Effects of Location of Baffle and Clearance between Baffle and Vessel Wall on Isolated Mixing Regions

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The effects of the location of the baffle on mixing pattern in laminar mixing is shown in this study. Decolorization experiments were conducted based on an oxidation-reduction reaction to investigate the mixing pattern. As a result, isolated mixing regions (IMR) like doughnut-rings were eliminated by setting the baffle at the optimum location, where the baffle and the IMR crossed each other. The velocity profile was measured by using particle image velocimetry under the baffle condition. The IMR was dissipated due to making unstable circulation flow when the baffle was placed with clearance between the baffle and the wall. It was shown that using conventional mixing equipment can eliminate the IMR easily by placing the baffle with clearance.

Introduction

Mixing processes are usually found in chemical, mineral and pharmaceutical processes and the mixing operation is one of the most important unit operations. The turbulent mixing is conducted when low viscosity fluids such as water are mixed. Otherwise, the mixing state becomes laminar mixing when high viscosity liquids or shear sensitive fluids are mixed. When small impellers such as paddles, turbine or propeller mix the fluids under low Reynolds (Re) number conditions, isolated mixing regions (IMR) like doughnut-rings appear above and below the impeller. The formation of IMR structure was observed experimentally (Metzner and Talyor, 1960; Lamberto *et al.*, 1996; Kato *et al.*, 2010) and computationally (Deouza and Pike, 1972; Kuncewicz, 1992; Lamberto *et al.*, 1999). Hashimoto *et al.* (2009) revealed the existence of filaments around the IMR tori using the tracer-particle method.

The IMR leads to long mixing time because material diffusion between the IMR and active mixing regions is dominant. Generally, a large diameter impeller such as an anchor impeller and helical ribbon impeller is used to eliminate the IMR. On the other hand, unsteady mixing was proposed to eliminate the IMR. Unsteady mixing means that the rotational speed or direction changes periodically or the impeller moves up-down to eliminate the IMR. Unsteady rotational speed or direction has been conducted by many scientists (Murakami *et al.*, 1980; Lamberto *et al.*, 1996; Yao *et al.*, 1998; Kato *et al.*, 2005; Yoshida *et al.*, 2009). Moving the impeller up-down was carried out by Nomura *et al.* (1997) and Kato *et al.* (2006). Moreover, various types of impellers were designed to make unsteady flow (Kato *et al.*, 2007; Yek *et al.*, 2010). These previous works promote chaotic mixing

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to destroy the IMR. However, each method needs a motor or an impeller with a complex mechanism. Thus, those techniques and machines require higher cost.

The aim of this study is to eliminate the IMR using conventional simple mixing equipment such as a paddle impeller and baffles. The power consumption in the laminar region is constant without and with baffles at equal Re. Hence, the location of the baffle was focused on and investigated for the effects of the location on the destruction of the IMR structure. The decolorization method was conducted to measure mixing time and observe mixing pattern. Additionally, flow velocity was measured with particle image velocimetry (PIV). The relation between the destruction of the IMR and the stream line was discussed.

1. Experiment

Figure 1 shows the experimental equipment. A transparent flat bottom cylindrical mixing vessel and the paddle impeller were used in this study. These were made of acrylic resin. Starch syrup solutions were used as the working fluid. The experimental equipment dimensions and fluid properties are listed in **Table 1**. Two vessels with different diameter were used to investigate the effect of the equipment scale on the destruction of IMR. The vessel was placed inside a rectangular outer acrylic tank filled with water in order to minimize optical distortions caused by the curvature of the tank. The baffle which was inserted to the vessel vertically was made of acrylic resin or stainless steel and the baffle height was equal to the liquid depth. The baffle width B_w, clearance C_w between the baffle and the vessel wall and the number of baffle n_B are listed in **Table 2**.

The measurement of mixing time and the observation of mixing pattern was conducted by visualizing flow to investigate the effects of C_w on the IMR. The decolorization method based on oxidation-reduction reaction was adopted to

(a) Dimensions

(b) Shematic illustration of PIV experiment.
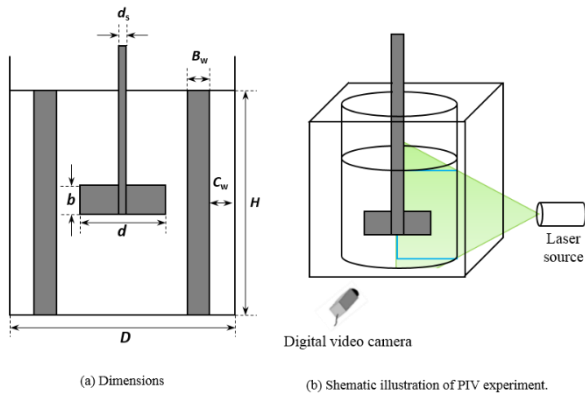
Fig. 1 Experimental set up

Table 1 Experimental equipment dimensions and fluid properties

Vessel:	
Inner diameter D,	0.15, 0.36 m
Fluid height H,	H/D=1.0
Impeller:	
Impeller diameter d,	d/D = 0.5
Impeller height b,	b/d =0.2
Number of impeller blade n_P,	2
Shaft diameter d_s,	0.008 m
Fluid (starch syrup solution):	
Density ρ,	1300–1385 kg・m^{-3}
Viscosity μ,	0.72–2.20 Pa・s

Table 2 Dimensions of baffle and clearance between baffle and wall

No.	B_W/D [-]	C_W/D [-]	n_B [-]
1	0.1	0	4
2	0.1	0.1	4
3	0.05	0.15	4
4	0.2	0	4
5	0.1	0.1	1
6	0.1	0.1	2

visualize the flow. Sodium thiosulfate and iodine were adopted as oxidation and reduction agent, respectively. Sodium thiosulfate and iodine were dissolved in starch syrup to obtain the same viscosity as the working fluid. The sodium thiosulfate sodium was added to the surface of working fluids colored with the iodine solution. The ratio of the iodine solution to the thiosulfate sodium solution was 1 to 1.4. This ratio allowed to determine decolorization easily (Takahashi *et al.*, 1985).

The velocity field in the vertical cross-section of the vessel was measured by using the PIV technique. Passive tracer was nylon particles whose diameter and density were 150–350 μm and 1020 kg/m^3, respectively. The tracer particles were dispersed in the vessel and lighted by laser sheet light vertically. The refraction light was captured by a digital video camera (HDR-CX420, Sony Marketing Inc.). The captured images were analyzed using the commercial software FlowExpert2D2C (KATOKOKEN Co. Ltd) to measure 2-dimensional velocity profile.

The power consumption P was measured by using the axial torque measurement method. Shaft torque was measured by
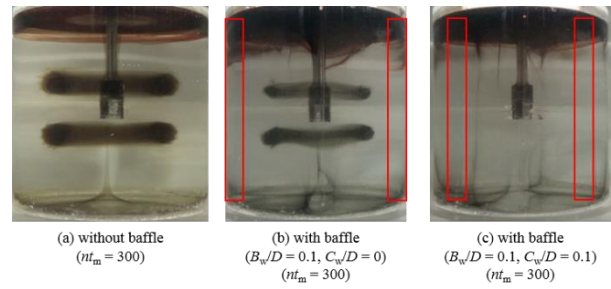

(a) without baffle
($nt_m = 300$)

(b) with baffle
($B_w/D = 0.1$, $C_w/D = 0$)
($nt_m = 300$)

(c) with baffle
($B_w/D = 0.1$, $C_w/D = 0.1$)
($nt_m = 300$)

Fig. 2 Decolorization experiment based on oxidation-reduction reaction at Re=30

(a) $B_w/D = 0.05$, $C_w/D = 0.15$
($nt_m = 300$)

(b) $B_w/D = 0.1$, $C_w/D = 0.1$
($nt_m = 300$)

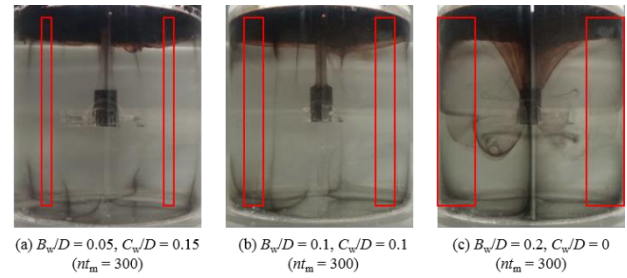(c) $B_w/D = 0.2$, $C_w/D = 0$
($nt_m = 300$)

Fig. 3 Effects of location of baffle edge on mixing pattern at Re=30
($B_w/D + C_w/D = 0.2$)

using a torque meter (SATAKE ST-3000, Satake Chemical Equipment Mfg Ltd.). P was calculated from $P=2\pi nT$ with the average torque T and the impeller rotational speed n.

2. Results and Discussion

Figure 2 shows the results of the decolorization experiment: (a) without baffle, (b) with baffle (B_W/D=0.1, C_W/D=0) and (c) with baffle (B_W/D=0.1, C_W/D=0.1). The IMR like doughnut-rings were observed above and below the impeller at nt_m=300 without baffle and with baffle ($B_W/D = 0.1$, $C_W/D = 0$) as shown in Figure 2 (a) and (b). The formation of IMR above and below the impeller is well known under these conditions. The fluid turns over in the vessel to form the IMR like doughnut-rings. On the other hand, the IMR was not observed in the mixing vessel at nt_m=300 with baffle ($B_W/D = 0.1$, $C_W/D = 0.1$) as shown in Figure 2 (c). It is considered that the change of the location of the baffle prevents the IMR from appearing in the mixing vessel.

The effects of the location of the baffle on the elimination of IMR was investigated. The width of the baffle used was B_W/D=0.05, 0.1 and 0.2. The baffle was placed at a location where the baffle intersected with the IMR tori. The distance between the baffle inner edge and the wall is such that $B_W/D+C_W/D$=0.2. **Figure 3** shows the results of the decolorization experiment. The IMR was not observed under each condition. However, a colored region remained behind the baffle in Figure 3(c). It is considered that the stagnant region behind the baffles increases with the baffle width.

The effects of the number of baffles (=n_B) on the elimination of the IMR was investigated. **Figure 4** shows the results of the decolorization experiment and the images were taken at nt_m=300. The IMR was not formed under each condition. The results mean that a weak baffle condition (n_B=1) is enough to eliminate the IMR.

Figure 5 shows the mixing pattern in a larger vessel. d/D in the larger vessel is equal to that in the smaller vessel. The IMR
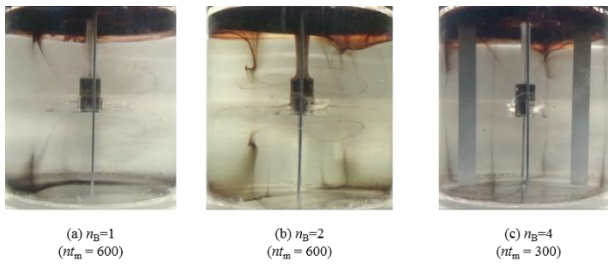
(a) n_B=1
(nt_m = 600)

(b) n_B=2
(nt_m = 600)

(c) n_B=4
(nt_m = 300)

Fig. 4 Effects of the number of baffle on mixing pattern at Re=30

Fig. 5 Mixing pattern of larger vessel at Re = 30 (nt = 300, D=0.36 m)

t=1/12T 1/6T 1/4T 1/3T 5/12T 1/2T

(a) C_W/D=0, B_W/D=0.1

t=1/12T 1/6T 1/4T 1/3T 5/12T 1/2T
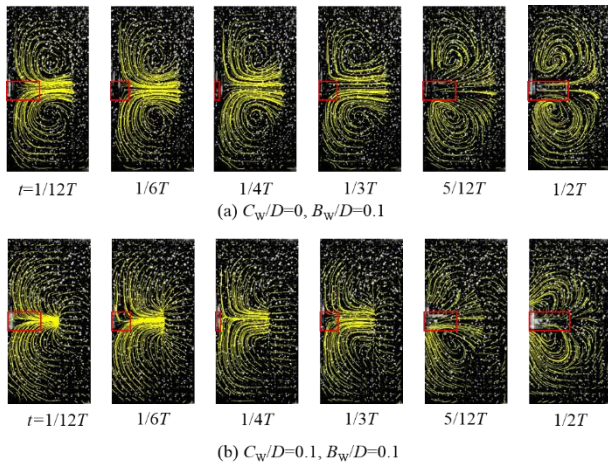
(b) C_W/D=0.1, B_W/D=0.1

Fig. 6 Streamline with C_W/D=0 and 0.1 and B_W/D=0.1

was not similarly observed in the larger vessel, because almost the same flow occurs in similar geometric equipment at the same Reynolds number.

Figures 6 (a) and (b) show the two dimensional streamline behind the baffle with C_W/D=0 and C_W/D=0.1 by using PIV. These pictures at every 1/12T are shown in Figure 6. The circulation flow shown as the streamline was observed at each impeller rotational period under the condition C_W/D=0 in Figure 6(a). The IMR like doughnut-rings were generated by this circulation flow. On the other hand, the circulation flow under the condition C_W/D=0.1 was not observed at almost all impeller rotational periods in Figure 6(b). This flow structure was caused by setting the baffle at the center of the circulation flow, because setting the baffle at that position prevented the discharge flow from turning over. As a result, the circulation flow was not formed and IMR like doughnut-rings were not generated.

Figure 7 shows the dependence of elimination of the IMR on Re with baffle (B_W/D=0.1, C_W/D=0.1). When Re is equal to or more than 20, the IMR were not observed. However, the IMR were observed above and below the impeller at Re = 10. Hashimoto *et al.* (2009) and Wang *et al.* (2013) stated that the core of IMR moved toward the impeller in radial direction with decreasing Re. It is considered that the core of IMR
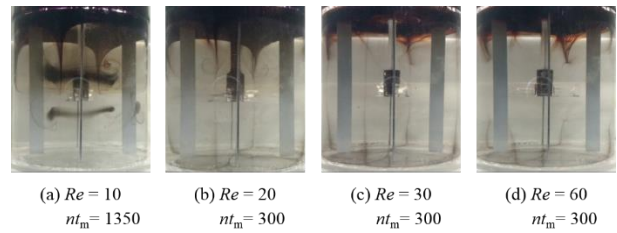

(a) Re = 10
nt_m = 1350

(b) Re = 20
nt_m = 300

(c) Re = 30
nt_m = 300

(d) Re = 60
nt_m = 300

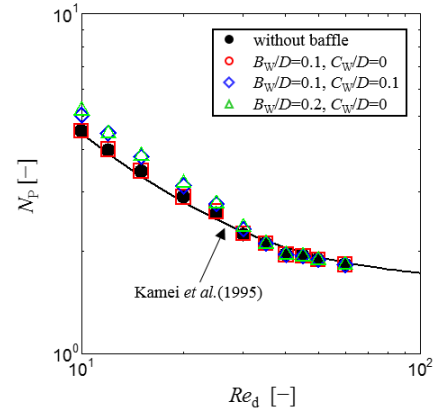**Fig. 7** Dependence of elimination of IMR on Re (B_W/D=0.1, C/D=0.1)

Fig. 8 Power Consumption without and with baffle

similarly moved in this work. Thus, the core of IMR did not cross with the baffle and the IMR remained in the vessel even when the baffle had clearance between the baffle and the wall.

Figure 8 shows the power number N_P calculated by N_P=$P/\rho n^3 d^5$. The power consumption was measured without baffle and with baffle (B_W/D=0.1, C_W/D=0; B_W/D=0.1, C_W/D=0.1 and B_W/D=0.2, C_W/D=0). The difference in N_P between the no baffle condition and baffle condition is less than 10% and N_P agreed well with each other. It is well known that there are no effects of the baffle on N_P in the laminar region. This shows that the IMR is dissipated just due to the suitable location of the baffle even for the same power consumption level.

Conclusion

Decolorization experiments were conducted to investigate the effects of the location of the baffle on the IMR structure like doughnut-rings using conventional mixing equipment. The baffle was placed at the location which crossed with the IMR. As a result, the IMR were eliminated when Re was equal to or more than 20.

It had been considered that the baffle had no effects on the destruction of IMR in laminar mixing. Therefore, many kinds of mixing methods needing complex mechanism were produced to dissipate the IMR. However, this study showed that simple mixing equipment was able to eliminate the IMR easily by placing the baffle at the optimum location.

Nomenclature

b	= impeller height	[m]
B_W	= baffle width	[m]
C_W	= clearance between baffle and vessel wall	[m]
d	= impeller diameter	[m]
D	= vessel inner diameter	[m]
d_S	= shaft diameter	[m]

H = liquid depth [m]
n = impeller rotational speed [s⁻¹]
n_P = number of blade [–]
N_P = power number ($=P/\rho n^3 d^5$) [–]
Re = Reynolds number ($=\rho n d^2/\mu$) [–]
T = impeller period [–]
t_m = mixing time [s]

ρ = fluid density [kg・m⁻³]
μ = fluid viscosity [Pa・s]

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