POWER CORRELATION FOR ANCHOR AND HELICAL RIBBON IMPELLERS IN HIGHLY VISCOUS LIQUIDS

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A new power correlation for both anchor and helical ribbon impellers in highly viscous Newtonian liquids is proposed on the basis of a physical model developed from an analytical approximate expression for the drag of a plate in viscous liquids bounded by a plane wall. The correlation, obtained by inserting the empirical factor of geometrical variables in the above expression, shows good agreement with experimental data of power consumption of anchor and helical ribbon agitators obtained in this work and other literature.

Introduction

Liquid agitation is one of the most common unit operations in the chemical industry. For the design of mixing equipment, it is necessary to predict its power consumption. For impellers producing high stress in a small portion of the vessel, such as turbines and propellers, there is fairly extensive information about power consumption in the literature. However, the power correlations published previously for close-clearance impellers, such as anchor and helical ribbon impellers, are relatively limited. Most of them are empirical and are restricted to particular impellers. In particular, those for helical ribbon impellers are not satisfactory.

In this work, power consumption measurements for anchor and helical ribbon agitators were carried out under laminar flow conditions in Newtonian liquids,
Table 1 Geometrical variables of anchor and helical ribbon impellers

<table>
<thead>
<tr>
<th>Geometry No.</th>
<th>d</th>
<th>c/D</th>
<th>D/s</th>
<th>L</th>
</tr>
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<tr>
<td>Anchor impellers*</td>
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<td></td>
</tr>
<tr>
<td>AC1</td>
<td>11.52</td>
<td>0.0500</td>
<td></td>
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<tr>
<td>AC2</td>
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<td>0.0250</td>
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<td>AC3</td>
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<td>AC4</td>
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<td>AC5</td>
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<td>Helical ribbon impellers**</td>
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<td></td>
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<tr>
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<td>72.59</td>
</tr>
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</table>

* D=H=12.80 h=L=11.50 w/D=0.02 [r]/(°)=0.094
** D=H=12.80 h=12.50 w/D=0.102 d/d/D=0.094

1. Experimental

The vessels were transparent acrylic resin cylinders with a flat bottom and a flat lid. Most measurements were carried out in a vessel without a free surface. A vessel with a free surface was also used to account for the influence of the lid wall on power. The geometrical configurations of anchor and helical ribbon impellers used are shown in Fig. 1 and the geometrical variables of these impellers are summarized in Table 1. The impellers were rotated in a clockwise direction and pumped upwards at the blade in each run. Newtonian aqueous solutions of corn syrup were used, having viscosities in the range of 10-300 poise. Agitation power was measured by a rotating torque meter and viscosities of the liquid were obtained from a coaxial cylinder viscometer.

2. Results and Discussion

The results of power consumption measurements are presented in the form of relationship of power number ($N_p$) to Reynolds number ($Re$). The relations for anchor and helical ribbon agitators are shown in Figs. 2 and 3 respectively. From these figures, it follows that the relations can be written as $N_p \cdot Re = \text{const.}$ in the laminar flow region.

To correlate the power consumption with geometrical variables, it may be useful to adopt a physical model which can represent the system approximately. Based on an analytical approximate expression, we discuss power correlation used for both anchor and helical ribbon impellers.

2.1 Power correlation for anchor impellers

Fluid flow around an anchor blade in an agitated vessel is similar to that around a flat plate moving at a low speed in viscous liquid bounded by a plate as shown in Fig. 4 (a). On the basis of Oseen's linearized equations of motion, Takaishi\cite{1} derived analytical approximate expressions for the drag coefficient of an elliptical cylinder in viscous liquids bounded by a plane wall and carried out numerical calculations of the drag for various thickness ratios of the major-axis length to
the minor-axis length. The drag $D_r$ applied by the liquid to the plate per unit length can be represented by the following equation as a special case of the thickness ratio $\tau=0$.

$$D_r = \frac{3\nu U^2 w}{g_x} \cdot C_p = \frac{8\pi \mu U}{g_x} \cdot \frac{1}{2 \ln (4 + 8c/w) - 1}$$  \hfill (1)

If the curvature of the vessel wall is negligible, Eq. (1) is applicable to power correlation for anchor impellers. The torque $T_M$ produced by the rotation of the impeller is defined as follows:

$$T_M = D_r \cdot L \cdot \frac{d}{2} \cdot n_p$$

For anchor agitators having $n_p = 2$:

$$T_M = \frac{8\pi \mu U d L}{g_x} \cdot \frac{1}{2 \ln (4 + 8c/w) - 1}$$  \hfill (2)

Consequently, we obtain the power $P$.

$$P = \omega T_M = 2\pi N \cdot \frac{8\pi \mu U d L}{g_x} \cdot \frac{1}{2 \ln (4 + 8c/w) - 1}$$  \hfill (3)

The velocity $U$ is equal to that of the blade tip $\pi dN$. Equation (3) can be rewritten as follows:

$$N_p \cdot Re = \frac{16\pi^3}{2 \ln (4 + 8c/w) - 1} \frac{L}{d}$$  \hfill (4)

This equation is a theoretical power correlation for anchor impellers.

As shown in Fig. 5, this correlation agrees approximately with the experimental data at large $c/D$. But the discrepancy between Eq. (4) and the experimental results increases with a decrease in clearance between the blade and the wall. Therefore, an empirical factor of the clearance was introduced in Eq. (4) with the help of the experimental data. The result is given by

$$N_p \cdot Re = \frac{16\pi^3}{2 \ln (4 + 8c/w) - 1} \frac{L}{d} \cdot f(D/c)$$  \hfill (5)

where

$$f(D/c) = 1 + 0.00735(D/c)^{0.825}$$

2.2 Power correlation for anchor and helical ribbon impellers

An anchor impeller is considered as a variety of helical ribbon impeller which has its blades at a right angle to the direction of motion. The power correlation for helical ribbon impellers is related to that for anchor impellers by the blade angle. We consider that a plate with an arbitrary angle is moving at a low speed in viscous liquid as shown in Fig. 4 (b). This motion is similar to that of the helical ribbon impeller. In this case, the drag experienced by the plate will be mostly dependent on the force normal to the plate. Therefore, power correlation for helical ribbon impellers was obtained by modifying Eq. (5) in terms of blade angle $\theta_B$ on the basis of the experimental data. The correlation is given by

$$N_p \cdot Re = \frac{16\pi^3}{2 \ln (4 + 8c/w) - 1} \frac{L}{d} \cdot f(D/c) \cdot (\sin \theta_B)^{0.50}$$  \hfill (6)

where

$$\sin \theta_B = s / \sqrt{(\pi d)^2 + s^2}$$

The authors carried out power consumption measurements also for agitators with a free surface, but the differences between the agitators with and without a free surface were hardly noticeable. The results are summarized in Table 2. The effects of the lid wall on power seem to be negligible.

Equation (6) is compared with the experimental data obtained in this work and other literature.$^4$-$^9$,12)
in Fig. 6. In this figure, Eq. (6) is shown to be quite satisfactory for predicting power consumption of anchor and helical ribbon impellers.

Conclusion

On the basis of a physical model, a new power correlation is proposed which takes into consideration geometrical variables such as the clearance between the blade and the wall, the blade angle, the blade length, the blade width and the impeller diameter. The influence on power of the distance of the impeller from the lid is proved to be negligible. This correlation can be used for anchor as well as helical ribbon impellers and shows good agreement with experimental data.

Nomenclature

\[ C_D = \text{drag coefficient} \quad \text{[cm]} \]
\[ e = \text{clearance between impeller and vessel wall} \quad \text{[cm]} \]
\[ D = \text{vessel diameter} \quad \text{[cm]} \]
\[ D_s = \text{shaft diameter} \quad \text{[cm]} \]
\[ g = \text{gravitational constant} \quad \text{[g/cm/G/sec}^2\text{]} \]
\[ H = \text{height of vessel} \quad \text{[cm]} \]
\[ h = \text{height of blade} \quad \text{[cm]} \]
\[ L = \text{length of blade} \quad \text{[cm]} \]
\[ N = \text{rotational speed of the impeller} \quad \text{[sec}^{-1}\text{]} \]
\[ N_p = \text{power number} \quad \text{[--]} \]
\[ n_p = \text{number of blades} \quad \text{[--]} \]
\[ p = \text{power consumption} \quad \text{[G/cm/sec]} \]
\[ Re = \text{Reynolds number} \quad \text{[--]} \]
\[ s = \text{impeller pitch} \quad \text{[cm]} \]
\[ T = \text{torque acting on impeller} \quad \text{[G/cm]} \]
\[ t = \text{thickness ratio of major-axis length to the minor-axis length of an elliptical cylinder} \quad \text{[--]} \]
\[ U = \text{velocity of uniform flow} \quad \text{[cm/sec]} \]
\[ w = \text{blade width} \quad \text{[cm]} \]
\[ \theta_B = \text{blade angle} \quad \text{[rad]} \]
\[ \mu = \text{viscosity} \quad \text{[g/cm/sec]} \]
\[ \rho = \text{density} \quad \text{[g/cm}^3\text{]} \]
\[ \omega = \text{angular velocity of impeller} \quad \text{[rad/sec]} \]

Literature Cited