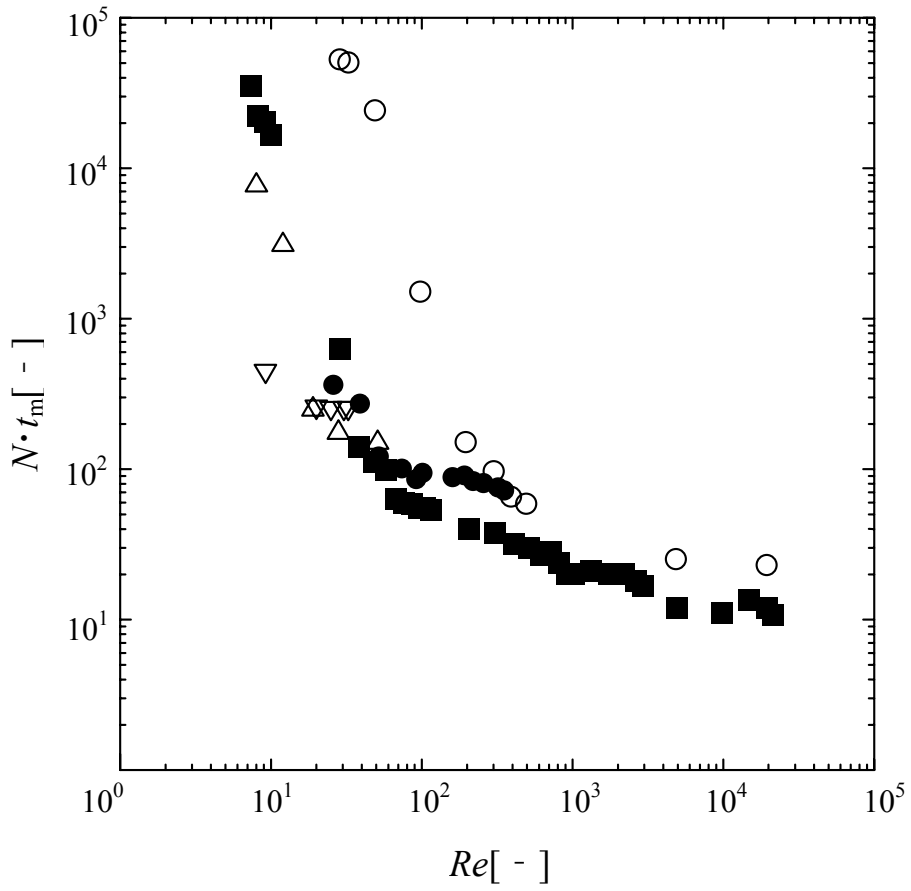


Fig.5 Relationship between dimensionless mixing time and Reynolds number
 Unsteady speed mixing(Type 1): ●
 Unsteady speed mixing (Type 2): ■
 Co-reverse periodic rotation(Yao *et al.*, 1998): △
 Time-periodic fluctuation of rotational speed (Yao *et al.*, 1998): ▽
 Steady speed mixing: ○