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Research Article

Correlation of Power Consumption of Double Impeller Based on Impeller Spacing in Laminar Region

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Power consumption is an important parameter for the design of mixing equipment. The aim of this study is to develop a new correlation of the power consumption of a double impeller. The effect of impeller spacing on the double-impeller flow pattern and power consumption was investigated in the laminar region. As a result, the effect of impeller spacing on the flow pattern was described based on the ratio of impeller spacing to the impeller blade height. Moreover, the power consumption of a double impeller could be correlated with the same ratio.

1. Introduction

Mixing is performed in many industries such as the chemical, food, pharmaceutical, and fermentation industries. In these industries, a high-aspect-ratio vessel is often used because of its limited footprint. The use of a single impeller in such vessels results in poor mixing performance. An unmixed region appears near the liquid surface and vessel bottom because the flow from the impeller underreaches the liquid surface and the vessel bottom. To improve mixing performance, multiple impellers are often used in high-aspect-ratio vessels [1]. Much research has been conducted to investigate the characteristics of multiple impellers. Yahata et al. [2] investigated the mixing regions of a double impeller and showed that the mixing regions above the upper impeller and below the lower impeller were constant. Komori and Murakami [3] compared the mixing efficiency and mixing time of single impellers with those of double impellers in a turbulent mixing vessel. They found that these factors were related to the flow patterns in the mixing vessel. Fasano et al. [4] studied the maximum allowed ratio of liquid height to tank diameter for a double impeller over a wide range of Reynolds numbers. Woziwodzki [5] studied the effect of unsteady rotating dual-turbine impellers on mixing of highly viscous Newtonian fluids. Several studies [6–9] employed computational fluid dynamics (CFD) to investigate the flow field in high-aspect-ratio vessels with multiple impellers. Arratia et al. [10] examined the mixing performance of multiple impellers in a shear-thinning fluid with yield stress. Xiao et al. [11] developed a new torus model of cavern formation in yield stress fluid for a single impeller and a double impeller using CFD.

Power consumption is one of the most important parameters in the design of mixing equipment because chemical engineers typically choose a motor based on power consumption. The power consumption of a double impeller in a turbulent region is twice that of a single impeller when the impeller spacing is 1 to 1.5 times the impeller diameter [12, 13]. Hiraoka et al. [14] showed that the maximum power consumption of a double impeller in a turbulent region is almost twice that of a single impeller at a ratio of impeller spacing to liquid depth greater than 0.35.

Double turbine impellers are used in gas-liquid mixing for chemical and biochemical processes. A turbine impeller is used to hold gas bubbles in gas-liquid mixing [7]. In these processes, the fluid often possesses non-Newtonian rheology, and the mixing is conducted in the laminar region. The power consumption in such non-Newtonian fluids is estimated using the Metzner–Otto method [15]. However, the power consumption characteristics of a double impeller in the laminar region of a Newtonian fluid have not been examined, and an estimation method for the power consumption of a double impeller has not yet been proposed. Therefore, it is impossible to estimate the power consumption in non-Newtonian fluids with the Meztner–Otto method.

In previous works [12, 13, 16], the power consumption of a double impeller was expressed as a function of the ratio of impeller spacing to impeller diameter. However, this function is not applied to double impellers with a large blade width because the impeller blades interfere with each other when ratio of impeller spacing to impeller diameter is small. Moreover, secondary flow occurs above and below the impeller blades. Therefore, it is considered that the flow structure of impellers depends on the impeller blade width, even if the ratio of impeller spacing to impeller diameter is constant. In the present study, we measured the power consumption of a double impeller with various impeller spacings in a Newtonian fluid and clarified the effect of impeller spacing on the power consumption based on the flow field in a mixing vessel. A turbine impeller is used in this study because double turbine impellers are often used in gas-liquid mixing with a high-aspect-ratio vessel. Moreover, we developed a new correlation regarding the power consumption of a double impeller based on the impeller spacing and impeller blade width. The experiment was conducted in the laminar region to estimate the power consumption in a non-Newtonian fluid in future work.

2. Materials and Methods

Figure 1 shows the experimental equipment. A transparent, flat-bottom cylindrical mixing vessel was used under the unbaffled condition. The inner diameter D of the vessel was 0.185 m. The mixing vessel was made with acrylic resin. The working fluid was a starch syrup solution (Kato Kagaku Co., Ltd.) with a density ρ_f of 1300–1380 kg/m^3 and a viscosity μ of 1.5–5.5 Pa·s. The liquid heights H were 0.148, 0.185, 0.241, and 0.278 m, which correspond to $H/D = 0.8$, 1.0, 1.3, and 1.5, respectively. In this study, we used several kinds of turbine impellers, the dimensions of which are listed in Table 1. In all experiments, the upper and lower impellers were of the same type and size. The impellers were set symmetrically at the half level of the liquid height, as shown in Figure 1. The spacing between the upper and lower impellers, L, was in the range of 0.014–0.14 m, which corresponds to $L/H = 0.076$–0.50.

The flow field in the mixing vessel was obtained through particle image velocimetry (PIV) and expressed as streamlines. The PIV experiments were carried out with the aforementioned mixing equipment, which was placed inside a rectangular acrylic tank shown in Figure 1(c). The outer rectangular tank was filled with tap water to minimize optical refraction. Nylon particles with diameters d_p of 150–350 μm and a density ρ_p of 1020 kg/m^3 were used as the passive tracer. The vertical cross section in the mixing vessel was illuminated using laser sheet light (Reliant 1000m, Laser Physics). The scattered light of the tracer particles was captured using a digital video camera (HDR-CX420, Sony Marketing Inc.). The captured images were analyzed using commercial flow analysis software FlowExpert2D2C (Katokoken Co., Ltd.). In this study, the right-hand side of the vertical plane was analyzed because the flow in the mixing vessel was symmetric with respect to the axial shaft.

Power consumption P was obtained using the axial shaft torque method. The shaft torque T was measured with a torque meter (ST-3000, Satake Chemical Equipment Mfg. Ltd.). The resolution of the torque meter was 0.0832 cN m, and the smallest experimental torque in this study was 1.24 cN m. Therefore, it is considered that the torque measurement was accurate. The power consumption was calculated as

$$P = 2\pi n T, \tag{1}$$

where n is the impeller rotation speed. The power consumption was described by the power number N_P, which was defined as

$$N_P = \frac{P}{\rho_f n^3 d^5}, \tag{2}$$

where d is the diameter of the impeller. The power number depends on the fluid density, fluid viscosity, impeller geometry, and vessel geometry.

3. Results and Discussion

3.1. Flow Field. We investigated the effect of impeller spacing on the flow field in the laminar region using PIV. The particle time constant τ_0 of passive particle was calculated as [17]

$$\tau_0 = d_p^2 \frac{\rho_p}{18\mu}. \tag{3}$$

The maximum particle time constant $\tau_{0,max}$ of the passive particle used in this study was 8.35×10^{-5} s. The characteristic time of flow T_c was calculated as

$$T_c = \frac{L_c}{U}, \tag{4}$$

where L_c is characteristic length and U is characteristic velocity. The minimum characteristic time $T_{c,min}$ in this study was 1.21×10^{-2} s when the impeller diameter and impeller blade tip velocity was adopted as L_c and U, respectively. Therefore, the passive particle was able to trace the flow in the stirred tank because of $\tau_{0,max} << T_{c,min}$.

Figure 2 shows the streamlines acquired using PIV. At $L/H = 0.059$ ($L/b = 1$), a pair of circulation loops was observed above and below the impellers. The double impeller functioned like a single impeller with twice the blade height at $L/H = 0.059$ ($L/b = 1$). The pumping flow from each impeller interferes with the decreased impeller spacing. Therefore, a circulation loop between the impellers was not observed. Finally, at $L/H = 0.3$ ($L/b = 5.0$), a pair of circulation loops was observed above and below each of the impellers. The impellers function independently at $L/H \geq 0.3$.

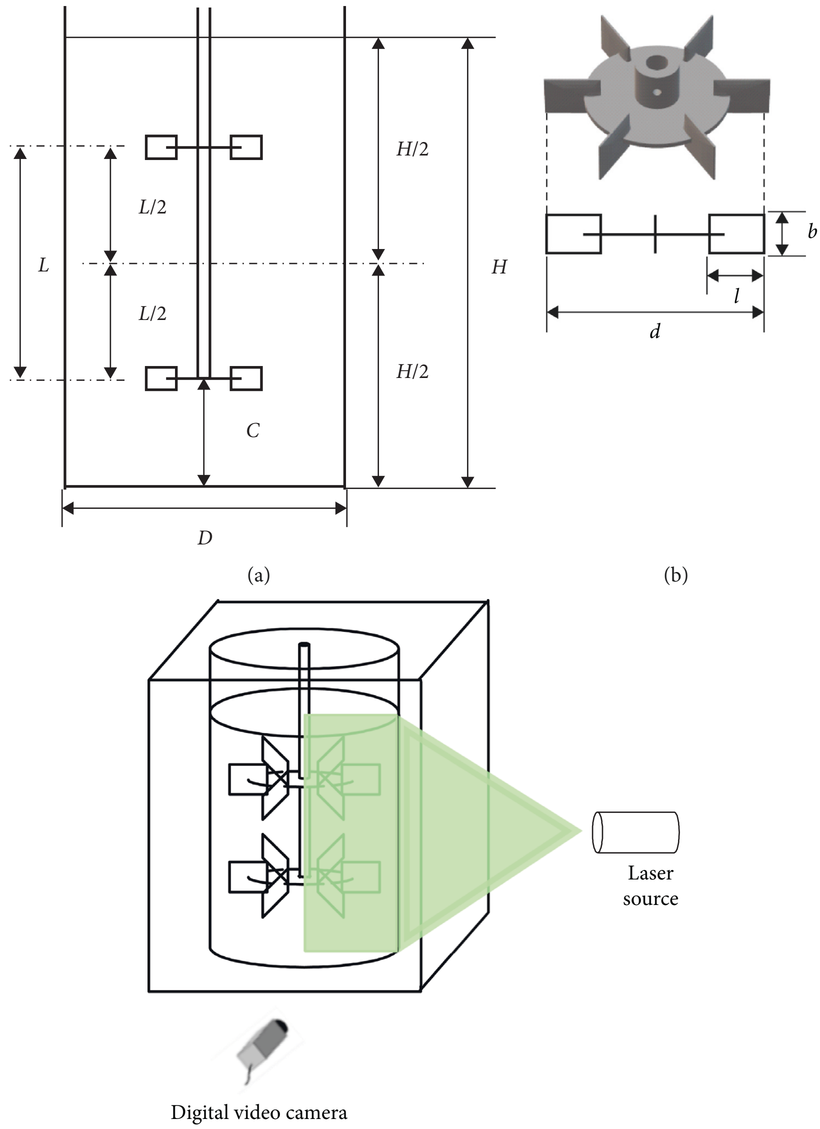


FIGURE 1: Experimental equipment. (a) Mixing vessel. (b) Turbine impeller. (c) Schematic illustration of PIV experiment.

TABLE 1: Specifications of the impellers.

Impeller no.	d/D (—)	b/d (—)	l/d (—)	d_C/d (—)	n_P (—)
1	0.54	0.20	0.25	0.65	6
2	0.43	0.20	0.25	0.65	6
3	0.43	0.30	0.25	0.79	6
4	0.43	0.40	0.25	0.79	6
5	0.39	0.20	0.25	0.69	6

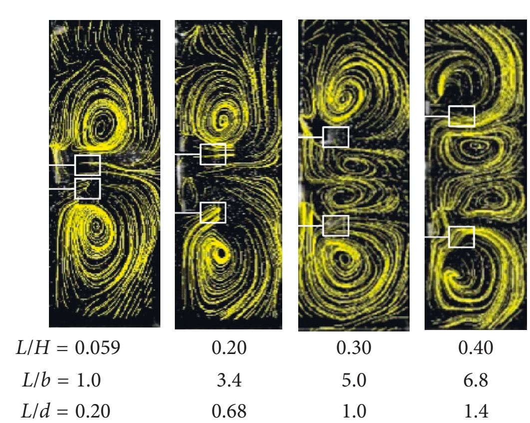
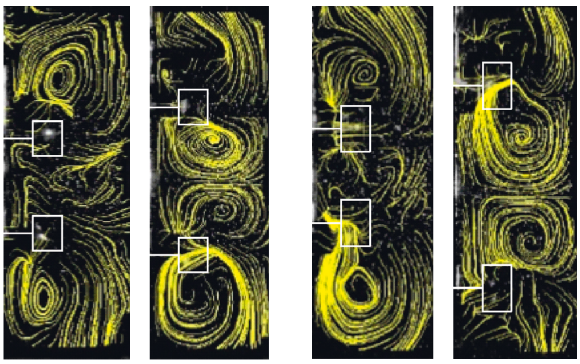


FIGURE 2: Streamlines with different impeller spacings at $Re = 8$ ($d/D = 0.43$, $b/d = 0.20$, $H/D = 1.5$).

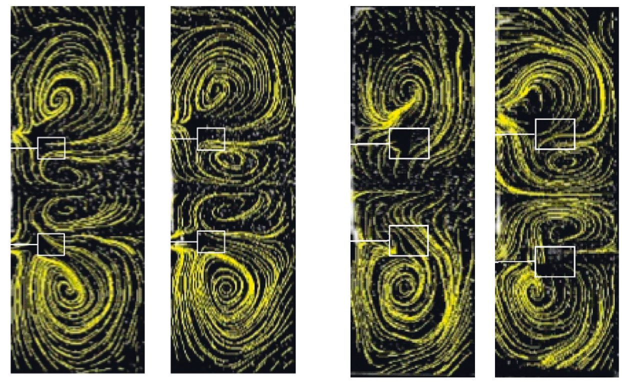
Figure 3 shows the effect of the impeller blade height on the flow pattern between the impellers. Figures 3(a) and 3(b) show the streamlines with $b/d = 0.3$ and 0.4, respectively. In Figure 2, which shows the streamlines with $b/d = 0.2$, the impeller functions independently at $L/H = 0.30$. However, the impellers with $b/d = 0.3$ or 0.4 do not function independently at $L/H = 0.30$. We focused on the ratio of



$L/H = 0.30$ 0.44 $L/H = 0.30$ 0.58
$L/b = 3.4$ 5.0 $L/b = 2.5$ 5.0
$L/d = 1.0$ 1.5 $L/d = 1.0$ 2.0

(a) (b)

Figure 3: Effect of impeller blade height on flow between impellers. (a) $b/d = 0.3$. (b) $b/d = 0.4$ at $\mathrm{Re} = 8$ ($d/D = 0.43$, $H/D = 1.5$).



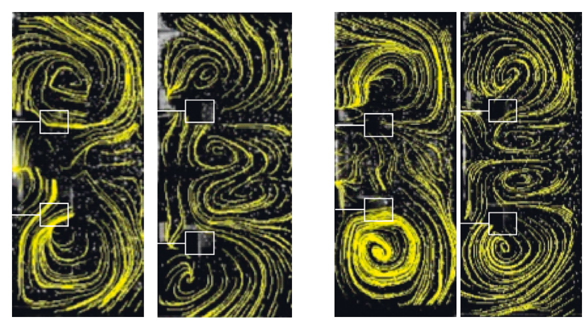
$L/H = 0.25$ 0.3 $L/H = 0.30$ 0.37
$L/b = 5.0$ 5.7 $L/b = 4.0$ 5.0
$L/d = 1.0$ 1.1 $L/d = 0.80$ 1.0

(a) (b)

Figure 4: Effect of impeller diameter on flow between impellers at $\mathrm{Re} = 8$ ($b/d = 0.2$, $H/D = 1.5$). (a) $d = 0.072$ m. (b) $d = 0.10$ m.

impeller spacing to impeller height, L/b. In Figures 2 and 3, the impellers function independently at $L/b = 5.0$ under each combination. Furthermore, we investigated the effect of impeller diameter on the flow between the impellers. Figure 4 shows the streamlines with different impeller diameters, where $d/D = 0.39$ and 0.54. The flow interaction between the impellers is independent of the impeller diameter, but it is dependent on the impeller blade height. Figure 5 shows the effect of liquid depth on the flow field between the impellers. For each liquid depth, each impeller functions independently at $L/b = 5.0$.

The circulation loops of the upper and lower impellers cause flow interaction between the impellers. The circulation loops are generated near the blade-edge corner and move upward and downward with increasing blade height. Therefore, the flow between impellers depends on the blade height, even if the impeller spacing is constant. In fact, the flow between impellers is related to L/b.



$L/H = 0.30$ 0.44 $L/H = 0.30$ 0.33
$L/b = 3.4$ 5.0 $L/b = 4.5$ 5.0
$L/d = 0.69$ 1.0 $L/d = 0.9$ 1.0

(a) (b)

Figure 5: Effect of liquid depth on flow between impellers at $\mathrm{Re} = 8$ ($d/D = 0.43$, $b/d = 0.2$). (a) $H/D = 1.0$. (b) $H/D = 1.3$.

3.2. Power Consumption. Figure 6 shows the power number calculated from power consumption under an impeller Reynolds number $\mathrm{Re} \leq 10$. The x-axis is the ratio of impeller spacing to impeller height, L/b, and the y-axis is the ratio of the power number of a double impeller, $N_{\mathrm{P,double}}$, to the power number of a single impeller of the same size, $N_{\mathrm{P,single}}$. The ratio $N_{\mathrm{P,double}}/N_{\mathrm{P,single}}$ increases with L/b until $L/b = 5.0$, and $N_{\mathrm{P,double}}/N_{\mathrm{P,single}}$ is constant at $L/b \geq 5.0$. The constant value is 2, which means that $N_{\mathrm{P,double}}$ is twice $N_{\mathrm{P,single}}$. The PIV observation of streamlines suggests that the upper impeller and lower impeller work independently at $L/b \geq 5.0$.

Figure 7 shows the power consumption at various distances between the lower impeller and off bottom. In other words, Figure 7 shows the effect of fluid height above the upper impeller. According to Figure 7, the distance between the lower impeller and the off bottom and, consequently, the fluid height above the upper impeller have no effect on power consumption in the laminar region. This result is in good agreement with our previous work [18], which shows that power consumption in the laminar region is independent of the distance between the impeller and the off bottom. Therefore, the power consumption of a double impeller is only dependent on L/b at each distance.

Figure 8 shows the result of the correlation of power consumption of the double impeller. The y-axis is the ratio of $N_{\mathrm{P}} \cdot \mathrm{Re}$ for a double impeller, $(N_{\mathrm{P}} \cdot \mathrm{Re})_{\mathrm{double\ impeller}}$, to the $N_{\mathrm{P}} \cdot \mathrm{Re}$ for a double impeller at $L/b = 1.0$, $(N_{\mathrm{P}} \cdot \mathrm{Re})_{L/b=1}$, because $N_{\mathrm{P}} \cdot \mathrm{Re}$ is constant in the laminar region. The solid line in Figure 8 represents the correlation, which is expressed as

$$\frac{(N_{\mathrm{P}} \cdot \mathrm{Re})_{\mathrm{double}}}{(N_{\mathrm{P}} \cdot \mathrm{Re})_{L/b=1}} = \left(\frac{L}{b}\right)^{0.20}, \qquad 1 \leq L/b < 5. \tag{5}$$

The dashed line in Figure 8 represents the relative error, which is ±5%. This correlation is in good agreement with the experimental values. $(N_{\mathrm{P}} \cdot \mathrm{Re})_{L/b=1}$ is equal to that of a single impeller with a blade height twice the blade height of a double impeller. The $N_{\mathrm{P}} \cdot \mathrm{Re}$ for a single impeller can be calculated from the correlation developed by many

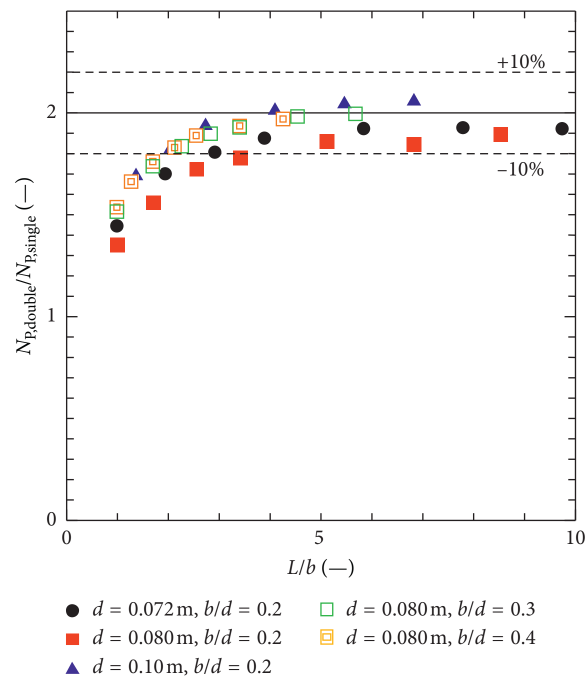


FIGURE 6: Effect of impeller spacing on power number at Re = 6. The solid line represents the constant value 2. The dotted lines represent the relative error of ±10% from the solid line.

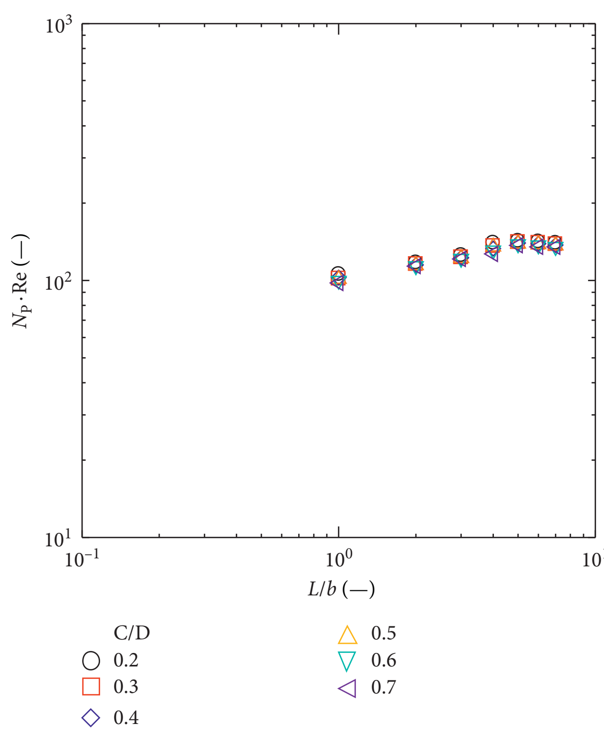


FIGURE 7: Effect of distance between the lower impeller and the off bottom on power consumption ($d/D = 0.43$, $b/d = 0.2$).

researchers [19–21]. For example, the correlation developed by Nagata et al. [20] can be expressed as

$$N_P = \frac{A}{\mathrm{Re}} + B\left(\frac{10^3 + 1.2\,\mathrm{Re}^{0.66}}{10^3 + 3.2\,\mathrm{Re}^{0.66}}\right)^p \left(\frac{H}{D}\right)^{(0.35+b/D)} (\sin\theta)^{1.2}, \quad (6)$$

$$A = 14 + (b/D)\left\{670\,(d/D - 0.6)^2 + 185\right\}, \quad (7)$$

$$B = 10^{\{1.3-4(b/D-0.5)^2-1.14(d/D)\}}, \quad (8)$$

$$p = 1.1 + 4\,(b/D) - 2.5\,(d/D - 0.5)^2 - 7\,(b/D)^4. \quad (9)$$

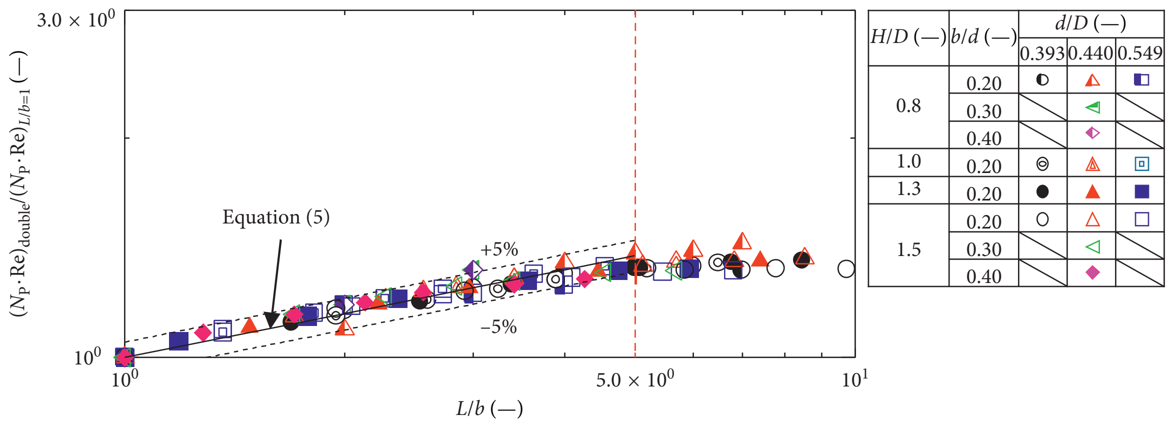


Figure 8: Correlation of power consumption for a double impeller. The solid line represents equation (5). The dotted lines represent the relative error of ±5% from equation (5). The red dashed line represents $L/b = 5.0$.

Therefore, the power consumption for a double impeller at an arbitrary impeller spacing in the range $1 \leq L/b < 5$ can be estimated by equation (5), and the power consumption for an impeller spacing of $5 \leq L/b$ can be estimated as twice that of a single impeller with the same size.

4. Conclusion

In this study, the effect of impeller spacing between impellers on the flow pattern and power consumption was investigated using turbine impellers under the laminar region. We first investigated the effect of impeller spacing on the flow pattern by using PIV. The change of flow pattern is described based on the ratio of impeller spacing between impellers to the impeller blade height, L/b. At $L/b = 1.0$, the double impeller functions like a single impeller. The flow between impellers interacts in the range $1 < L/b < 5$. Each of the double impeller functions independently in the range $5 \leq L/b$.

The power consumption of a double impeller in the range $1 \leq L/b < 5$ can be simply correlated by equation (5), and that of a double impeller in the range $5 < L/b$ is twice that of a single impeller of the same size. The power consumption is closely related to the flow pattern. A chemical engineer can estimate the power consumption of a double impeller by using this developed correlation.

Nomenclature

A: Proportional constant used in equation (6) (–)
b: Impeller blade height (m)
B: Proportional constant used in equation (6) (–)
d: Impeller diameter (m)
d_c: Impeller disc diameter (m)
d_p: Tracer particle diameter (m)
D: Vessel inner diameter (m)
H: Liquid depth (m)
l: Impeller width (m)
L: Impeller spacing (m)
L_c: Characteristic length (m)
n: Impeller rotational speed (1/s)
n_P: Number of blades (–)
N_P: Power number $(= P/\rho_f n^3 d^5)$ (–)
p: Exponent used in equation (6) (–)
P: Power consumption (W)
Re: Reynolds number $(= \rho_f n d^2/\mu)$ (–)
T: Shaft torque (N·m)
T_c: Characteristic time of flow (s)
$T_{c,min}$: Minimum characteristic time of flow (s)
u_{ps}: Settling velocity (m/s)
U: Characteristic velocity (m/s)

Greek letters

ρ_f: Fluid density (kg/m^3)
ρ_p: Tracer particle density (kg/m^3)
θ: Angle of blades to the horizontal plane (–)
μ: Fluid viscosity (Pa·s)
τ_0: Particle time constant of passive tracer (s)
$\tau_{0,max}$: Maximum particle time constant of passive tracer (s).

Data Availability

The experimental data used to support the finding of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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