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Numerical Simulation and Analysis of Power Consumption and Metzner-Otto Constant for Impeller of 6PBT

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Abstract: Majority of non-Newtonian fluids are pseudoplastic with shear-thinning property, which means that the viscosity will be different in different parts of the stirred tank. In such mixing process, it is difficult to predict accurately the power consumption and mean shear rate for designing novel impeller. Metzner-Otto method is a widely accepted method to solve these questions in mixing non-Newtonian fluids. As a result, Metzner-Otto constant will become a key factor to achieve an optimum way of economical mixing. In this paper, taking glycerine and xanthan gum solutions as research system, the power consumption, stirred by the impeller composed of perturbed six-bent-bladed turbine (6PBT) with differently geometrical characteristics in a cylindrical vessel, is studied by means of computational fluid dynamics (CFD). The flow is modeled as laminar and a multiple reference frame (MRF) approach is used to solve the discretized equations of motion. In order to determine the capability of CFD to forecast the flow process, the torque test experiment is used to measure the glycerine solution power consumption. The rheological properties of the xanthan gum solutions are determined by a Brookfield rheometer. It is observed that the power consumption predicted by numerical simulation agrees well with those measured using torque experiment method in stirring glycerine solution, which validate the numerical model. Metzner-Otto constant is almost not correlated with the flow behavior index of pseudoplastic fluids. This paper establishes the complete correlations of power constant and Metzner-Otto constant with impeller geometrical characteristics through linear regression analysis, which provides the valuable instructions and references for accurately predicting the power consumption and mean shear rate of pseudoplastic fluids in laminar flow, comparatively.

Keywords: impeller composed of perturbed six-bent-bladed turbine, pseudoplastic fluids, power constant, Metzner-Otto constant

1 Introduction

Stirred tanks are widely used in chemical industries and biotechnological processes for mixing highly viscous non-Newtonian fluids[1]. Majority of these non-Newtonian fluids are pseudoplastic with shear-thinning property, and some also possess a yield stress. The rheological complexities of pseudoplastic fluids can cause a variety of difficulties, including most important changes in viscosity during processing. For example, shear-thinning fluids are viscous at the beginning, and then once the shear rate is increased the viscosity will drops dramatically, as well as being different in different parts of the mixing tank. In these situations, it is difficult to predict accurately the power consumption and mean shear rate in a stirred vessel to achieve a optimum way of economical mixing. Apparent viscosity concept proposed by Metzner and Otto[2] has been adapted widely and become a classical method of solving the power consumption for mixing of non-Newtonian fluids. The concept assumes that the mean shear rate $\dot{\gamma}$ is proportional to the rotation speed of impeller, where the proportional coefficient k_s is referred to as the Metzner-Otto constant. The power curve of non-Newtonian fluids obtained using the Metzner-Otto method is consistent with that of Newtonian fluids. This explains the fact that the Metzner-Otto method is a widely used method to design impellers for non-Newtonian fluids applications[3–4]. As a result, the k_s value has become a key factor to predict power consumption. It is readily agreed that k_s is a function of impeller geometry, but there are some conflicting conclusions regarding the relationship between k_s and fluid rheological index n. For instance, BECKNER, et al[5], and SAWINSKY, et al[6], concluded that k_s decreases sharply as n increases. However, CALDERBANK, et al[7], SCHILO[8] and SESTAK, et al[3], found that k_s decreases weakly as n increases. TANGUY, et al[9], and CARREAU, et al[10], reported that k_s increases slowly with the increasing n. The work of POLLARD, et al[11] and RIEGER, et al[12] showed that k_s is a constant that should be insensitive to the rheological properties of the

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fluids in the laminar regime for any given impeller geometry. Generally, close-clearance impellers, such as anchors, helical screws or helical ribbons, are recommended for mixing highly viscous non-Newtonian fluids as the most effective mixers. However, such impellers, for example helical ribbons, are sensitive to highly shear-thinning behavior which reduces their mixing effectiveness[13].

The impeller composed of perturbed six-bent-bladed turbine (6PBT) is an improved shape on basis of six-bent-bladed turbine (6BT) with its good mixing performance and its capacity of operating over a wide viscosity range. The six bent blades are perturbed up and down, respectively, to generate the periodically changeable flow in a stirred tank and then induce the chaotic mixing of pseudoplastic fluids[14]. Therefore, the aim of this paper is to use computational fluid dynamics (CFD) as a tool to study the power consumption of the 6PBT impeller with different geometries in stirring pseudoplastic fluids possessing yield stress. The experimental power values are used to validate the CFD model. The influence of pseudoplasticity is analyzed using the classical approaches found in the literature, such as Metzner-Otto concept[2] and Rieger-Novak method[12]. This work provides the complete correlations of power constant and Metzner-Otto constant with impeller geometry. These results can be used to accurately predict the power consumption and mean shear rate of the pseudoplastic fluids in laminar flow region, comparatively.

2 Experimental Setup and Procedure

The experimental setup is shown in Fig. 1. The mixing vessel used in this work consists of a transparent cylindrical tank of diameter (T) 0.21 m. The flat-bottomed tank was fitted with four equally spaced flat baffles, each with a width (w) equal to $T/10$. The fluid height (H) was maintained constant at a height equal to the tank diameter. The 6PBT impeller was mounted on a centrally located shaft of diameter 0.016 m and driven by a variable-speed motor. The impeller was positioned at an off-bottomed clearance (C) of $T/3$ and backswept angle of blade is θ. Further details about the geometrical characteristics of the stirred tank are showed in Fig. 1. The torque and speed of the impeller were measured using a rotary-torque transducer.

A Newtonian fluid (glycerine solution) and seven types of opaque xanthan gum solutions in water at different mass concentrations ranging from 0.5 wt %–2.0 wt % were used in this work. The rheological properties of the fluids were determined by a Brookfield rheometer.

For Newtonian fluid, the viscosity is independent of the shear rate at a fixed temperature. The density ρ of glycerine solution measured is 1260 kg/m^3, and its viscosity η=0.799 Pa • s. Theoretical and experimental studies[15] have shown that the power number N_p is inversely proportional to the Reynolds number Re in the laminar flow:

$$N_p Re = K_p, \tag{1}$$

$$Re = \rho N D^2 / \eta, \tag{2}$$

where N is impeller speed, and D is impeller diameter.

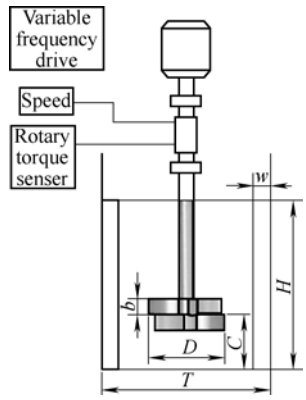


Fig. 1. Experimental setup

The power consumption P drawn by the impeller, was computed by means of the torque

$$P = 2\pi N \boldsymbol{M}, \tag{3}$$

where $\boldsymbol{M}$ is the moment vector about the center of the impeller.

Then the power number N_p was calculated as follows

$$N_p = P / \rho N^3 D^5. \tag{4}$$

The xanthan gum solution is a pseudoplastic fluid with a yield stress. Thus, its rheology can be described by Herschel-Bulkley model[16-17]:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_y + K\dot{\gamma}^n, \tag{5}$$

where $\boldsymbol{\tau}$, $\boldsymbol{\tau}_y$, K, $\dot{\gamma}$ and n are shear stress, yield stress, consistency index, shear rate and flow behavior index, respectively.

Table 1 summarizes the rheological parameters of xanthan gum solutions with seven mass concentrations based on measured data.

Table 1. Rheological parameters of xanthan gum solutions

Mass content w/%	Consistency index K/(Pa • s^n)	Flow behavior index n	Yield stress $\boldsymbol{\tau}_y$ /Pa
0.50	0.24	0.67	0.59
0.75	1.45	0.45	0.75
1.00	3.53	0.38	3.10
1.25	7.50	0.32	4.45
1.50	12.70	0.26	7.28
1.75	19.50	0.25	9.30
2.00	28.60	0.24	13.30

Metzner-Otto correlation was used to obtain apparent Reynolds number for Herschel-Bulkley fluids. According to this correlation, the mean shear rate can be related to the impeller speed by

$$\dot{\gamma}_{\mathrm{avg}} = k_{\mathrm{s}} N , \tag{6}$$

where k_s is Metzner-Otto constant and it is assigned a value of 11.5 for the radial flow impeller[18], $\dot{\gamma}_{avg}$ is mean shear rate.

The mean shear rate can be used to evaluate the apparent viscosity η_a of the solutions using Herschel-Bulkley rheological model:

$$\eta_{\mathrm{a}} = \frac{\boldsymbol{\tau}}{\dot{\gamma}_{\mathrm{avg}}} = \frac{\boldsymbol{\tau}_{\mathrm{y}} + K\left(k_{\mathrm{s}} N\right)^{n}}{k_{\mathrm{s}} N} . \tag{7}$$

The apparent Reynolds number Re^* can be defined as

$$Re^* = \frac{k_{\mathrm{s}} \rho N^2 D^2}{\boldsymbol{\tau}_{\mathrm{y}} + K\left(k_{\mathrm{s}} N\right)^{n}} \tag{8}$$

Metzner-Otto and Rieger-Novak methods are widely used to solve k_s value. Metzner-Otto method defines Re_n and K_{pn} by

$$Re_{\mathrm{n}} = \rho N^{2-n} D^2 / K , \tag{9}$$

$$K_{\mathrm{pn}} = N_{\mathrm{p}} Re_{\mathrm{n}} , \tag{10}$$

where Re_n is Reynolds number for non-Newtonian fluids, K_{pn} is power constant for non-Newtonian fluids, it is a function of n, so that

$$k_{\mathrm{s}} = \left(\frac{K_{\mathrm{pn}}}{K_{\mathrm{p}}}\right)^{\frac{1}{n-1}} . \tag{11}$$

The k_s value can be directly calculated from Eq. (11) and this method is also referred to as direct calculation of k_s.

Rieger-Novak method is denoted as the slope method based on the linearized Eq. (11):

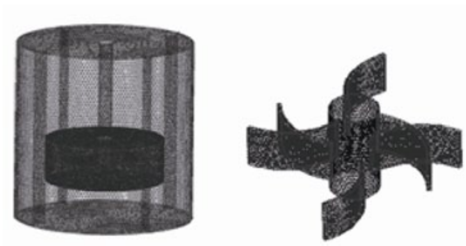
$$\ln K_{\mathrm{pn}} = \ln K_{\mathrm{p}} - (1-n)\ln k_{\mathrm{s}} . \tag{12}$$

If $\ln K_{pn}$ has a linear relationship with ($1-n$), it shows that k_s is independent of the flow behavior index *n*. Then the k_s value can be obtained from the slope of the straight line resulting from the plot of $\ln K_{pn}$ versus ($1-n$).

WANG, et al[19], found that when k_s is independent of the flow behavior index *n*, the slope method which avoids exponential operation, can be applied to predict k_s more accurately than direct calculation method. Therefore, Rieger-Novak method was adopted to determine k_p and k_s value through CFD data- processing in this work.

3 CFD Simulations

Fluent V6.3 (Fluent Inc.) was used to simulate the steady-state 3D flow field in laminar regime by solving the conservation of mass and momentum equations. It utilized the steady-state multiple reference frames (MRF) technique to realistically model the rotation of the impeller in the mixing vessel. This technique has been found to yield flow field predictions comparable to those obtained using the sliding mesh (SM) model[20–21]. A pre-processor (Gambit 2.3, Fluent Inc.) was used to discretize the flow domain with a tetrahedral mesh. The domain is segmented into two zones: stator zone and rotor zone (Fig. 2). Grid independence was verified by demonstrating the additional requirement on mesh cells that did not change the calculated power number and velocity magnitude in the regions of high velocity gradients close to the impeller blades by more than 3%. The original 3D mesh of the model for calculation domain had about 342 100 cells by taking the 6PBT impeller of $D/T = 0.5$, $b = T/10$ as an example. The number increased to about 660 500 to verify the grid independency. This increase changed the velocity and power number in regions of high velocity gradients by more than 3%. When the number of cells further increased to 1 086 432, the velocity and power number changed by less than 3% in the regions of high velocity gradients. Therefore, 1 086 432 cells were employed. The same mesh density was used to determine the number of cells for the other 6PBT impellers with differently geometrical characteristics.



(a) Stirred tank (b) 6PBT impeller

Fig. 2. Computational grids of the stirred system

No slip boundary conditions were imposed at the solid walls of the tank and the impeller, while the free surface at the top of the vessel was treated as a flat, shear free boundary. The xanthan gum solution rheology was modeled as Herschel-Bulkley fluid. Simulations were considered converged when the scaled residuals were below 1×10^{-5} for each transport equation. The original condition was determined as 0.

4 Results and Discussions

4.1 Validation of CFD model

CFD results for the power consumption of the 6PBT impeller ($D/T = 0.5$, $b/D = 0.2$ and $\theta = 30^\circ$) in glycerine solution at different rotational speeds were compared to experimental data (Fig. 3) to validate the model. These results show good agreement between calculated power consumption and the experimentally determined values, which validated the laminar flow model developed in this study.

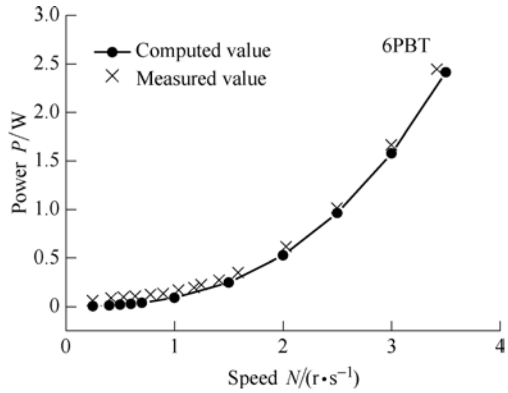


Fig. 3. Comparison between calculated powers and experimental values at different rotational speeds

Fig. 4 shows the calculated power number N_p versus the apparent Reynolds number Re^* in Newtonian and pseudoplastic fluids. It can be seen that the line with the slope of -1 fits the data quite well at Re^* less than 30, namely, the critical Reynolds number is 30 in laminar regime for pseudoplastic fluids. Based on the apparent viscosity method, all the power number curves for shear-thinning fluids are in coincidence with those of Newtonian fluids.

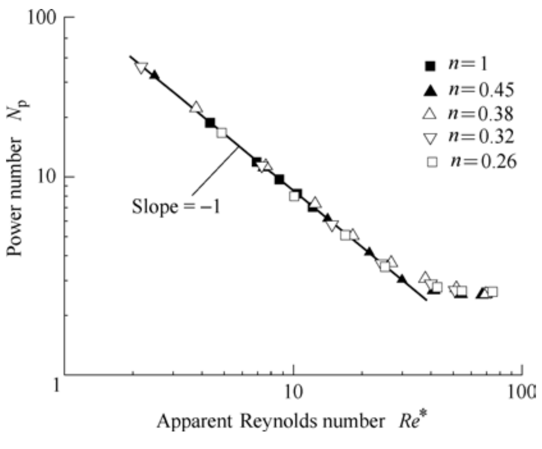


Fig. 4. Calculated power number vs. apparent Reynolds number for 6PBT impeller

4.2 CFD solution of k_s and K_p

Fig. 5 shows typical power consumption of the shear thinning fluids in laminar regime for illustrating the effects of rheological index (using 6PBT impeller with $D/T = 0.5$, $b/D = 0.2$ and $\theta = 30^\circ$). It is observed that power consumption decreases as a function of the level of rheological index for a given Re_n, and a group of parallel lines are also presented with the slope of -1 from a log-log plot of N_p versus Re_n. Thus, K_{pn} values are dependent on n value and decrease with n.

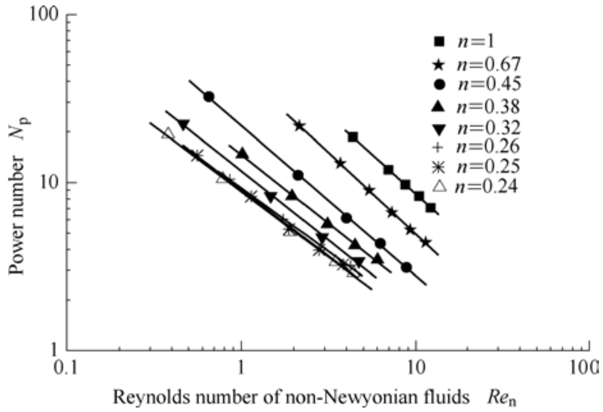


Fig. 5. Curve of N_p vs Re_n for 6PBT impeller

The relationship curve of ln K_{pn} versus $(1-n)$ for 6PBT impeller was plotted in Fig. 6 using the data from Newtonian and the pseudoplastic fluids based on Riger-Novak method. It can be seen that ln K_{pn} has a linear relationship with $(1-n)$. So k_s is independent of the flow behavior index n for 6PBT impeller, which is consistent with the conclusion of other radial impeller, according to the above analysis. It is determined that the value of k_s is 14.8 by the line slope, and the value of K_p is 84.2 as $n=1$.

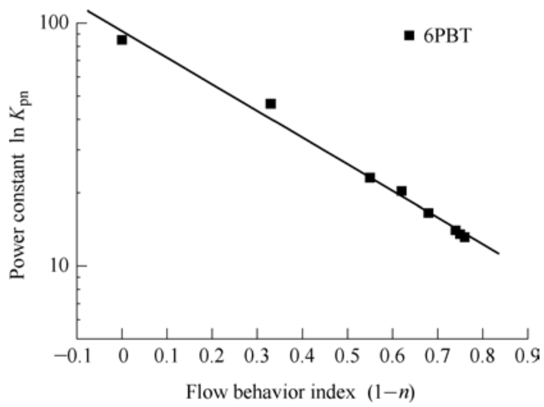


Fig. 6. Relationship of ln K_{pn} vs $(1-n)$ for 6PBT impeller

4.3 Complete correlations of K_p, as well as k_s, with impeller geometrical characteristics

The power consumptions of ten 6PBT impellers with differently geometrical characteristics in laminar regime were numerically calculated at rotatory speed of 15 r/min, 30 r/min, 45 r/min, 60 r/min, 75 r/min, and 90 r/min, respectively, by using xanthan gum solutions in water at seven mass concentrations. The K_p value of the 6PBT impeller could be solved by the above method, and the value of k_s was obtained by the line slope of ln K_{pn} versus $(1-n)$. These results are summarized in Table 2.

Table 2. K_p and k_s values for 6PBT impeller with differently geometrical characteristics

Diameter ratio D/T	Width to diameter ratio b/D	Backswept angle θ /(°)	Power constant K_p	Metzner-Otto constant k_s
0.45	0.22	45	82.8	14.6
0.55	0.22	60	85.4	13.3
0.7	0.16	45	73.3	11.9
0.7	0.2	30	84.9	12.7
0.5	0.16	45	68.5	15.1
0.6	0.124	45	68.2	15.9
0.55	0.16	60	60.8	10.9
0.65	0.2	60	83.2	12.4
0.65	0.124	45	78.9	10.8
0.5	0.2	30	80.9	13.8

For all the 6PBT impellers, a linear regression analysis on K_p and k_s data provided the following correlations in the laminar regime with a standard error of 7.31 % and 6.82%, respectively.

$$K_p = 152.93\left(\frac{D}{T}\right)^{-0.042}\left(\frac{b}{D}\right)^{0.371}\theta^{-0.040}, \quad (13)$$

$$k_s = 26.1\left(\frac{D}{T}\right)^{0.125}\left(\frac{b}{D}\right)^{0.396}\theta^{0.019}. \quad (14)$$

In order to verify the regression correlations, the power consumption of the 6PBT impellers in laminar regime was calculated again at the other rotatory speed of 9 r/min, 18 r/min, 24 r/min, 36 r/min, 54 r/min, and 72 r/min, respectively. Table 3 shows the computed results.

Table 3. K_p and k_s values of the 6PBT impellers at other speeds

D/T	b/D	θ /(°)	K_p	k_s
0.45	0.22	45	79.7	13.6
0.55	0.22	60	79.8	14.3
0.7	0.16	45	65.9	12.5
0.7	0.2	30	75.6	11.7
0.5	0.16	45	64.5	11.1
0.6	0.2	30	73.4	15.7
0.55	0.16	60	66.1	11.9
0.65	0.2	60	70.2	15.9
0.65	0.124	45	65.7	12.8
0.5	0.2	30	75.9	14.8

The following correlations were obtained by the linear regression analysis on K_p and k_s data:

$$K_p = 253.9\left(\frac{D}{T}\right)^{0.244}\left(\frac{b}{D}\right)^{0.382}\theta^{-0.105}, \quad (15)$$

$$k_s = 16.1\left(\frac{D}{T}\right)^{-0.465}\left(\frac{b}{D}\right)^{-0.036}\theta^{-0.139}. \quad (16)$$

The standard errors of the two correlations on K_p and k_s are 8.47 % and 7.61%, respectively. It can be seen that the standard errors have very slight variations. Therefore, the above two sets of K_p and k_s data (in Table 2 and Table 3) were put together and a linear regression analysis was conducted once again. K_p and k_s could be correlated by the following equations with a standard error of 6.80 % and 5.93 %, respectively.

$$K_p = 173.82\left(\frac{D}{T}\right)^{0.087}\left(\frac{b}{D}\right)^{0.343}\theta^{-0.057}, \quad (17)$$

$$k_s = 19.9\left(\frac{D}{T}\right)^{-0.177}\left(\frac{b}{D}\right)^{0.150}\theta^{-0.065}. \quad (18)$$

It is noticed that the values of the standard error drop slightly, which indicates that the computed value of K_p and k_s, obtained by the above three sets of the complete correlations, seems similar. The error of 6.80 % and 5.93 % on K_p and k_s data, respectively, is a fully acceptable result for engineering design. Here, Eqs. (17) and (18) are adopted as the final regression correlations in this study to solve the K_p and k_s value of the 6PBT impeller. The ranges of two correlations covered are $D/T = 0.45 \sim 0.7$, $b/D = 0.124 \sim 0.22$, $\theta = 30^\circ \sim 60^\circ$.

5 Conclusions

(1) Ten types of 6PBT impeller were investigated quantitatively in terms of power consumption as a function of impeller geometry and the pseudoplasticity of the fluid in the laminar region by using the CFD method. The numerical power consumption results with Newtonian fluid were in good agreement with the experimental data, which validated the laminar model developed in this study.

(2) A shift of the upper limit Reynolds number was observed as 30 in various shear thinning fluids for the laminar regime towards transitional flow regime.

(3) For 6PBT impeller, based on Rieger and Novak's method, the K_{pn} value is close dependent on n value and decrease with n. The ln K_{pn} has a linear relationship with $(1-n)$, therefore, k_s is nearly independent of n value even for highly shear thinning fluids and depends only on the impeller geometrical characteristics.

(4) The computed data of K_p and k_s from the slope method are correlated with the geometrical ratios D/T, b/D and θ through the linear regression analysis with different speeds. The standard errors of the two correlations, K_p and k_s, are 6.80 % and 5.93 %, respectively, values acceptable for engineering design. As a result, the correlations can be used to predict accurately the power consumption and average shear rate of pseudoplastic fluids in laminar flow.

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