POWER CONSUMPTION OF HELICAL RIBBON AGITATORS IN HIGHLY VISCOUS PSEUDOPLASTIC LIQUIDS

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Introduction

Most viscous liquids handled in chemical and food industries are non-Newtonian liquids. The agitation of these liquids in a vessel requires high power, and an accurate prediction of power consumption is, therefore, very important. One of the best impellers for the agitation of these liquids is a helical ribbon impeller. However, the power correlations published previously for helical ribbon impellers in non-Newtonian liquids do not agree with each other and are not available for the different geometries.

In this work, power consumption measurements for helical ribbon impellers of different geometrical variables were carried out under laminar flow conditions in pseudoplastic liquid, which is the most typical non-Newtonian liquid. On the basis of Metzner and Otto's method,[4] an empirical correlation for prediction of the power consumption of helical ribbon impellers in pseudoplastic liquid is proposed.

1. Basic Concept

The method proposed by Metzner and Otto[4] has been used very frequently for power correlation in the agitation of non-Newtonian liquids.[1-3,5,6] In this method, the effective shear rate in an agitation system was assumed to be proportional to the rotational speed of the impeller:

$$\dot{\gamma}_e = k_m \cdot N \tag{1}$$

where k_m depends on geometrical variables of impellers and properties of liquids. If k_m in Eq. (1) is given in advance, the apparent viscosity of the non-Newtonian liquid is evaluated from measurement of the flow curve by using the following equation:

$$\mu_a = \tau / \dot{\gamma}_e \tag{2}$$

For Newtonian liquids, power consumption of helical ribbon impellers can be expressed as:

$$N_P \cdot Re = C \tag{3}$$

where C is a geometrical constant. Assuming that this relation is valid for non-Newtonian liquids as well, the power for the non-Newtonian liquid can be calculated from replacing the Reynolds number in Eq. (3) with an apparent Reynolds number based on μ_a from Eq. (2).

Reversing the above-mentioned procedure, the values of k_m can be determined. That is, from the power measurement at a specified rotational speed of the impeller for a non-Newtonian liquid and a power correlation for Newtonian liquid in a given agitated vessel, the apparent viscosity for the non-Newtonian liquid is calculated as follows:

$$\mu_a = d^2 N \rho \frac{N_P}{C} = \frac{P}{d^3 N^2} \frac{1}{C} \tag{4}$$

The effective shear rate corresponding to this apparent viscosity is estimated from measurement of flow curve. Therefore, the value of k_m can be obtained from Eq. (1). If a correlation of k_m with geometrical variables of impellers and properties of liquid is given, a general estimation of power consumption of a non-Newtonian liquid becomes possible.

2. Experimental

The general configuration of a helical ribbon impeller is shown in **Fig. 1** and the geometrical variables of the impellers used are summarized in **Table 1**. The experimental procedure was as described in the previous papers for Newtonian liquid.[7,8] Aqueous solutions of corn syrup were used as Newtonian liquids. Aqueous solutions of carboxymethyl cellulose and mixtures of these solutions and corn syrup were used as pseudoplastic liquids. The rheological behavior of the pseudoplastic liquids could be expressed by the following power-law model:

$$\tau = K \cdot \dot{\gamma}^n \tag{5}$$

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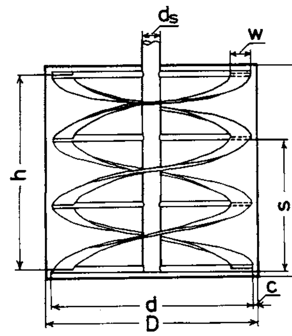


Fig. 1. Geometrical configuration of helical ribbon impeller.

Table 1. Geometrical variables and measured k_m for helical ribbon impellers

Geometry No.	c/D	s/D	w/D	k_m
DH1	0.0227	0.914	0.102	37.9
DH2	0.0623	0.966	0.101	24.7
DH3	0.0970	0.956	0.102	19.3
DH4	0.0583	0.643	0.102	32.7
DH5	0.0502	0.452	0.102	37.7
DH6	0.0404	1.26	0.102	28.2
DH7	0.0457	1.89	0.102	24.3
DH8	0.0448	0.912	0.0771	24.3
DH9	0.0449	0.916	0.128	28.8
DH10	0.0416	0.932	0.153	31.5
DH11	0.0431	0.914	0.203	30.5

$D=H=128$ mm $n_p=2$ $d_s/D=0.0938$.

where K and n are consistency and flow behavior indexes, respectively, and their values are shown in **Table 2**.

3. Results and Discussion

Geometrical variables of helical ribbon impeller can be used to estimate the constant C in Eq. (3), as described elsewhere.[7,8] From the power consumption measurements of Newtonian liquids, the values of C for impellers used in this work were determined. They agree with the estimated ones, and are used for determination of k_m according to the procedure described in Section 1.

The relations between the effective shear rate, $\dot{\gamma}_e$, and the rotational speed, N, are shown in **Fig. 2**. This figure shows that the value of k_m is independent of the properties of liquids used in this work.

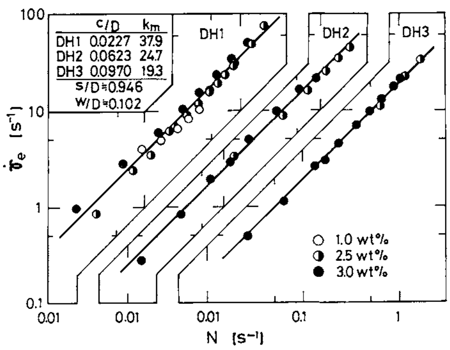
The values of k_m determined experimentally are summarized in Table 1. The relation between k_m and each of three geometrical ratios, c/D, s/D and w/D, is shown in **Fig. 3**. This figure indicates that k_m can be correlated by the following equation:

$$k_m = \alpha(c/D)^{\beta}(s/D)^{\gamma}(w/D)^{\delta} \tag{6}$$

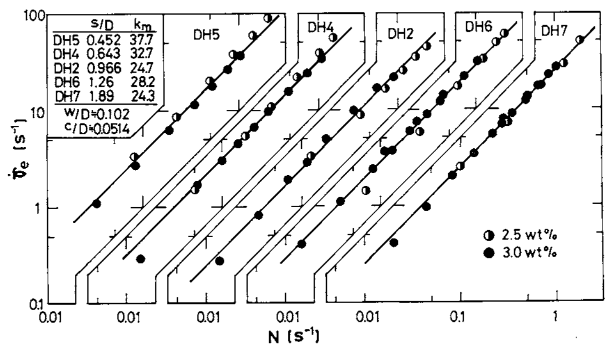
The four constants in Eq. (6) were determined by a multiple non-linear regression using the experimental data shown in Table 1. The values of α, β, γ and δ were 11.4, -0.411, -0.361 and 0.164, respectively. **Figure 4** shows the comparison of calculated and experimental values of k_m obtained in this work and other published sources.[2,3,5,6] The agreement between them is satisfactory.

Table 2. Properties of test liquids

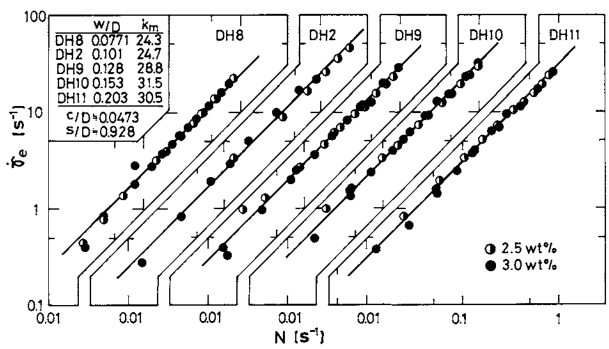
Liquid No.	n [—]	K [Pa·s^n]
1.0 wt% CMC	0.768–0.770	2.22–2.46
2.5 wt% CMC	0.543–0.566	1.20–1.72
3.0 wt% CMC	0.443–0.473	4.12–6.33



(a) effect of clearance



(b) effect of impeller pitch



(c) effect of blade width

Fig. 2. Relations between effective shear rate and rotational speed.

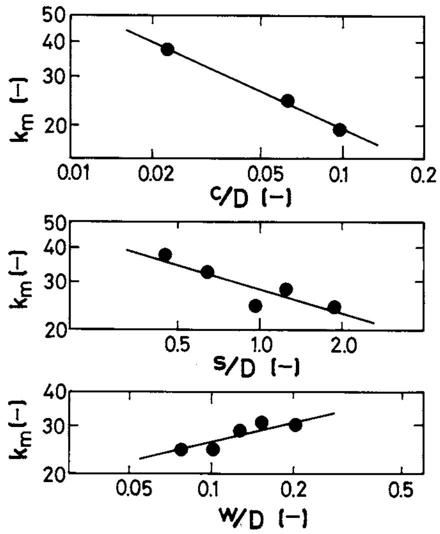


Fig. 3. Relation between k_m and each of three geometrical ratios.

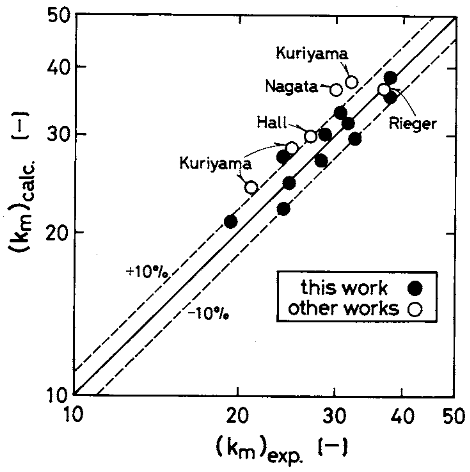


Fig. 4. Correlation of k_m.

Nomenclature

C	=	geometrical constant in Eq. (3)	[—]
c	=	clearance between blades and wall	[m]
D	=	diameter of vessel	[m]
d	=	diameter of impeller	[m]
d_s	=	diameter of shaft	[m]
H	=	height of vessel	[m]
h	=	height of impeller	[m]
K	=	consistency index	[$Pa \cdot s^n$]
k_m	=	constant in Eq. (1)	[—]
N	=	rotational speed of impeller	[s^{-1}]
N_P	=	power number ($=P/\rho d^5 N^3$)	[—]
n	=	flow-behavior index	[—]
P	=	power consumption	[W]
Re	=	Reynolds number ($=d^2 N\rho/\mu$)	[—]
s	=	impeller pitch	[m]
w	=	blade width	[m]
$\alpha, \beta, \gamma, \delta$	=	constants in Eq. (5)	[—]
$\dot{\gamma}$	=	shear rate	[s^{-1}]
$\dot{\gamma}_e$	=	effective shear rate in vessel	[s^{-1}]
μ	=	viscosity	[$Pa \cdot s$]
μ_a	=	apparent viscosity	[$Pa \cdot s$]
ρ	=	density	[$kg \cdot m^{-3}$]
τ	=	shear stress	[Pa]

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