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Research Article

Effect of inside Surface Baffle Conditions on Just Drawdown Impeller Rotational Speed

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The effect of inside surface baffle installation conditions on the minimum impeller rotational speed for just the drawdown of floating solid N_{JD} was investigated. The inside surface baffle condition is the condition in which a partial baffle is placed with a clearance between the baffle and the vessel wall. In this study, a baffle with an insertion length of 0.2 times the liquid height was used. Moreover, the effect of baffle angle on N_{JD} was investigated. The N_{JD} was measured visually at least three times. The results showed that the effect of the radial installation position of the inside surface baffle on N_{JD} depended on the impeller position. In addition, even baffles placed parallel to the tangential flow were found to decrease N_{JD}.

1. Introduction

There are many studies of solid-liquid mixing using particles having heavier a density than the mixing liquid [1–7]. On the one hand, there are few studies using floating particles having lighter density than the mixing liquid [8–13]. However, solid-liquid mixing operations for floating particles are found in many industrial processes, such as food, paint, rubber pellet remelting, and sewage treatment [14]. In addition, foamed polyurethane foam has recently been used as a carrier in microbial cultures for biodiesel production, which requires drawdown of floating solids [15].

The first research on the drawdown of floating solids was by Joosten et al. [8]. Joosten et al. [8] reported the use of partial baffles allowed to suspend floating solids at low rotational impeller speed.

Some research on the mechanism of the drawdown of floating solids has been reported. Khazam and Kresta [16] reported that the drawdown of floating solids was caused by 1: stable central vortex, 2: turbulent engulfment, 3: mean drag. Pukkella et al. [17] reported the theoretical basis of partial baffles. Gong et al. [18] showed the mechanism of floating solids in the laminar region.

The minimum impeller rotational speed to suspend floating solids is the important process parameter for solid-liquid mixing of the floating solids as well as the solid-liquid mixing of the settling solids. The minimum impeller rotational speed is important because the dissolution rate of the solid solute increases rapidly with increasing impeller rotational speed up to this minimum impeller rotational speed, after which the rate of increase slows down [19]. The reason for the rapid increase in the dissolution rate up to the minimum impeller rotational speed is that the wetted surface area of solids increases with the increase of the impeller rotational speed, after which the wetted surface area of solid is constant. This minimum impeller rotational speed was defined as the minimum rotational speed for complete suspension [19]. A simple visual measurement method has been proposed to determine the minimum speed for complete suspension as the rotational speed at which no particles remain stationary at the bottom of the tank for more than 1 or 2 seconds [1, 2, 19]. This minimum speed was defined as the minimum impeller rotational speed for just suspension Zwietering [1]. Using the same criteria as for settling particles, Joosten et al. [8] defined the minimum rotational speed for just drawdown of floating solids as the speed at which no particles remain at the liquid surface. Thring and Edwards [9] investigated the effects of impeller installation method, impeller type, and solid particle concentration on N_{JD} and power consumption and reported that N_{JD} was highly dependent on impeller type and independent of solid concentration and impeller clearance.

The central vortex appears in the center of a mixing vessel when the impeller rotates in the vessel. In solid-liquid mixing with floating solids, the centrifugal force difference between the liquid and the floating particle cases the floating solids to agglomerate into the vortex. This agglomeration makes N_{JD} increase [8, 16, 20]. There are several research on the effects of impeller type and baffle shape on N_{JD} in order to reduce N_{JD}.

Kuzumanic and Ljubicic [21] studied the effects of impeller diameter, impeller position, and blade angle on N_{JD} using up-pumping pitched paddle blades and reported their optimal shapes. Taskin and Mcgrath [22] investigated the effects of blade shape, number of blades, and impeller mounting position on the power consumption at N_{JD} and reported that a down-pumping impeller mounted at 3/4 of the liquid height can be operated at low power consumption to avoid air contamination from the liquid surface. Özcan-Taskin and Wei [23] showed that the suspension mechanism of floating solids is different for both up-pumping and down-pumping impellers.

Hemrajani et al. [24] reported that N_{JD} was reduced by eccentric mixing in a vessel with partial baffles. Nomura and Iguchi [25] also reported that the suspension of floating solids was achieved at a low rotational speed when the impeller was eccentric than when the impeller was placed in the center of the mixing vessel.

Xu et al. [26] reported on the suspension of floating solids in a three-phase gas-liquid-solid system in a high aspect ratio mixing vessel. They found that a three-stage impeller combination consisting of an up-pumping propeller impeller at the top, a down-pumping propeller impeller at the middle, and a six-blade turbine impeller at the bottom was efficient for suspending floating solids in terms of power consumption, gas holdup, and distribution. Tagawa et al. [27] reported that N_{JD} decreased with increasing aeration flow rate for suspending floating solids in a three-phase gas-liquid-solid system. The reason is that air bubbles rising near the tank wall break up agglomeration of the floating solids remaining near the tank wall on the liquid surface.

Several studies have been conducted using baffles to reduce N_{JD}. Joosten et al. [8] studied the effect of the size and number of baffles on N_{JD} and found that a single baffle was effective for drawdown of floating solids. Thring and Edawards [9] investigated the vertical position of partial baffles and concluded that the vertical position of partial baffles had no effect on N_{JD}. Siddiqui [28] reported that in a high aspect ratio mixing vessel, a partial baffle could suspend floating solids at a low rotational speed than a full-length baffle. Khazam and Kresta [29] reported N_{JD} of the length of the baffle inserted into the mixing vessel and found that N_{JD} was lowest when a short baffle was placed at the liquid surface along the vessel wall. The study by Atibeni et al. [30], in which the width and shape of the baffles were varied, found that triangle baffles were more effective in suspending floating solids. Liu et al. [31] studied the effect of the number of baffles on N_{JD} and reported that N_{JD} was lowest when one baffle was used. Furukawa et al. [32] reported that N_{JD} was reduced by placing a partial baffle away from the wall surface.

It has been reported that partial baffles placed away from the mixing vessel wall can suspend floating solids at low rotational speeds [32], however, the optimal location of baffle has not been reported. The baffle is typically installed perpendicular to the mixing vessel wall. However, this installing method creates a stagnant area behind the baffle, and floating solids remain in this area, resulting in high N_{JD}. In this study, the effects of the radial position of the partial baffles and the angle of the baffles on N_{JD} and power consumption per unit volume at N_{JD}, were investigated.

2. Experimental Method and Setup

Figures 1(a)–1(d) shows the schematic diagram of the experimental setup. The cylindrical mixing vessel with the flat bottom was used. The inner diameter T of the vessel was 0.150 m. The liquid height H was equal to T. A pitched blade paddle impeller made of stainless steel was used. The impeller diameter D was 0.070 m, the blade height was 0.014 m, and the blade angle θ was 60°. The impeller was used as an up-pumping pitched blade paddle (PBPU) and a down-pumping pitched blade paddle (PBPD). The clearance C between the center of the impeller and the bottom of the vessel was $C/H = 0.2$ –0.7.

Tap water was used as the working fluid. The liquid viscosity μ_L was 0.001 Pa·s. The liquid density ρ_L was 998 kg·m^{-3}. The floating solids made of polypropylene were oval shape with 4.6 mm as the long axis length and 3.8 mm as the short axis length measured by the image analysis with Image J [33]. The average solid density ρ_S measured by pycnometer method [34] was 845 kg·m^{-3}. The volume concentrations of floating solid were 3, 5, 7%.

The baffle width B_W was $B_W/T = 0.1$ and the baffle height h_B was $h_B/H = 0.2$, 1. The number of baffle was four. The clearance C_W between the baffle and the vessel wall was $C_W/T = 0, 0.1, 0.2, 0.3$. The baffle angle θ_B was defined as the following that $\theta_B = 0°$ was parallel to the tangential flow and $\theta_B = 90°$ was perpendicular to the vessel wall shown in Figure 1(e). θ_B was 0°, 45°, 90°, 135°. In this study, four baffle conditions were used: (1) no baffle condition ($n_B = 0$), (2) standard baffle condition($n_B = 4$, $h_B/H = 1$, $C_W/T = 0$, $\theta_B = 90°$), (3) surface baffle on the wall condition($n_B = 4$, $h_B/H = 0.2$, $C_W/T = 0$, $\theta_B = 0°$, 45°, 90°, 135°), (4) inside surface baffle condition($n_B = 4$, $h_B/H = 0.2$, $C_W/T = 0.1$–0.3, $\theta_B = 0°$, 45°, 90°, 135°). The baffle conditions are summarized in Table 1.

There are two definitions of N_{JD}. One is the definition of N_{JD} as the rotational speed at which no particles remain on the liquid surface, as shown by Joosten et al. [8] The other is the definition of N_{JD} as the rotational speed at which there are no particles on the liquid surface for more than 1 or 2 seconds, as shown by Bakker and Frijlink [35]. Kuzmanic

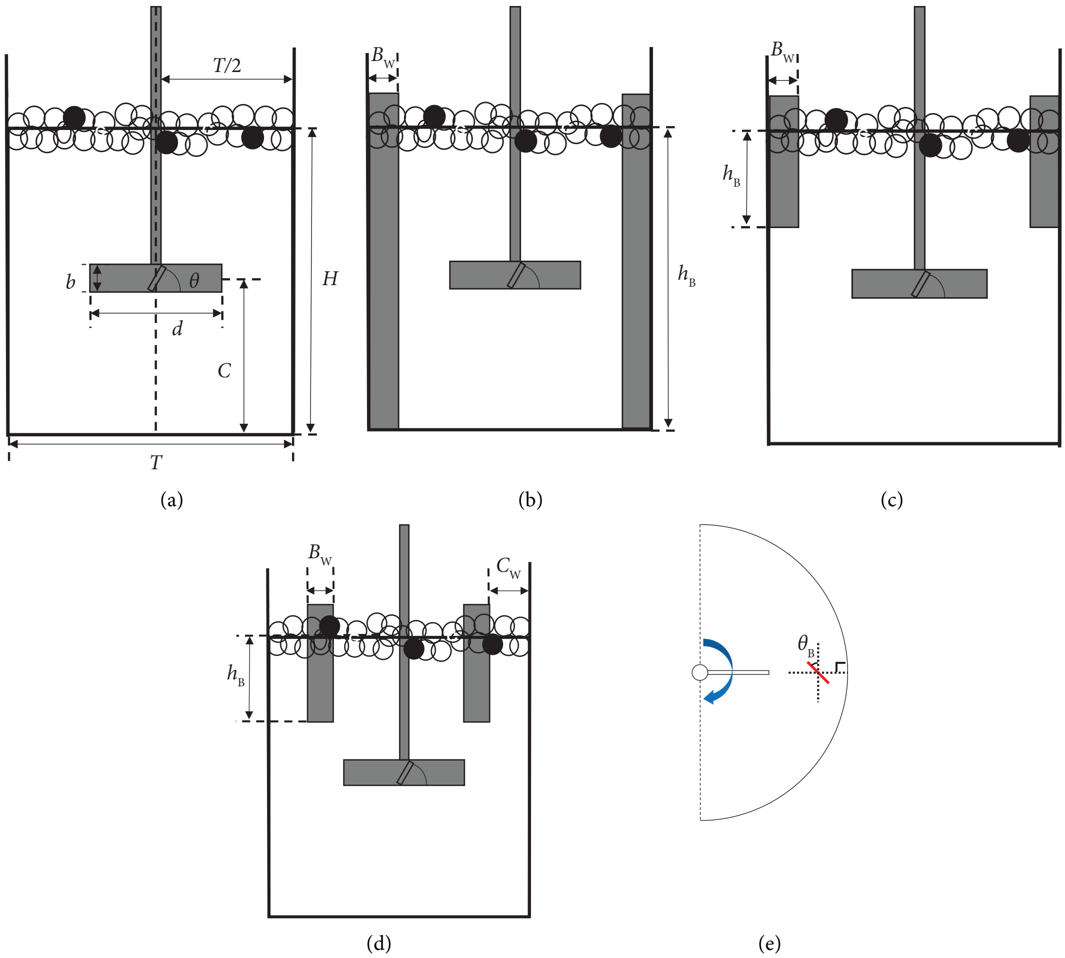


Figure 1: Schematic diagram of experimental equipment. (a) No baffle condition. (b) Standard baffle condition. (c) Surface baffle on the wall condition. (d) Inside surface baffle condition. (e) Baffle angle.

Table 1: Dimensions of baffle condition.

Baffle condition	n_B (–)	B_W/T (–)	h_B/T (–)	C_W/T (–)	θ_B (degree)
(a) No baffle condition	—	—	—	—	—
(b) Standard baffle condition	4	0.1	1	0	90°
(c) Surface baffle on the wall condition	4	0.1	0.2	0	0, 45°, 90°, 135°
(d) Inside surface baffle condition	4	0.1	0.2	0.1, 0.2, 0.3	0, 45°, 90°, 135°

and Ljubicic [21] reported that N_{JD} measured according to these two definitions gave the same results. In this study, the later definition of N_{JD} was adopted. The floating solids on the liquid surface were recorded with a digital video camera (HDR-CX470, Sony Marketing Inc., Japan) during agitation. N_{JD} was measured by visual observation of the recorded images. Each experiment was repeated at least three times.

Power consumption P (W) was calculated from torque T_q (N·m) measured by the torque measurement method. The torque meter was SATAKE ST-3000(SATAKE Multimix Co.). Since the torque is not output as a constant value even during steady-state operation, the average value of T_q was obtained from waveform data. The power consumption was calculated by the following equation using the average torque.

$$P = 2\pi n T_q, \quad (1)$$

where n(s^{-1}) was the impeller rotational speed. The details of measurement setup were given in our previous literature [36]. The power consumption per unit volume at N_{JD}, $P_{V,JD}$ (W/m^3), was measured when the rotational speed was N_{JD}.

3. Results and Discussion

Figure 2 shows N_{JD} for PBPU and PBPD under four baffle conditions in 3 vol%. θ_B was 90° under each baffle conditions and C_W/T was 0.3 under the inside surface baffle condition. Regardless of the pumping direction and the clearance between the impeller and the tank bottom, N_{JD} under the inside surface baffle condition and the surface baffle on the wall condition was lower than that under the no baffle condition and the standard baffle condition. These results are in qualitative agreement with those of Khazam and Kresta [29], and the measurement method is considered reasonable.

N_{JD} under the no baffle condition was higher than that under the surface baffle on the wall condition and the inside surface baffle condition, regardless of the pumping direction. As reported in the studies of Khazam and Kresta [16] and Xu et al. [20], the drawdown of floating solids was inhibited when the floating solids were trapped by the central vortex. Therefore, N_{JD} was higher under the no baffle condition.

N_{JD} under the standard baffle condition increased as the impeller approached the bottom of the vessel, resulting in the highest N_{JD} among the other baffle conditions. Furukawa et al. [32] showed the velocity profile in a mixing vessel at $C/H = 0.3$ under the standard baffle condition, with the measured results showing slower velocities in the downward direction near the surface baffle. When the mixing vessel was mounted near the bottom of the vessel, N_{JD} was higher due to the lower fluid velocity required to draw floating solids from the liquid surface.

N_{JD} with the partial baffle placed near the surface was lower than the N_{JD} under the no baffle and standard baffle conditions. Based on the velocity distributions under the surface baffle condition shown by Furukawa et al. [32], this is because the flow from the liquid surface to the impeller blade is enhanced by the partial baffle, and the floating solids are more easily drawn in. On the other hand, under the inside surface baffle condition, unlike the other baffle conditions, N_{JD} increased as the impeller approached the liquid surface. This trend under the inside surface baffle condition was also observed by Furukawa et al. [32]. Qualitative visual observations showed that the closer the impellers were to the liquid surface, the higher the central vortex between the surface baffles became and the more the surface baffles were partially exposed. The exposed baffles reduced the flow draw the floating solids into the liquid. This resulted in higher N_{JD}.

3.1. Effect of Pumping Mode on N_{JD}. N_{JD} for PBPD shown in Figure 2(b) was slightly lower than N_{JD} for PBPU shown in Figure 2(a) under the all baffle conditions except N_{JD} for $C/H = 0.7$ with the standard baffle. The effect of pumping mode on N_{JD} was agree with Takahasi and Sasaki [12] where N_{JD} for PBPD was lower than that for PBPU under standard baffle condition. The pumping direction of the PBPD was the same as the direction in which the floating solids were drawn in, resulting in lower N_{JD} of PBPD. The reason why N_{JD} for PBPU at $C/H = 0.7$ under the standard baffle condition was lower than that for PBPD at $C/H = 0.7$ under the standard baffle condition was that the formation of aggregation of floating solids near the impeller shaft was prevented due to the intensified up-pumping flow under the standard baffle condition when PBPU was placed at $C/H = 0.7$. As a result, N_{JD} for PBPU at $C/H = 0.7$ under the standard baffle condition was lower than that for PBPD. However, the difference of N_{JD} between PBPD and PBDU was small.

3.2. Effect of C_W/T on N_{JD}. Figure 3 shows the effect of baffle location on N_{JD} under the surface baffle on the wall condition and the inside surface baffle condition. When surface baffle was placed away from the mixing vessel wall, N_{JD} for both impellers at $C/H = 0.2$, 0.5, and 0.7 decreased, unchanged and increased with the increase of C_W/T, respectively. Baffles away from the wall intensified the vertical velocity near liquid surface compared to that with partial baffles on the wall [32]. Floating solids were aggregated at the center of the vessel due to the difference in centrifugal force caused by the density difference between the liquid and the floating solids. As a result, the downward flow at the center of the vessel is considered to cause the drawing in of floating solids at low N_{JD} at $C/H = 0.2$. On the one hand, N_{JD} for $C/H = 0.5$ and 0.7 did not decreased. The downward flow near the liquid surface at the center for $C/H = 0.5$ and 0.7 is also considered to be intensified similarly to the flow for $C/H = 0.2$. However, the depth of the surface vortex increased with the increase of C/H. The surface vortex made the partial baffles partially exposed. As a result, N_{JD} at $C/H = 0.5$ and 0.7 with the surface baffle unchanged and increased, respectively.

3.3. Effect of θ_B on N_{JD}. Since the stagnation of floating solids behind the surface baffle is one of the factors that increase N_{JD}, we investigated the effect of θ_B on the N_{JD} under the inside surface baffle condition. The results are shown in Figure 4. N_{JD} at $\theta_B = 0^\circ$ was higher than that at other baffle angles for the range of conditions examined, where the maximum impeller submergence did not exceed $C/H = 0.2$. However, N_{JD} at $\theta_B = 0^\circ$ shown in Figure 4 was lower than N_{JD} under no baffle condition shown in Figure 2, even though the baffle at $\theta_B = 0^\circ$ was parallel to the tangential flow. In addition, the depth of the surface vortex at $\theta_B = 0^\circ$ was much shallower than in the unbaffled condition, as judged by visual observation. This means that the baffle installed at $\theta_B = 0^\circ$ functions as a baffle, although its performance is slightly worse than that of the other θ_B. The reason why N_{JD} at $\theta_B = 0^\circ$ is higher than that at other θ_B is considered to be that the surface baffle becomes less effective as a surface baffle. Therefore, the floating solids tend to agglomerate around the shaft. On the one hand, N_{JD} for $\theta_B = 45^\circ$ and 135° were slightly different from those for $\theta_B = 90^\circ$. Visual observation from the top of the mixing vessel confirmed that $\theta_B = 45^\circ$ and 135° prevented floating solids from remaining behind the baffle. However, since the effect of the baffle was weaker than that of $\theta_B = 90^\circ$, N_{JD} were almost the same.

3.4. Effect of Solid Concentration on N_{JD}. Figure 5 shows N_{JD} results for PBPU and PBPD at particle volume fractions of 3, 5, and 7 vol%. Under all baffle conditions, N_{JD} was highest at 7 vol% and lowest at 3 vol% for the range of conditions examined, where the maximum impeller submergence did not exceed $C/H = 0.2$. This indicates that N_{JD} increases with increasing particle volume fraction. This trend was also reported in the studies of Kuzmanic and Ljubicic [21], Bao et al. [37], and Khazam and Kresta [16]. Increasing the

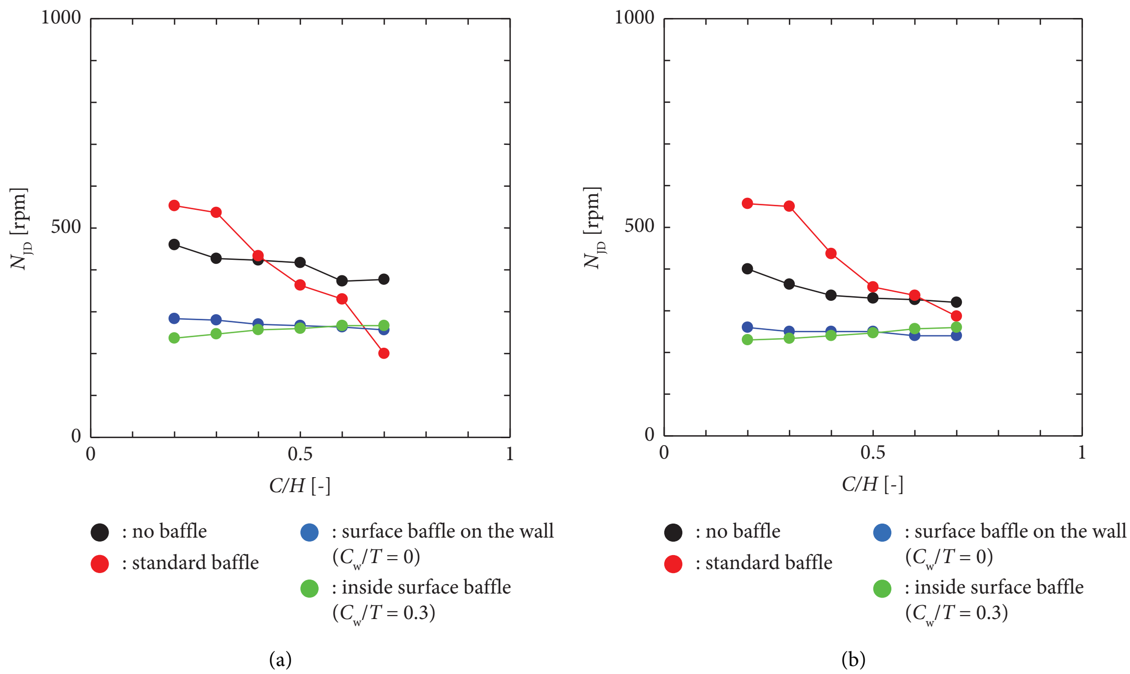


FIGURE 2: Comparison of just drawdown speed N_{JD} among 4 baffle conditions ($\theta_B = 90^\circ$, 3 vol%). (a) PBPU. (b) PBPD.

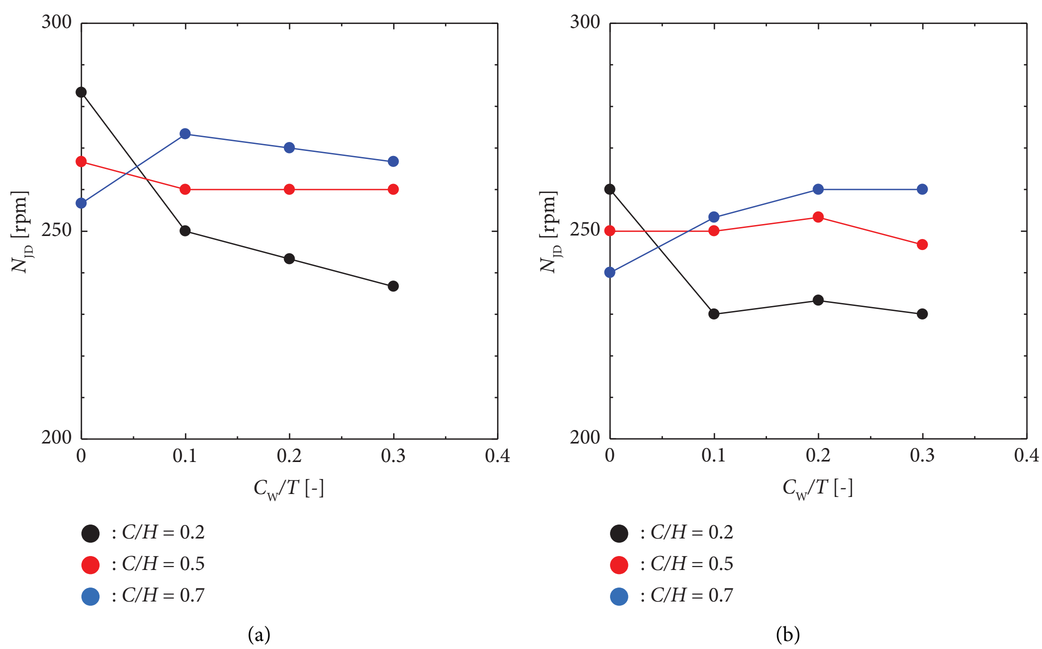
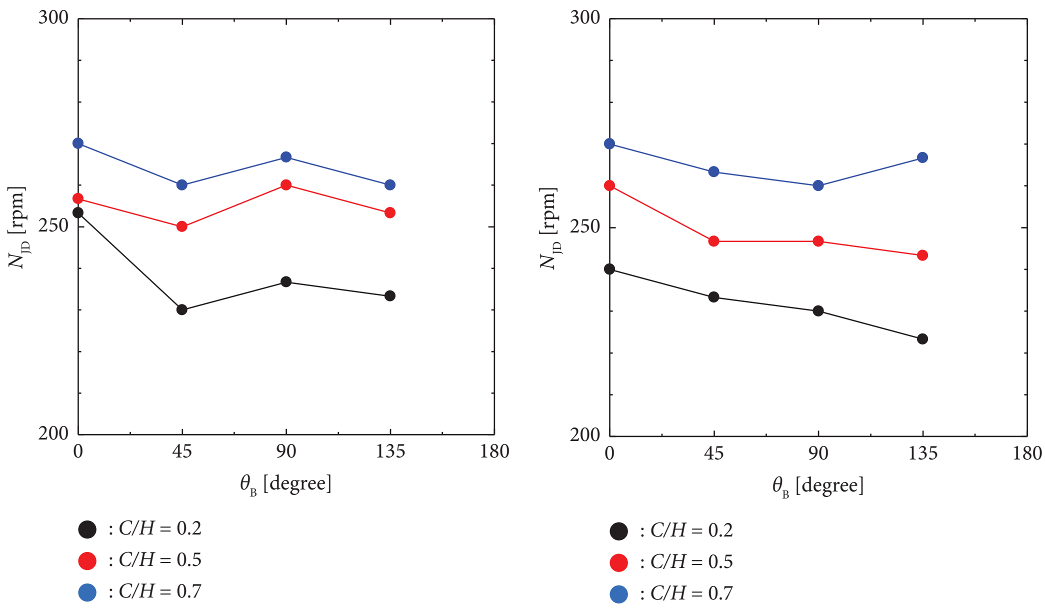


FIGURE 3: N_{JD} at different clearance between baffle and vessel ($\theta_B = 90^\circ$, 3 vol%). (a) PBPU. (b) PBPD.

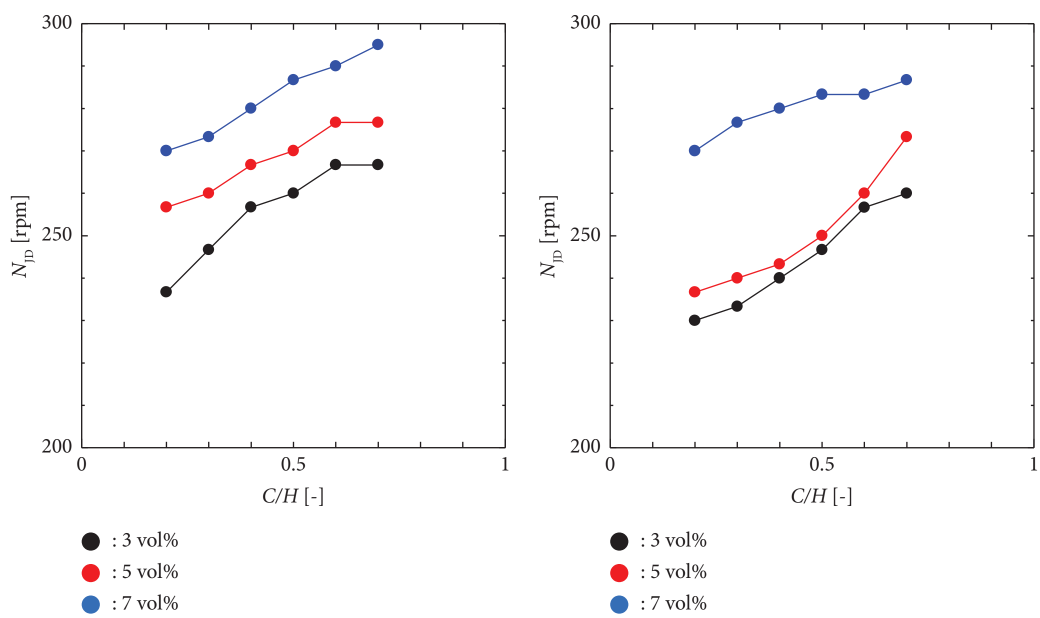
amount of floating solids requires more power consumption to draw in more floating solids, resulting in higher N_{JD}.

3.5. Effect of C_W/D on $P_{V,JD}$. Figure 6 shows the effect of C_w on $P_{V,JD}$ under the surface baffle on the wall condition and the inside surface baffle condition. For each $P_{V,JD}$ of C_w/T, both PBPU and PBPD show similar trends in N_{JD}, as shown in Figure 3 for the range of conditions examined, where the maximum impeller submergence did not exceed $C/H = 0.2$. In other words, the $P_{V,JD}$ of $C_w/T = 0.30$ was the lowest for almost all conditions. Takeda and Hoshino [38] reported that a clearance between the mixing vessel wall and the baffle decreases the drag force due to the baffle and the power consumption decreases. The more the baffle is inside, the larger the clearance between the tank wall and the baffle. The larger the clearance, the more tangential flow escapes without



(a) (b)

Figure 4: Effect of baffle angle on N_{JD} ($C_W/T = 0.3$, 3 vol%). (a) PBPU. (b) PBPD.



(a) (b)

Figure 5: Effect of solid concentration on N_{JD} ($C_W/D = 0.3$, $\theta_B = 90^\circ$). (a) PBPU. (b) PBPD.

hitting the baffle. Therefore, $P_{V,JD}$ decreases due to the small drag force.

3.6. Effect of θ_B on $P_{V,JD}$. Figure 7 shows the effect of θ_B on $P_{V,JD}$ under the inside surface baffle condition. $P_{V,JD}$ with $\theta_B = 0^\circ$ for each impeller was smallest for the range of conditions examined, where the maximum impeller submergence did not exceed $C/H = 0.2$. On the one hand, $P_{V,JD}$ with $\theta_B = 90^\circ$ for each impeller was the largest among the examined conditions. The reason for this is clear that the drag force for $\theta_B = 0^\circ$ is the smallest and that for 90° is the largest of the baffle angles examined.

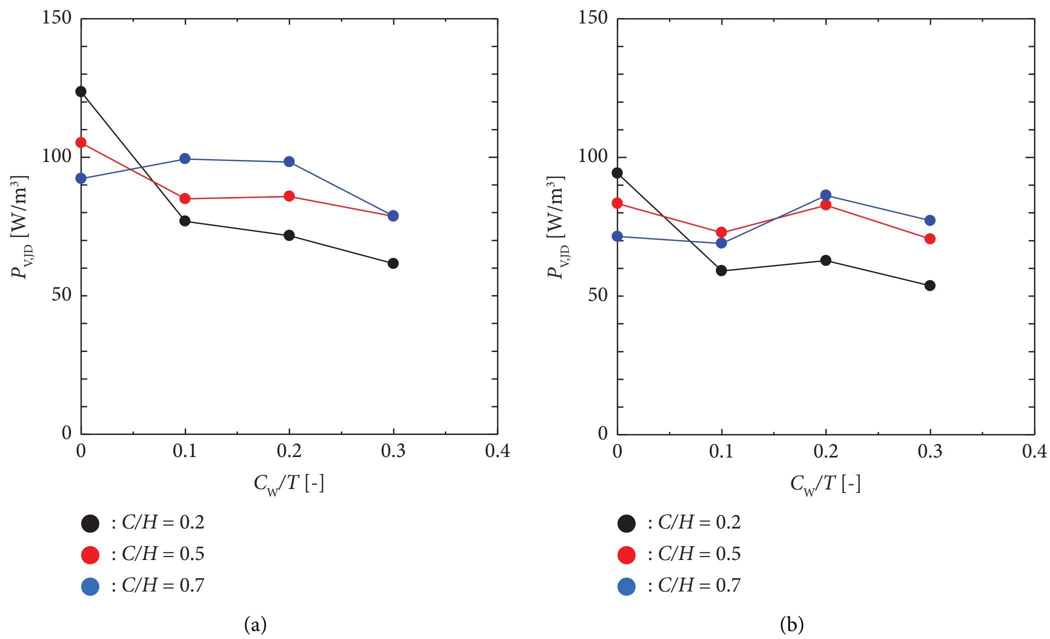


Figure 6: Effect of C_W/D on volumetric power consumption at just drawdown speed $P_{V,\mathrm{JD}}$ ($\theta_B = 90°$, 3 vol%). (a) PBPU. (b) PBPD.

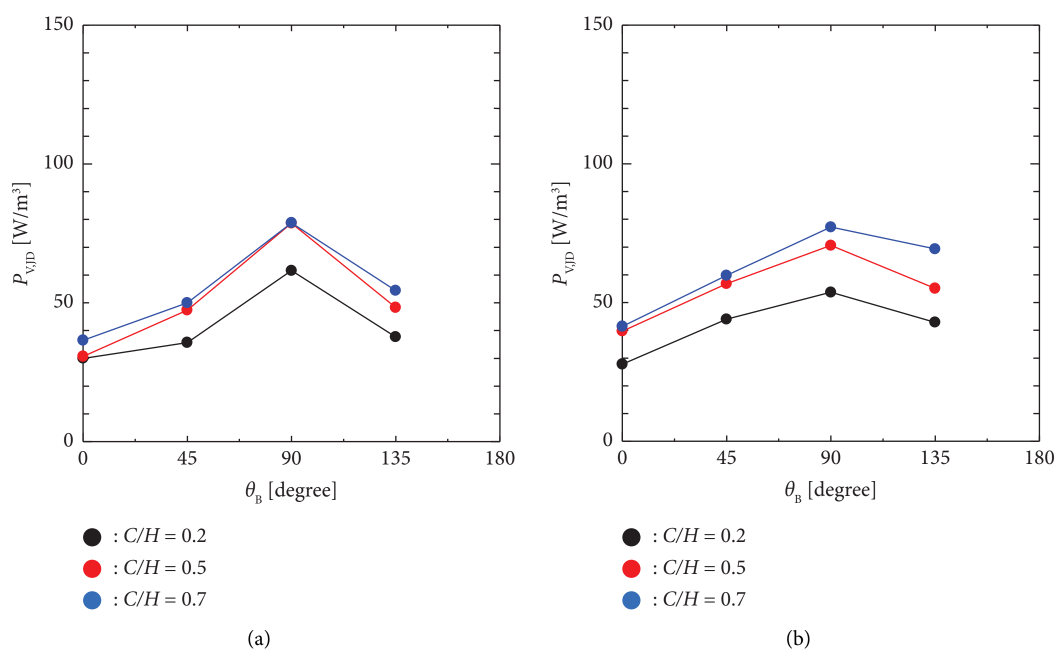


Figure 7: Effect of θ_B on $P_{V,\mathrm{JD}}$ ($C_W/D = 0.3$, 3 vol%). (a) PBPU. (b) PBPD.

4. Conclusion

In this study, the effect of inside surface baffle on drawdown of floating solids was investigated. N_{JD} and $P_{V,\mathrm{JD}}$ were measured with various C_W/T and θ_B. Comparison of N_{JD} and $P_{V,\mathrm{JD}}$ among all baffle conditions used in this study gave the following results.

The main finding of this research was that the effect of the radial installation position of the inside surface baffle on N_{JD} for each impeller decreased, unchanged, and increased for $C/H = 0.2$, 0.5, and 0.7, respectively. $P_{V,\mathrm{JD}}$ for each impeller was the smallest at $\theta_B = 0°$ and the largest at $\theta_B = 90°$. Furthermore, it is found that the baffle placed at $\theta_B = 0°$ is also effective as a baffle when placed parallel to the primary tangential flow.

In the future, it is necessary to clarify the mechanism of the baffle effect at $\theta_B = 0°$. This will be useful not only for solid suspensions, but also for homogeneous mixing.

Nomenclature

b: Impeller height (m)
B_W: Baffle width (m)
C: Clearance between impeller and vessel bottom (m)
C_W: Clearance between baffle and vessel wall (m)
D: Impeller diameter (m)
h_B: Baffle height (m)
H: Liquid depth (m)
n: Impeller rotational speed (s^{-1})
N_{JD}: Minimum impeller rotational speed for just drawdown of floating solid (min^{-1})
n_B: Number of baffle (–)
n_P: Number of blade (–)
P: Power consumption (W)
$P_{V,JD}$: Power consumption per unit volume at N_{JD} ($W{\cdot}m^{-3}$)
T: Vessel inner diameter (m)
T_q: Shaft torque (N·m)
θ: Impeller blade angle (degree)
θ_B: Baffle angle (degree)
μ_L: Liquid viscosity (Pa s)
ρ_L: Liquid density ($kg{\cdot}m^{-3}$)
ρ_S: Solid density ($kg{\cdot}m^{-3}$).

Data Availability

The data that support the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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