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journal or publication title	Journal of chemical engineering of Japan
volume	42
number	1
page range	6-9
year	2009-01-20
URL	http://id.nii.ac.jp/1476/00005413/

doi: 10.1252/jcej.08we222(http://dx.doi.org/10.1252/jcej.08we222)

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Keywords: Mixing, Agitation, Power Consumption, Correlation, Propeller Impeller

Power consumption in unbaffled and baffled agitated vessels with propeller and pfaudler type impellers is measured over a wide range of Reynolds numbers from laminar to turbulent flow regions. The power correlation for the propeller and pfaudler type impellers is derived from modification of the previously proposed power correlation for a paddle impeller. The calculated correlation values agree well with experimental ones, and the same correlation can be applied to both propeller and pfaudler type impellers.

Introduction

Mixing and agitating vessels are widely used in chemical, biochemical, food and other industries. Power consumption is the most important parameter to estimate mixing performance. To estimate power consumption, the correlation of Nagata *et al.* (1956) has traditionally been used. However, this correlation was developed for two-blade paddle impellers, which do not always have the same numerical values of power consumption as those for multi-blade impellers. Kamei *et al.* (1995, 1996) and Hiraoka *et al.* (1997) developed the new correlation of power consumption shown in **Table 1**, and this correction is more accurate than Nagata's. However, the new correlation also cannot calculate the power consumption for other types of impellers, such as propeller and pfaudler type impellers used as axial flow impellers.

The propeller and pfaudler type impellers are used for low-viscosity liquid and solid － liquid suspensions, and the propeller type has been widely used in vessels ranging from portable type to large tanks. There are no correlations for these impellers. Therefore, we have developed a new correlation of power consumption for propeller and pfaudler type impellers, based on the correlations of Kamei and Hiraoka.

1. Experimental

A schematic diagram of a mixing vessel is shown in **Figure 1**. The vessel for the measurement of power consumption is a flat-bottom cylindrical vessel of inner diameter D = 200 mm. Three kinds of baffled conditions were used: unbaffled, four baffles of $B_W = D/10$ (i.e. the standard baffled condition), and fully baffled. The baffles were plate type. Also used were two kinds of impellers, a propeller and a pfaudler type, as shown in **Figure 2**. These propellers are not the marine type that have a constant pitch ratio; instead, they are variable pitch impellers, which are similar to pitched paddle impellers. The diameter, blade width and blade angle are shown in **Table 2.** The propeller impeller was symmetrically set up at one-half the level of the liquid depth (C/H = 0.5) and at one-fourth (C/H = 0.25) to obtain down-flow. The pfaudler type impeller was set up at the same level as the propeller (C/H = 0.25, 0.5) as well as slightly above the bottom (bottom clearance of 1 mm). For measurement of the power consumption, the liquids used were desalted water and varying starch-syrup solutions (μ = 0.003－13 Pa・s). The liquid was filled to the height equal to the vessel diameter ($H = D$). The power consumption P (=$2\pi nT$) was measured with the shaft torque T and rotational speed n by using a torque meter (ST-3000, Satake Chemical Equipment Mfg., Ltd.). The range of rotational speed was from 60 to 540 rpm to avoid a large vortex at the liquid-free surface of the vessel center.

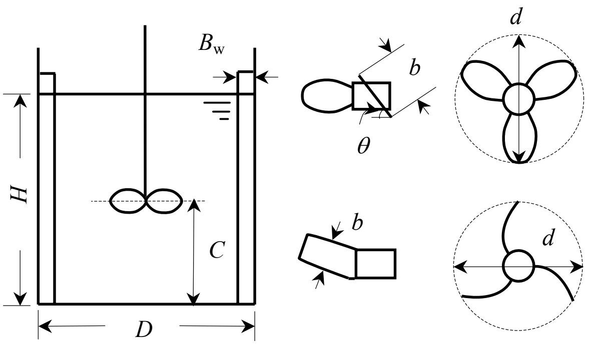

Fig. 1 Schematic diagram of experimental apparatus

Table 1 Correlation of power number for paddle impeller

Unbaffled condition

$$N_{P0} = \{[1.2\pi^4\beta^2]/[8d^3/(D^2H)]\}f$$

$$f = C_L/Re_G + C_t\{[(C_{tr}/Re_G) + Re_G]^{-1} + (f_\infty/C_t)^{1/m}\}^m \quad \text{(T.1)}$$

$$Re_d = nd^2\rho/\mu$$

$$Re_G = \{[\pi\eta\ln(D/d)]/(4d/\beta D)\}Re_d$$

$$C_L = 0.215\,\eta n_p(d/H)[1-(d/D)^2]+1.83(b\sin\theta/H)(n_p/2\sin\theta)^{1/3}$$

$$C_t = [(1.96X^{1.19})^{-7.8} + (0.25)^{-7.8}]^{-1/7.8}$$

$$m = [(0.71X^{0.373})^{-7.8} + (0.333)^{-7.8}]^{-1/7.8}$$

$$C_{tr} = 23.8(d/D)^{-3.24}(b\sin\theta/D)^{-1.18}X^{-0.74}$$

$$f_\infty = 0.0151(d/D)\,C_t^{0.308}$$

$$X = \gamma n_p^{0.7}b\sin^{1.6}\theta/H$$

$$\beta = 2\ln(D/d)/[(D/d)-(d/D)]$$

$$\gamma = [\eta\ln(D/d)/(\beta D/d^5)]^{1/3}$$

$$\eta = 0.711\{0.157 + [n_p\ln(D/d)]^{0.611}\}/\{n_p^{0.52}[1-(d/D)^2]\}$$

Baffled condition

$$N_P = [(1+x^{-3})^{-1/3}]N_{Pmax}$$

$$x = 4.5(B_w/D)n_B^{0.8}/N_{Pmax}^{0.2} + N_{P0}/N_{Pmax}$$

Fully baffled condition

$$N_{Pmax}\ \left\{\begin{array}{ll} = 10(n_p^{0.7}b/d)^{1.3} & (n_p^{0.7}b/d) \leqq 0.54 \\ = 8.3(n_p^{0.7}b/d) & 0.54 < (n_p^{0.7}b/d) \leqq 1.6 \\ = 10(n_p^{0.7}b/d)^{0.6} & 1.6 < (n_p^{0.7}b/d) \end{array}\right.$$

Table 2 Geometry of impellers used

Propeller 1	**Propeller 2**	**Pfaudler**
$d/D =$ **0.365**	$d/D = 0.345$	$d/D =$ **0.475**
$b/d = 0.253$	$b/d = 0.326$	$b/d = 0.126$
$n_p = 3$	$n_p = 3$	$n_p = 3$
$\theta = \pi/4$	$\theta = \pi/6$	$\theta = \pi/2$

Fig. 2 Photograph of propeller and pfaudler type impellers

2. Results and Discussion

2.1 Unbaffled condition

When the correlations in Table 1 were used for the propeller and pfaudler type impellers, the estimated values agreed with the measured ones in the laminar region, but the estimated ones were approximately 1.5－2 times as large as the measured ones in the transition and turbulent regions, as shown in **Figure 3**.

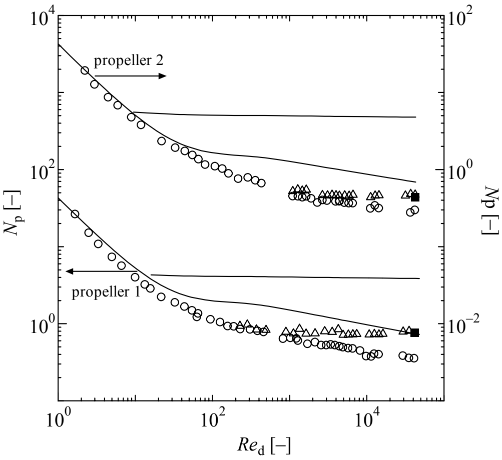

Fig. 3 Power correlation of Table 1 applied to propeller type impeller (—cal.; ○N_{P0}; △N_p; ■N_{pmax})

The correlations of Table 1 were developed for paddle and pitched paddle impellers. The blades of the propeller and pfaudler impellers do not have sharp edges. The laminar term C_L in Eq. (T.1) in Table 1 can be used without modification. Because the deviation from correlations to measured values in the turbulent region was large, the turbulent terms C_t and m in Table 1 were modified to reproduce the measured values, as follows.

$$C_t=[(3X^{1.5})^{-7.8}+(0.25)^{-7.8}]^{-1/7.8} \qquad (1)$$

$$m=[(0.8X^{0.373})^{-7.8}+(0.333)^{-7.8}]^{-1/7.8} \qquad (2)$$

2.2 Fully baffled condition

As shown in Table 1, three kinds of equations must be used according to the value of the impeller similarity parameter ($n_p^{0.7}b/d$) for a paddle impeller; however, only one equation is needed for the propeller and pfaudler impellers, as follows.

$$N_{Pmax} = 6.5(n_p^{0.7}b\sin^{1.6}\theta/d)^{1.7} \qquad (3)$$

In the present experimental conditions, the values of N_{Pmax} for the propeller and pfaudler impellers were almost the same as N_p of the standard baffled condition, shown in Figure 3.

2.3 Baffled condition

The exponent of the blade angle term only was modified, as follows.

$$N_P = [(1+x^{-3})^{-1/3}]N_{Pmax}$$

$$x = 4.5(B_W/D)n_B^{0.8}/\{(2\theta/\pi)^{0.72}N_{Pmax}^{0.2}\} + N_{P0}/N_{Pmax} \qquad (4)$$

2.4 Correlations of power number

The new correlations for the propeller and the pfaudler type impellers are shown in **Table 3. Figures 4, 5** and **6** show the values estimated by Table 3 and the measured ones. The same correlations can be used for the propeller and the pfaudler type impellers, regardless of the clearance between the vessel bottom and impeller.

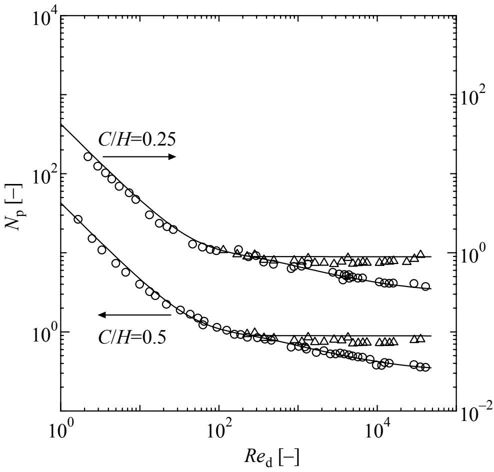

Fig. 4 Power diagram of propeller type impeller (1)
(—cal.; ○N_{P0}; △N_p)

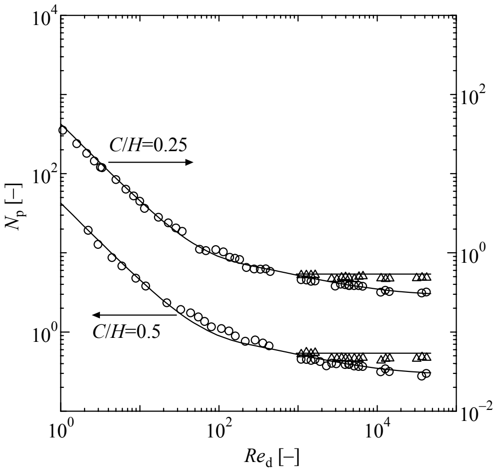

Fig. 5 Power diagram of propeller type impeller (2)
(—cal.; ○N_{P0}; △N_p)

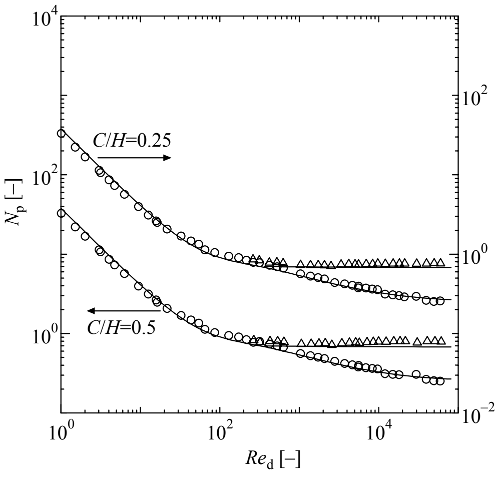

Fig. 6 Power diagram of pfaudler type impeller
(—cal.; ○N_{P0}; △N_p)

Table 3 New correlations of power number for propeller and pfaudler

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Unbaffled condition

$$N_{P0} = \{[1.2\pi^4\beta^2]/[8d^3/D^2H)]\}f$$

$$f = C_L/Re_G + C_t\{[(C_{tr}/Re_G) + Re_G]^{-1} + (f_\infty/C_t)^{1/m}\}^m$$

$$Re_d = nd^2\rho/\mu$$

$$Re_G = \{[\pi\eta\ln(D/d)]/(4d/\beta D)\}Re_d$$

$$C_L = 0.215\,\eta n_p(d/H)[1-(d/D)^2]+1.83(b\sin\theta/H)(n_p/2\sin\theta)^{1/3}$$

$$C_t = [(3X^{1.5})^{-7.8}+(0.25)^{-7.8}]^{-1/7.8}$$

$$m = [(0.8X^{0.373})^{-7.8}+(0.333)^{-7.8}]^{-1/7.8}$$

$$C_{tr} = 23.8(d/D)^{-3.24}(b\sin\theta/D)^{-1.18}X^{-0.74}$$

$$f_\infty = 0.0151(d/D)\,C_t^{0.308}$$

$$X = \gamma n_p{}^{0.7}b\sin^{1.6}\theta/H$$

$$\beta = 2\ln(D/d)/[(D/d)-(d/D)]$$

$$\gamma = [\,\eta\ln(D/d)/(\beta D/d)^5]^{1/3}$$

$$\eta = 0.711\{0.157 + [n_p\ln(D/d)]^{0.611}\}/\{\,n_p{}^{0.52}[1 - (d/D)^2]\}$$

Baffled condition

$$N_P = [(1 + x^{-3})^{-1/3}]N_{Pmax}$$

$$x = 4.5(B_W/D)n_B{}^{0.8}/\{(2\theta/\pi)^{0.72}N_{Pmax}{}^{0.2}\} + N_{P0}/N_{Pmax}$$

Fully baffled condition

$$N_{Pmax} = \quad 6.5(\,n_p{}^{0.7}b\,\sin^{1.6}\theta/d)^{1.7}$$

Conclusions

A new correlation of power consumption, based on the correlation of Kamei and Hiraoka, was developed for propeller and pfaudler type impellers, and it was shown that the estimated values of the power number agree very closely with the measured ones. In future work, this correlation will be expanded to other impellers.

Nomenclature

b	= height of impeller blade	[m]
C	= clearance between bottom and impeller	[m]
D	= vessel diameter	[m]
d	= impeller diameter	[m]
f	= friction factor	[−]
H	= liquid depth	[m]
N_P	= power number (=$P/\rho n^3d^5$)	[−]
N_{P0}	= power number in unbaffled condition	[−]
N_{Pmax}	= power number in fully baffled condition	[−]
n	= impeller rotational speed	[−]
n_b	= number of baffle plates	[−]
n_p	= number of impeller blades	[−]
P	= power consumption	[W]
Re_d	= impeller Reynolds number (=$nd^2\rho/\mu$)	[−]
Re_G	= modified Reynolds number	[−]
T	= shaft torque	[N・m]

θ = angle of impeller blade [－]

μ = liquid viscosity [Pa・s]

ρ = liquid density [kg/m^3]

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