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Study of various curved-blade impeller geometries on power consumption in stirred vessel using response surface methodology

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1. Introduction

Several types of impellers have been designed and created for various applications in chemical, pharmaceutical, petroleum and food processes through standard stirred vessels. Paddled; propellers and turbines are among some of the common types of impellers used in mixing processes. Proper impeller selection for each process requires precise information about the viscosity of fluid, operating conditions, system flow regime, etc. [1]. Power drawn by a rotating impeller has a significant role in the design of the mixing systems and the best choices for impellers are those with the lowest power consumption [2]. Thus, a comparison of different impellers would be helpful in determining the choice of an appropriate impeller for a dispersion process. Several works determined the power number of a wide range of impellers designs such as down pumping 45° pitched blade turbines [3–6], up pumping 45° six pitched blade turbine [3] and Sawtooth impeller [6], Rushton turbine [7–11], Concave blade (semi circular) [3,9,12–14], 6SRGT Scaba [3,15,16], Propeller [4,17], Lightnin A6000 impellers [18], A310 Fluidfoil impellers [18], Prochem T [15,19], Parabolic bladed disc turbine [3] and curved pitched blade turbine [4] have performed through the stirred vessels. Table 1 shows some power number values for various impeller types.

Published literature on mixing showed the employment of different types of impellers for various applications but the Rushton turbine is still a very common and applicable type. However, there are several drawbacks associated with the Rushton turbine such as a considerable drop in the power input and mass transfer in the aerated system [9,20,21], in addition to high levels of shear stress in the district of the impeller and a non homogeneous spatial distribution of the energy dissipation rate inside the tank [22]. Compared to the Rushton turbine, Hydrofoil impellers, such as Prochem Maxflow T and Lightnin A315 show a much lower power reduction over a wide range of gas flow rates [23]. Moreover, the curved or hollow blade impellers, such as SCABA and concave blade turbines, also provide better gassed
**Nomenclature**

- \( N_{Re} \): Reynolds number, dimensionless
- \( P \): power required by the impeller, kg m^2/s^3
- \( \rho \): density, kg/m^3
- \( N \): rotational speed of impeller, rev/s
- \( D \): impeller diameter, m
- \( \mu \): viscosity, kg/s m
- \( \tau \): torque, Nm
- \( m \): mass defined by the load cell, kg
- \( g \): acceleration of gravity, 9.8, m/s^2
- \( d \): a distance from the motor to the central rod (Fig. 1), m
- \( Q \): flow rate of discharged gas through the impeller region, m^3/s
- \( D \): impeller diameter, m
- \( n \): number of variables
- \( \alpha \): distance of axial point from the center point
- \( \beta_0 \): constant coefficient
- \( \beta_1 \): quadratic coefficient
- \( \beta_2 \): linear effect
- \( \beta_{i,j} \): interaction coefficients
- \( x_1 \) and \( x_2 \): coded values

Experimental design technique is a very helpful technique to provide statistical models and giving better recognition of the interactions between the parameters. Furthermore, response surface methodology (RSM) is a compilation of mathematical and statistical techniques which can be employed to determine the importance of affecting parameters [27-29]. There is no information available in literature regarding the modeling of the interaction between angles, central disk size and Reynolds number with power number. Therefore, in this work central composite design (CCD) based on response surface methodology (RSM) were used to evaluate the effects of blades curvature angles and central disk sizes on power consumption in different Reynolds and flow numbers in stirred vessels and to prepare a model through experimental data.

2. **Experimental setup**

2.1. Setup

All the measurements were carried out in a 0.4 m diameter (T) flat bottom vessel which was constructed from a transparent scratch proof PerspeX. The tank was equipped with four equally spaced wall mounted baffles (B) of width, B = T/10. The ratio of impeller clearance (C) to tank diameter (T) followed the standard geometries and was equivalent to 0.133 m. The sparger was provided with 24 equally spaced holes of 0.002 m in diameter with the same outer diameter and impellers equivalent to 0.133 m.

![Diagram of load cell setup](image)

Fig. 1. Schematic of the load cell set-up to determine power number: (A) load cell; (B) connector; (C) rod; (D) a distance from the motor to the central rod; (E) panel; (F) motor; and (G) weight.

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Table 1

<table>
<thead>
<tr>
<th>Impeller type</th>
<th>( N_{Re} ) values</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down pumping 45° pitched blade turbines (PBT)</td>
<td>1.7 [5]</td>
<td></td>
</tr>
<tr>
<td>Down pumping 45° four pitched blade turbine</td>
<td>0.99 [6]</td>
<td></td>
</tr>
<tr>
<td>Down pumping 45° six pitched blade turbine</td>
<td>2.1 [4]</td>
<td></td>
</tr>
<tr>
<td>Savonius impeller</td>
<td>0.32 [6]</td>
<td></td>
</tr>
<tr>
<td>Concave blade (semi circular) impeller</td>
<td>2.8 [9]</td>
<td></td>
</tr>
<tr>
<td>Concave blade (semi circular) impeller</td>
<td>3.8 [12]</td>
<td></td>
</tr>
<tr>
<td>Concave blade (semi circular) impeller</td>
<td>2.8 [40]</td>
<td></td>
</tr>
<tr>
<td>Concave blade (semi circular) impeller</td>
<td>3.0 [13]</td>
<td></td>
</tr>
<tr>
<td>Lightnin 6000 impellers</td>
<td>0.23 [18]</td>
<td></td>
</tr>
<tr>
<td>A310 fluidlift impellers</td>
<td>0.30 [18]</td>
<td></td>
</tr>
<tr>
<td>Propeller</td>
<td>0.67 [17]</td>
<td></td>
</tr>
<tr>
<td>Curved pitched blade turbine</td>
<td>0.89 [4]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>2.41 [4]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>5.0 [45]</td>
<td></td>
</tr>
<tr>
<td>Corveax pitched blade turbine</td>
<td>2.29 [4]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>5.0 [7]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>5.18 [44]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>6.0 [8]</td>
<td></td>
</tr>
<tr>
<td>Standard six blade Rushton turbine</td>
<td>5.4 [9]</td>
<td></td>
</tr>
</tbody>
</table>
sparger was located concentrically to the impeller at a vertical position of 0.13 m below the turbine at the bottom of the vessel. Regardless of the position, the sparger always discharged gas toward the turbine region. Tap water was used directly as a working fluid and the liquid height was equal to the tank diameter (T). In advance of each test, the tank was filled with fresh water regularly. Meanwhile, the temperature was at about 25 °C (room temperature). A load cell was employed to measure weight or force for the determination of power. The load used in this work had different standard weights and the calibration curve was plotted using averaged mV and grams so as to increase the accuracy and the performance of the system. A schematic of the experimental set up and load cell design are illustrated in Fig. 1. Based on the objectives of this project, i.e., to use six curved blade turbines, it focused on six curved blade impellers with different blade curvature angles and central disc sizes. In addition, a comparison was also made with the well-known six straight bladed Rushton turbine. The description and schematic of each impeller is given in Fig. 2 and Table 2.

2.2. Power and power number determination

In the same geometrical systems, Reynolds number has a critical correlation with power consumption due to the dependency of flow regimes, whether it is laminar or turbulent. In other words, the power drawn is extremely dependent on Reynolds number \([7,10,30]\). Reynolds number \((N_R)\) is demonstrated in Eq. (1) which reveals the ratio of inertial forces to viscous forces.

\[
N_R = \frac{\rho ND^2}{\mu}
\]

The power variances have been investigated in aerated and un-aerated conditions with various types of impellers, speeds, tank geometries, etc. by several researchers \([7,20,31,32]\). The power number of impellers is evaluated using the following expression \([7,33]\):

\[
N_P = \frac{P}{\rho ND^3}
\]

![Fig. 2. The Schematic of different types of impellers utilized in this work: (1) 6RT; (2) 6 curved blade impellers; and (3) various curvature angles.](image)
Table 2  
Type of impellers investigated in the experimental part.

<table>
<thead>
<tr>
<th>No.</th>
<th>Impeller</th>
<th>Outer dia. (D) (cm)</th>
<th>Curvature angle</th>
<th>Central disk size</th>
<th>Blade length (mm)</th>
<th>Blade thickness (mm)</th>
<th>D/T</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 curve blade without central disk (ND)</td>
<td>13.3</td>
<td>180°</td>
<td>0</td>
<td>4.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>2</td>
<td>6 curve blade with 1/20 central disk (CB1/20)</td>
<td>13.3</td>
<td>180°</td>
<td>1/20</td>
<td>4.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>3</td>
<td>6 curve blade with 1/40 central disk (CB1/40)</td>
<td>13.3</td>
<td>180°</td>
<td>1/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>4</td>
<td>6 curve blade with 3/40 central disk (CB3/40)</td>
<td>13.3</td>
<td>180°</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>5</td>
<td>6 curve blade with 3/40 central disk (CB3/40)</td>
<td>13.3</td>
<td>180°</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>6</td>
<td>6 curve blade elliptical shape with 3/40 central disk (CB(ellipse))</td>
<td>13.3</td>
<td>180°</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>7</td>
<td>6 curve blade with 3/40 central disk (CB160°)</td>
<td>13.3</td>
<td>180°</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>8</td>
<td>6 curve blade with 3/40 central disk (CB140°)</td>
<td>13.3</td>
<td>180°</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
<tr>
<td>9</td>
<td>6 flat blade Rushton turbine with 3/40 central disk (RT)</td>
<td>13.3</td>
<td>0</td>
<td>3/40</td>
<td>3.3</td>
<td>2.0</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Generally, the power consumption is calculated directly from the measurements of the torque and the shaft speed onto which the impeller had been mounted using the following equation:

\[
P = 2\pi N T\tag{3}
\]

In this work, the power consumption was evaluated by the load cell setup. When a force is applied to it in a definite manner, a load cell produces an output signal that is relative to the applied force [34]. The following expression was used to determine the power consumption:

\[
P = 2\pi N T \frac{d}{d}
\]

2.3. Flow number determination

The relationship between the aerated and un-aerated power ratio \(P_{a}/P_{u}\) and the gas flow number, \(N_{Q}\), at a constant impeller speed, is commonly employed to express the effect of variations in the gas flow rate on the cavity structure and vessel hydrodynamics [35]. The Aeration number or gas flow number, \(N_{Q}\), is proportional to the gas flow divided by the impeller pumping capacity.

\[
N_{Q} = \frac{Q}{ND^3}\tag{5}
\]

2.4. Statistical analysis

Response surface methodology (RSM) is a compilation of mathematical and statistical techniques for modeling, analysis and determination of regression model equations and operating conditions through quantitative data of appropriate experiments [36,37]. RSM has already been verified as a reliable statistical tool in the investigation of some chemical engineering processes [27,38-41]. In this study, RSM design called central composite design (CCD) was employed as a proper experimental design with a minimum number of experiments to analyze the effect of the curvature angle and Reynolds number in addition to central disk size and Reynolds number on the power number [41,42]. Furthermore, this method was applied to analyze the effect of the curvature angle and flow number as well as central disk size and flow number on power ratio \(P_{a}/P_{u}\). With this method, a core factorial is created that forms a cube with sides that are two coded units in length (from \(-1\) to \(+1\) as noted in Table 3).

The coded values of each factor level, which are independent variables consisting of the Reynolds number, \(X_{1}\), angle size, \(X_{2}\), disc size, \(X_{3}\), flow number, \(X_{4}\), and their coded levels for the CCD are illustrated in Table 3.

The required number of experiments for the CCD method consists of \(2^{n}\) factorial runs with \(2n\) fixed axial runs and replicate tests at the center; where \(n\) is the number of variables. Thus, the total number of tests (\(N\)) is evaluated from:

\[
N = 2^{n} + 2n + n_{c}\tag{6}
\]

Hence, for the two variable sets consisting of “curvature angle, Reynolds number” and “disk size, Reynolds number”, 4 factorial runs, 4 fixed axial runs and 5 replications of center points were chosen. Replication numbers of center are employed to predict the experimental standard error of prediction. Therefore, the total number of experiments for each set of experiments of curvature angle, Reynolds number and disk size, Reynolds number with four variables is 13. The same operations were established on “flow number, disk size” and “flow number, angle” variables sets. The low and high levels are coded as \(-1\) and \(+1\), the independent variables are coded to the \((-1, 1)\) interval, respectively. The axial points are placed at \((\pm \alpha, 0)\) and \((0, \pm \alpha)\), where the distance of the axial point from center is \(\alpha\). The value of \(\alpha\) depends on the number of points in the factorial portion of the design. In fact, the value of \(\alpha\) can be calculated by Eq (7) [36].

\[
\alpha = (2)^{0.25}\tag{7}
\]

In this study, the value of \(\alpha\) was fixed at 1. Modification of the experimental data is done by a second-order polynomial regression model:

\[
y = \beta_0 + \sum_{i=1}^{4} \beta_i x_i + \sum_{i=1}^{4} \sum_{j=i+1}^{4} \beta_{ij} x_i x_j\tag{8}
\]

The variance analysis (ANOVA) is applied to verify the significance of the models, factors, coefficients and regression, statistically [41,43]. Design expert software (DOE) version 8.0.7.1, Stat-Ease, Inc., Minneapolis, USA, was employed to perform statistical analysis, and regression models. The complete design matrices of the experiments performed, together with the results obtained for both un-aerated and aerated system, are shown in Tables 4 and 5.

3. Results and discussion

3.1. Power number

In this study, the value of 5.9 was obtained for the power number of Rushton turbine in a Reynolds number range of
0.88 \times 10^5 to 2.75 \times 10^5. These results proved to be in a good agreement with literature reported power number values in a range of 5.0–6.0 [7,11.44–46]. In order to improve the accuracy of the results, the experiments were repeated three times. After computing the data, the power numbers against Reynolds number were plotted for various impellers.

3.1.1. Development of regression model for power number

The correlations between responses ($N_p$) and three independent parameters, Reynolds number, central disk size and curvature angle, were investigated through central composite design. Five runs were performed at the center point to determine the experimental error. Sequential model sums of squares were selected the highest order polynomial where the additional terms are significant and the model is not aliased. Experimental design software suggested a quadratic model. Table 4 displays the results of the experimental design as well as the experimental results. Regression analysis was performed to fit the quadratic model to the power number response in terms of central disk size and curvature angle.

Eqs. (9) and (10), shown below, express the relationship between $N_p (Y_1)$ with Reynolds number ($X_1$) and curvature angle ($X_2$) and also the relationship between $N_p (Y_2)$ with Reynolds number ($X_1$) and central disk size ($X_3$) in terms of coded factors:

$$Y_1 = 3.824483 + 0.325X_1 - 0.705X_2 - 0.1675X_1 X_2 - 0.07569X_1^2 + 0.23431X_2^2$$

Fig. 3. Predicted vs. actual value of power number ($N_p$) in terms of: (a) curvature angle and (b) central disk size.

Full text is available at:

http://www.sciencedirect.com/science/article/pii/S1876107012001691