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RESEARCH ARTICLE

Optimization of the Operating and Design Conditions to Reduce the Power Consumption in a Vessel Stirred by a Paddle Impeller

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Abstract
Design of the impeller blade is a determining factor in power consumption and mixing quality, which determines consequently the cost of the mixing operation. This study explores the flow patterns and the power required for stirring a Newtonian fluid by paddle impellers. Investigations are carried out via three dimensional (3D) numerical simulations. Effects of the blade curvature, blade diameter, blade number and Reynolds number are analyzed. The curved blade is found to be more efficient to reduce the power consumption, compared with the straight blade. A new correlation is proposed for predicting the power required with two-curved-bladed impellers. The straight and very large blade creates a dead zone in the space between the blade tip and the vertical wall of vessel. This issue may be overcome by the curved blade, which increases consequently the well-mixed region size. A wider well-mixed region may be obtained with the larger curved blade, but with an additional energy cost.

Keywords
impeller design, flow patterns, power consumption, curved-blade, paddle impeller

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1 Introduction

The mechanically agitated vessel is widely used in many industrial operations such as in the chemical, biochemical, pharmaceutical, food, paint, wastewater treatment, petroleum and other industries. Due to the complexity of the three-dimensional hydrodynamics inside the agitated vessels, many problems are still addressed. One of the main problems often encountered is how to reduce the power required for achieving the mixing operation.

The power number is a global macro-mixing parameter depending largely on the flow structures, which are highly influenced by the impeller design [1]. Many researchers interested to the study of power consumption in several impellers and applications. Among others, Yang et al. [2] for a novel grid disc impeller, Ghotli et al. [3] for six-curved bladed turbines, Bao et al. [4] for a coaxial mixer, Machado and Kresta [5] for confined impellers (A310 and Intermig); for Rushton turbines [6-9], pitched blade turbines [10-13], retreat curve impellers [14], Intermig impeller [15].

Design of the impeller blade is an important parameter to be investigated in mixing systems [16-24]. Due to the different blade shapes available in industries, the fluid flows inside the vessel and the power consumed change, increasing the necessity of optimizing the blade geometry.

Almost all studies published were stick only to a standard two-bladed impeller having a straight blade. Youcefi [18] performed experiments with Newtonian and viscoelastic fluids. Abid et al. [19] and Bouzit et al. [20] simulated the 3D flow fields inside a vessel filled with a Newtonian fluid and stirred by a two-straight-bladed impeller. Ameur and Bouzit [21] proposed a new correlation for predicting the power required when stirring shear thinning fluids by two-straight-bladed impellers. With the same impeller, Youcefi and Youcefi [22] measured the power consumption and mixing times in viscoelastic fluids when changing the blade height.

From laminar to turbulent flow regimes, Kato et al. [25] studied the effect of Newtonian liquid height on the power consumption of straight paddle impellers. Haitsuka et al. [26] measured the mass transfer volumetric coefficient and power consumption in vessels equipped with different large-paddle stirrers under aeration. They reported that the wide paddle stirrer did not decrease the aerated power consumption, because no wide cavity was created.

In eccentric mixing, Tanabe et al. [27] explored the torque and horizontal load on a straight paddle impeller. Their results of time series revealed the periodic oscillation of the torque and horizontal load. By using the CFD method, the effects of the blade width, the number of blades and the rotational speed on the starting torque of a vertical paddle impeller were explored by Nishi et al. [28]. For Newtonian liquids mixed in vessels with a dished bottom, Furukawa et al. [29] correlated the power consumption and mixing patterns for straight large paddle impellers. For complex fluids and straight paddle impellers, Ameur [30, 31] studied the effects of several geometrical and operating conditions including the blade height, the blade width and the blade attack angles on the flow patterns and power consumption.

Liu et al. [23] studied the performance of a novel large two-bladed impeller, which is based on the Maxblend and Fullzone impellers. The new design has adaptability to viscous systems, as reported by these authors.

The optimum design of a mixing system for minimum costs is achieved by the correct choice of the impeller geometry and its location, of the vessel shape, impeller rotational speed and fluid properties [32-36]. Our search in the literature shows that no paper is published dealing with a two-curved-bladed impeller. So, it is necessary to introduce enhancements in the blade design in order to increase the energy efficiency of the mixer.

Thus, the purpose of the present study is to model a stirred tank driven by a large two-bladed impeller. The effect of blade curvature on the power consumption and the flow fields is investigated.

2 Details on the mixing system

Geometry of the stirred system consists of a cylindrical tank with a flat bottom having a diameter (D) equal to 300 mm and a height H/D = 1.66. The liquid level is kept equal to the vessel height. The stirrer has two blades with a height T/D = 1.6 and it is placed at a distance c/D = 0.066 to not scrape the bottom of the tank. The blade thickness (b_t) is taken as b_t/D = 0.0066. Water liquid is used as a working fluid (density ρ = 997 [kg/m^3] and dynamic viscosity μ = 8.899x10^{-4} [kg/ms]).

Several design parameters have been changed, it concerns: the blade curvature, its diameter and its number. Six geometries were realized for testing the blade curvature (b_c) effect, which are: $b_c^* = b_c/D$ = 0, 0.016, 0.033, 0.05, 0.066 and 0.116, respectively. Other four geometries were performed when varying the blade diameter (d), which are: d/D = 0.5, 0.66, 0.82 and 0.98. And finally, the blade number (α) is changed from 2 to 8 (six geometries, α = 2, 3, 4, 5, 6 and 8).

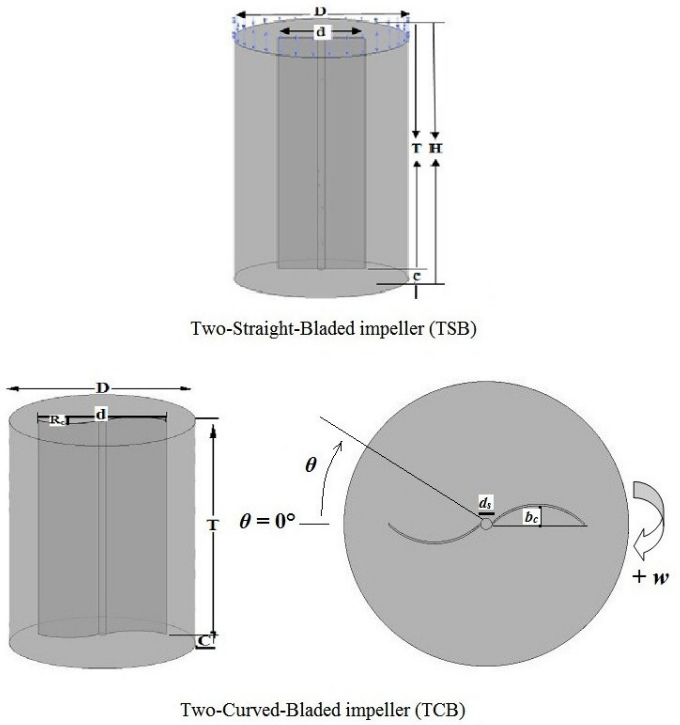


Fig. 1 Geometry of the mixing system

3 Mathematical equations

For a Newtonian fluid, the Reynolds number (Re) is defined as:

$$Re = \frac{\rho N d^2}{\eta} \tag{1}$$

where ρ is the density and N is the rotational speed of the impeller. In this study, the Reynolds number is changed from 0.1 to 30 (i.e. the flow regime remains laminar).

The power consumption (P) is calculated by integration on the viscous dissipation (Q_v) in all the vessel volume as:

$$P = \eta \int_{vessel\ volume} Q_v \, dv \tag{2}$$

The power number (Np) is calculated as:

$$N_P = \frac{P}{\rho N^3 d^5} \tag{3}$$

4 Computational model

Computations were achieved with the help of the CFD code CFX 16.0 (Ansys Inc.). This computer program is based on the finite volume method to solve the equations of momentum conservation. The geometry of the mixing system is created by the pre-processor ICEM CFD 16.0 and the computational domain is then divided into small grids (tetrahedral meshes, Fig. 2).

The mesh density has an extremely important effect on the accuracy of the predicted results. Therefore, various mesh tests were performed before beginning any investigation. The first mesh had about 489,521 elements. This density was increased by about two times (992,256 elements) and two times again (1,482,512 elements). The velocity at the blade tip and the power consumption were determined for each mesh density. The obtained results revealed that the second mesh (992,256 elements) is sufficient, since the variations did not exceed 2% (Table 1). For all geometrical configurations studied, the mesh density was varied from 990,000 to 1,010,000 elements.

The numerical approaches adopted play an important role in accurate prediction of the mixing characteristics. In our simulations, the mixing system is modeled by the Rotating Reference Frame (RRF) technique, i.e. the stirrer is modeled as stationary and the vessel walls are modeled as rotating zones. This technique is suitable for unbaffled stirred tanks. Several studies have been achieved with the RRF approach for unbaffled vessels and accurate results were obtained [37-41]. The impeller rotation speed is low and the flow regime is laminar. The vessel is considered as covered and the liquid height is kept equal to the vessel height. So the interaction with air is avoided and single phase simulations are performed. For the convection terms, the second order upwind scheme was selected. A pressure-correction method of the type Semi-Implicit Method for Pressure Linked Equations Consistent (SIMPLEC) is used to perform the pressure-velocity coupling. Other details of the numerical method performed in our investigations can be found in our previous paper [42].

Calculations were performed in a platform with Core i7 CPU 2.20 GHz and 8.0 GB of RAM. Simulations were considered to be converged when the residual targets of velocities and pressure drop below 10^{-7}. Most simulations converged after 1000-1500 iterations and 5-6 hours in CPU time.

Table 1 Details on mesh tests

	Mesh 1	Mesh 2	Mesh 3
Number of grid elements	489,521	992,256	1,482,512
V^*_{max}	0.64923	0.66013	0.66124
Np	11.59	12.32	12.41
Computational time [second]	10,526	18,523	32,957

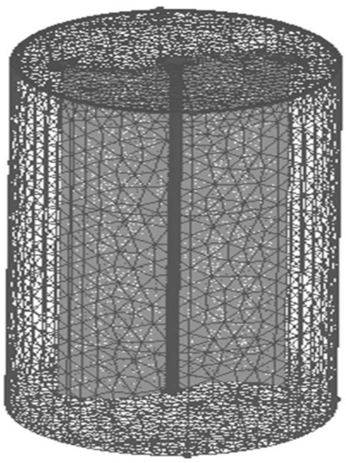
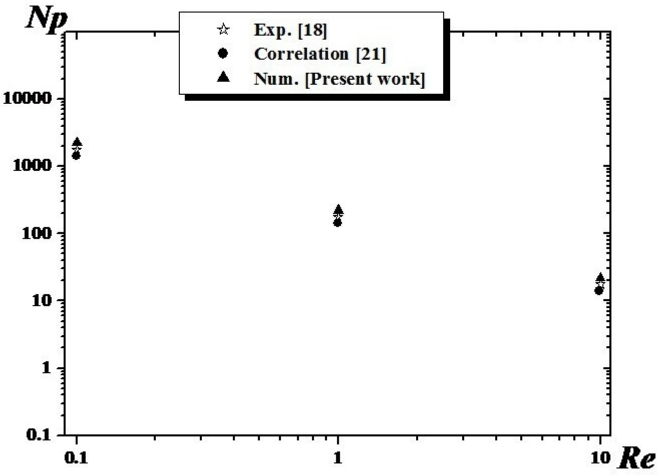


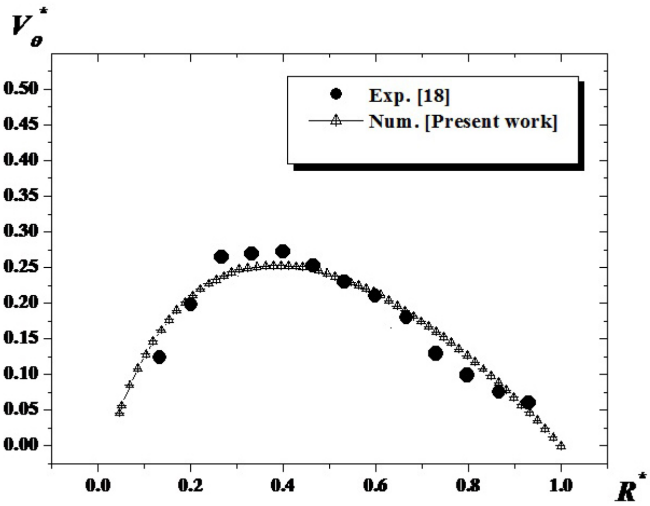
Fig. 2 Meshes generated (tetrahedral grids)

5 Validation of the numerical results

Before starting the numerical investigation, it is necessary to check the reliability of the computer program used. To this end, reference was made to the experimental work of Youcefi [18]. With the same geometry of the mixing system and the same fluid used by Youcefi, the variations of power consumption vs. Reynolds number and the tangential velocity vs. vessel radius are presented in Figs. 3a and 3b, respectively. As remarked on these figures, the comparison between our predicted results and the other experimental data shows a satisfactory agreement.



(a)



(b)

Fig. 3 Validation of the predicted results, (a) Power number vs. Reynolds number, (b) Tangential velocity vs. the vessel radius, at *Re* = 04

6 Results and discussion

6.1 Effect of the blade curvature

The main purpose of the present paper is to investigate the effects of some design parameters on the power consumption and mixture quality in a stirred tank reactor.

We are interested to the mechanical stirring of viscous fluid with a paddle agitator. The size of the impeller blade requires a high power to complete the mixing operation. So, as a solution to this issue, we suggest a new design: it is the curved blade instead of the classic straight blade.

In this section, we explore the effectiveness of this design by realizing six geometries and which are $b_c^* = b_c/D = 0$, 0.016, 0.033, 0.05, 0.066 and 0.116, respectively. We note that the blade diameter is kept constant for these geometries.

On a horizontal plane located at the middle height of the tank (at the vertical coordinate $Z^* = Z/D = 0.5$), the flow fields are shown in Fig. 4a. The velocity reaches its maximum at the blade tip for each case. For the case $b_c^* = 0$ (i.e. a straight blade), a dead zone appears on the extension line of the blade (near the vessel wall). If Reynolds number is low, the flow will rotate in block for this type of mixers, so that will create a dead zone near the vertical wall of the vessel.

The curved blade can overcome this issue as shown in Fig. 4a. With the same blade diameter, the size of the dead zone decreases with the curved blade $b_c^* = 0.066$, and more with a greater curvature $b_c^* = 0.116$. Consequently, an increase in the well-stirred region size will be obtained (Fig. 4b).

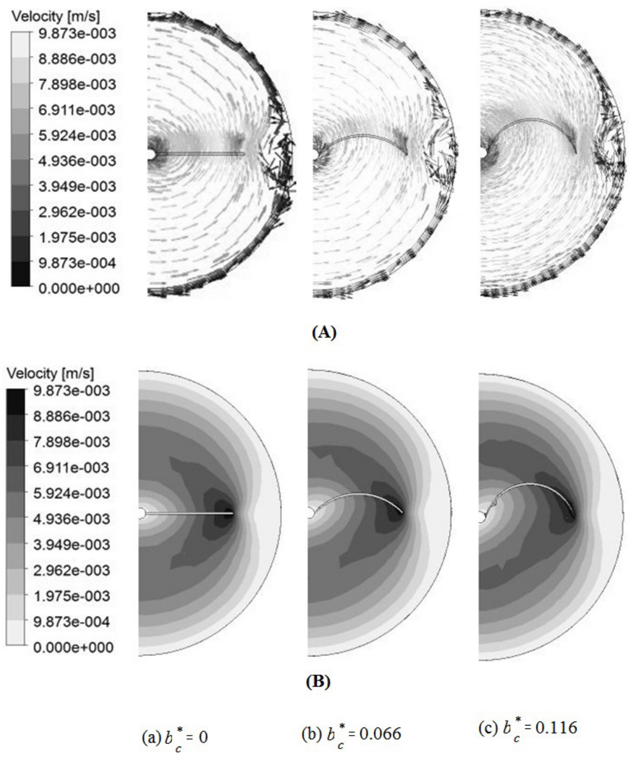


Fig. 4 Velocity contours for $d/D = 0.5$, $Re = 30$, $\alpha = 2$, $Z^* = 0.5$

The power drawn by a rotating stirrer has a significant role in designing the mixing systems. Preferred stirrers are those with the lowest power requirements [42]. Therefore, a comparison between stirrers with different geometries would be helpful for the best choice of the appropriate one.

The curved blade can be considered as a very valiant design, since the increase of the blade curvature reduces the viscous dissipation and consequently the power consumption (Fig. 5).

For example, for $Re = 30$, the power numbers for the straight blade ($b_c^* = 0$) and the curved blade ($b_c^* = 0.0116$) are 7.47 and 2.35, respectively, i.e. a reduction by more than three times.

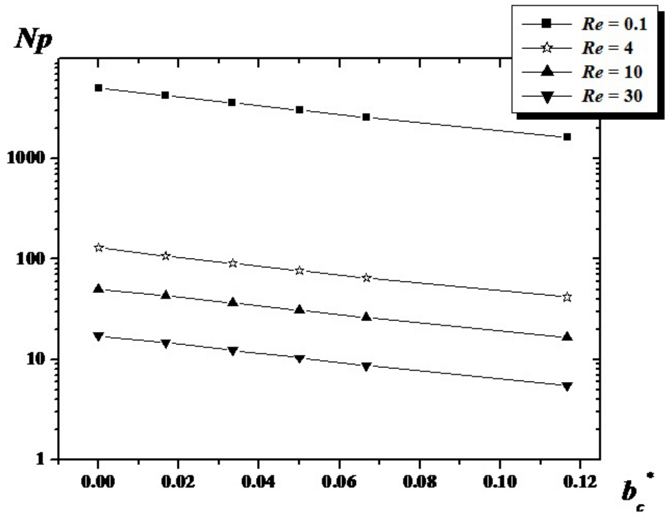


Fig. 5 Power number vs. blade curvature for different Re, at $d/D = 0.66$

6.2 Effect of diameter and length of the blade

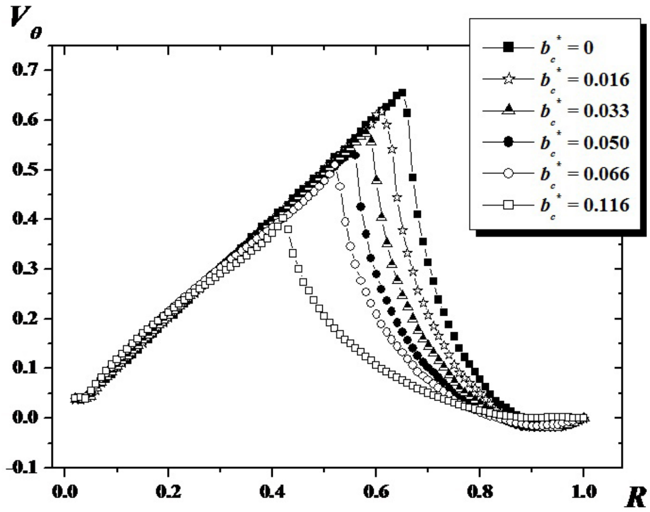
This type of mixer creates a tangential flow, i.e. the tangential velocity component dominates in the entire volume of the tank [20-22]. Based on this, changes in the tangential velocity are followed along the vessel radius for two angular positions (θ): $\theta = 0°$ (on the extension of the blade, Fig. 6a) and $\theta = 90°$ (on the perpendicular mediator of the blade, Fig. 6b). The maximum value of velocity is reached at the blade tip for all geometries (Fig. 6a). When moving away from the area swept by the impeller, the flow rate decreases continually until becoming neglected at the vessel wall.

At low Reynolds number and for a curved blade with a small diameter and length, a dead zone appears on the extension of the blade (Fig. 7). Increasing the diameter and length of the blade will decrease the size of the dead zone, giving then a large area of good mixtures, but with additional power consumption (Fig. 8).

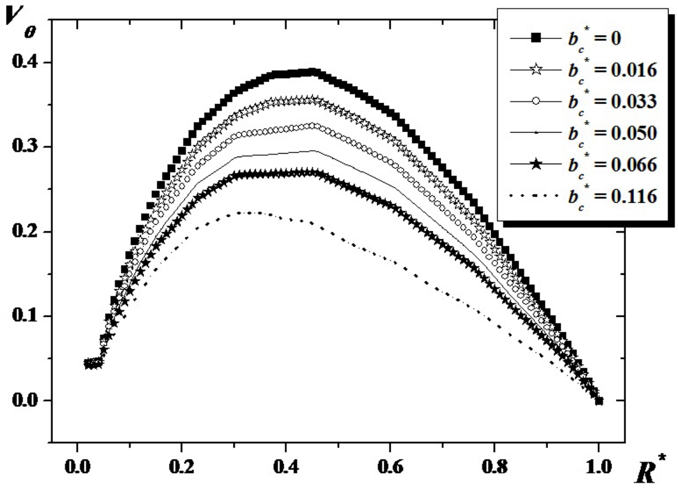
For example, for $Re = 10$, the power number for the curved blade ($b_c^* = 0.116$) with diameter $d/D = 0.5$ and 0.92 are 20.31 and 322.21, respectively, i.e. an increase by more than 15 times.

6.3 Effect of the blade number

The number of blades is another parameter that can strongly influence the viscous dissipation and power requirements. Fig. 9 shows the variation in the power consumed for six impeller geometries with different numbers of blades (α), which are: $\alpha = 2$, 3, 4, 5, 6 and 8. As clearly shown, the increase in blades number increases the power consumption. For example, the impeller with 8 straight blades of diameter $d/D = 0.92$ requires more power, about 2.5 times more than a two-bladed impeller with the same diameter.



(a)



(b)

Fig. 6 Tangential velocity for $Re = 30$, $\alpha = 2$, $d/D = 0.66$, $Z^* = 0.85$, (a) $\theta = 0°$, (b) $\theta = 90°$

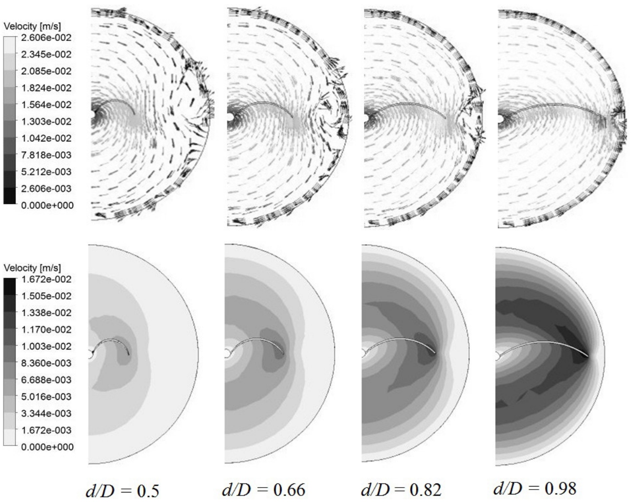


Fig. 7 Flow fields for $b_c^* = 0.066$, $Re = 10$, $\alpha = 2$

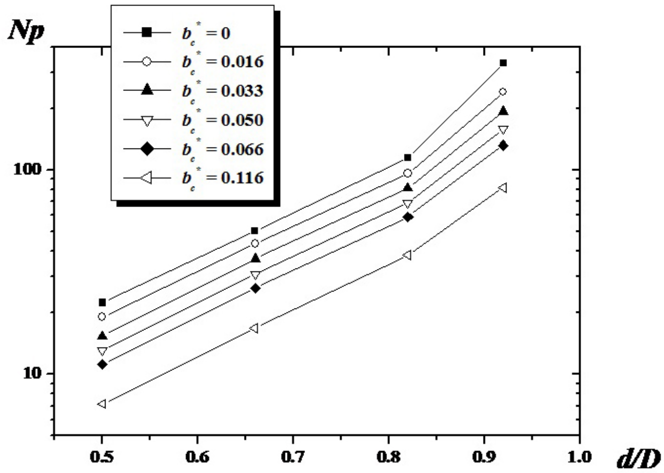


Fig. 8 Power number vs. blade diameter for different b_c^*, $Re = 10$, $\alpha = 2$

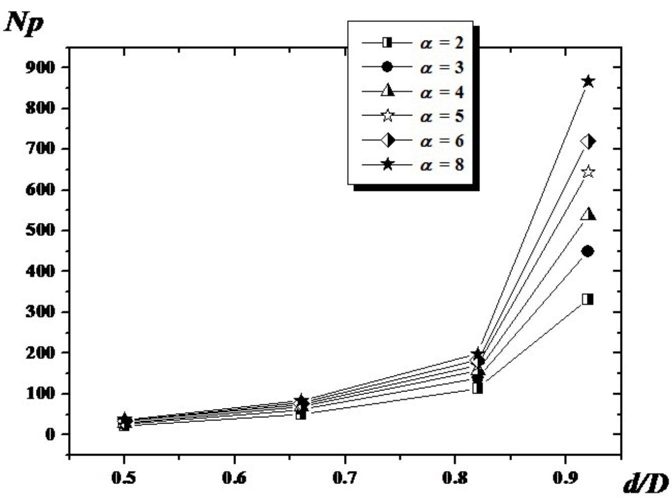


Fig. 9 Power number (Np) vs. blade diameter (d/D) for different blade numbers (α), at $Re = 10$, $b_c^* = 0$

For $Re = 10$ and an impeller with straight-blades of diameter $d/D = 0.92$, the power numbers for the blade numbers $\alpha = 2$, 3, 4, 5, 6 and 8 are $Np = 332.34$, 450.41, 538.41, 644.89, 719.98, and 866.35, i.e. an increase by about 35%, 62%, 93%, 116%, 160%, respectively.

6.4 Optimizing the mixing system

The curved blade exhibits a very effective solution to minimize the power consumption if one wants to reduce the mixing time by using a mixer with a great number of blades.

As shown in Fig. 10, the power consumption may be kept constant if the curvature blade is increased at the same time with increasing the number of blades.

6.5 Correlation

$$Np = 16.74\, Re^{-0.995}\, e^{\left(\frac{1}{D}\left(5.26\, d - 10.83\, b_c\right)\right)} \quad (4)$$

At the end of the manuscript, we propose a new correlation to predict the power required for the agitation of a viscous Newtonian fluid, while changing the Reynolds number, the blade curvature and its diameter. We compared the results obtained by the proposed correlation and those obtained by numerical simulations, and a good agreement was found (Fig. 11).

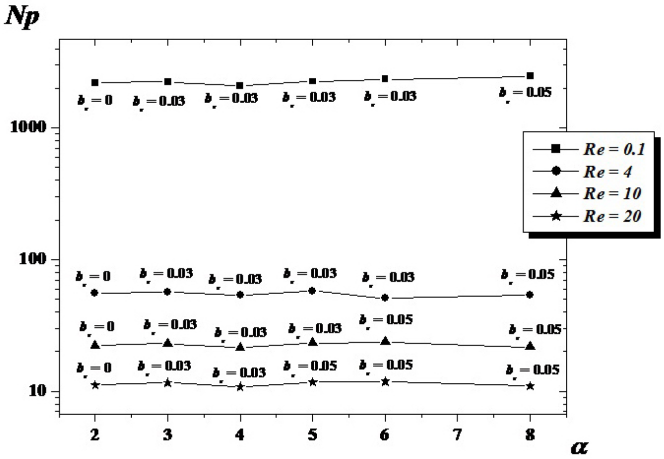


Fig. 10 Power number (*Np*) vs. blade number (*α*) for different Re and b_c^*, *d/D* = 0.5

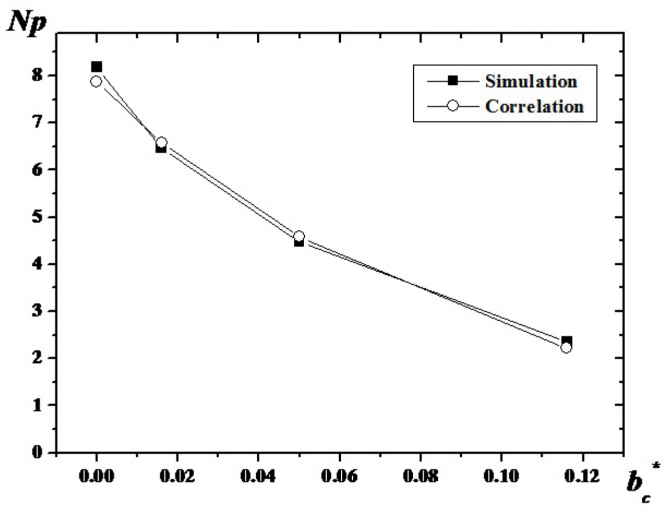


Fig. 11 Power number for *d/D* = 0.82, *Re* = 30

7 Conclusion

Numerical simulations of viscous Newtonian fluid flows in a mechanically stirred tank were performed. Stirring is provided by a paddled impeller rotating at low speeds. The predicted results show that the impeller with two straight and wide blades generates a tangential flow. And if the impeller rotational speed is low, the flow rotates in block which yields a dead zone on the extension of the blade (near the vertical wall of the tank). The curved blade may reduce the size of these dead regions.

For the same blade diameter and the same Reynolds number, the increase of the blade curvature reduces greatly the power consumption.

For a curved blade with a small diameter and at low Reynolds number, the size of the good mixing zone is very small. The increase of the blade diameter of can extend this area (for the same *Re*), but with an additional energy cost.

The increased number of blades can reduce the mixing time, but it requires more energy. For example, the power consumption of an eight-straight-blade impeller is greater by about 2.5 times that the two-straight-bladed-impeller, for the same diameter, curvature and *Re*. As an optimized design, the power consumption may be kept almost constant, if we increase the blade curvature at the same time when increasing the number of blades.

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