Geometrical modifications of the anchor impeller to enhance the overall performances in stirred tanks

Modyfikacje geometryczne mieszadła kotwicowego w celu zwiększenia ogólnej wydajności zbiorników z mieszaniem

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The performance of modified anchor impellers in stirred tanks is investigated. The classical anchor impeller is taken as a reference, then the upper part of the blade arm is curved at different degrees (α). Three geometrical configurations are explored, namely: α = 0° (which corresponds to the standard shape of anchor impellers), 45°, and 90°. The study is achieved numerically by using a finite volume method based CFD tool. The case of highly viscous Newtonian fluids under laminar flow conditions is considered. From the obtained results, the newly modified anchor impeller has allowed an enhancement in the axial circulation of liquid and a reduction in power requirements. The curved blade with 90° yielded a decrease in power number by about 2.5%, compared to the classical anchor impeller.
Keywords: modified anchor impellers, stirred tanks, newtonian fluid, power consumption, hydrodynamic

W pracy przebadano działanie zmodyfikowanych mieszadeł kotwicowych w zbiornikach z mieszaniem. Jako element referencyjny przyjęto klasyczne mieszadło kotwicowe, w którym górną część ramienia łopatki zakrzywiono pod różnym kątem (α). Przebadano trzy konfiguracje geometryczne, a mianowicie: α = 0° (co odpowiada standardowemu kształtowi mieszadła kotwicowego), 45° i 90°. Badania realizowano numerycznie przy użyciu metody objętości skończonych CFD. Rozważany przypadek dotyczy wysoko lepkich płynów newtonowskich w warunkach przepływu laminarnego. Na podstawie uzyskanych wyników zmodyfikowane mieszadło kotwicowe umożliwiło zwiększenie osiowej cyrkulacji cieczy i zmniejszenie zapotrzebowania na moc. Zakrzywiona łopatka o kącie 90° spowodowała spadek liczby mocy o około 2,5% w porównaniu z klasycznym mieszadłem kotwicowym.
Słowa kluczowe: zmodyfikowane mieszadła kotwicowe, zbiorniki z mieszaniem (mieszalniki), płyn newtonowski, pobór mocy, hydrodynamika.

Introduction

Agitation in cylindrical tanks is an ordinary operation to fulfill many objectives in various areas, such as the food, polymer, paint, pharmaceutical, and petroleum industries. The quality of the final product in mixing systems is highly related to the hydrodynamic induced by the impeller. So, detailed knowledge of the flow patterns in the whole vessel volume is needed. Additional difficulties for the optimization of processes often occur with highly-viscous fluids [1].

In the mixing of fluids with low viscosity, the impeller systems consisting of one or more turbines are generally used. However, and when the working fluids exhibit high viscosity, the close-clearance impellers are recommended. In this case, the impeller is recommended to be used in the laminar regime [2, 3]. For instance, in polymerization processes, an efficient mixing is desired to avoid some phenomena like dead zones and hot spots and to control the molecular weight distribution of the final product [4]. If turbines are used in mixing highly viscous liquids, the rapid decay of flow velocities may be induced, resulting thus in low blending quality [5].

Among the different kinds of close-clearance impellers that are available in industries, the anchor impeller has proved its efficiency. As reported by Chhabra and Richardson [6], the anchor is suitable for the mixing of viscous Newtonian and non-Newtonian fluids. The flow pattern induced by an anchor impeller is tangential, and it generates secondary radial and axial flows at high rotational speeds [7]. Karray et al. [8] explored the efficiency of standard anchor impellers for mixing Newtonian fluids. They observed a significant deformation of the anchor arm when operating in the turbulent flow regime. To overcome this issue, they proposed inserting an anchor blade.

Espinosa-Solares et al. [9] investigated the combined influence of bottom clearance and wall clearance on power requirements. Their result revealed a decrease in power input with the raise of the bottom and wall clearance, which is resulted from the variation of flow patterns. The experimental study performed by Triveni et al. [10] on the mixing of Newtonian and non-Newtonian fluids by anchor impellers revealed an increase in the fraction of the well-mixed region from 0.7 to 0.95 with increased impeller speeds. This increase in mixing quality was observed for both Newtonian and non-Newtonian fluids, but the increase was small for viscous liquids. Prajapati and Ein-Mozaffari [2] used the CFD method to determine the mixing characteristics of viscoplastic fluids with anchor impellers. The optimum values of the stirrer clearance-to-vessel diameter and the stirrer width-to-vessel diameter ratios were 0.079 and 0.102, respectively. They also reported that the four-bladed anchor impeller provides better performance than the two-bladed anchor. Ameur [11] suggested adding vertical and/or horizontal arms in the blade of the classical anchor to avoid the deformation of blades. Ameur and Ghenaim [12] combined the Scaba-anchor impellers to enhance the overall perfor-

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mance in mixing shear-thinning fluids. For anchor impellers, Kamla et al. [13] compared the performance of rectangular, octagonal, and circular shapes of blades. Their results revealed that the octagonal shape yielded the widest well-stirred region over the other cases. However, the lowest power input was obtained with the circular shape of blades.

In the present paper, a new modification in the blades of anchor impeller is introduced. The primary purpose is to enhance the circulation of fluid particles within the vessel and to reduce power consumption. The study is achieved for a highly viscous Newtonian fluid under laminar flow conditions.

Case study

The geometry of the stirred system is illustrated in Figure 1. It consists of a cylindrical, unbaffled, and flat-bottomed tank (diameter: D = 300 mm, height: H/D = 1) fitted with an anchor agitator. The glycerol (density ρ = 1262 [kg·m^{-3}] and viscosity μ = 1.495 [Pa·s]) is used as a working fluid. The liquid level is kept equal to the vessel height. The impeller is placed at a clearance (c) from the vessel base c/D = 0.066. Further details on the other geometrical parameters are provided in Table 1.

Effects of the inclination (α) of the upper part of the blade are investigated by realizing three geometrical configurations, which are: α = 0° (which corresponds to the classical anchor), 45°, and 90°, respectively.

Table 1. Details on the geometrical parameters

H/D	d/D	h/D	c/D	a/D	b/D	d_s/d
1	0.5	0.95	0.066	0.04	0.02	0.06

Theoretical tools

The power number (Np) is an essential parameter to determine the performance of a stirred system. It is defined as follows:

$$Np = P:(rN^3d^5) \qquad (1)$$

where P is the power consumption, and N is the impeller rotational speed. The Reynolds number Re is the ratio between the viscous and inertia forces:

$$Re = (\rho Nd^5):\mu \qquad (2)$$

The dimensionless axial and radial coordinates Z^* and R^* are defined respectively as:

$$R^* = 2R/D \qquad (3)$$
$$Z^* = Z/D \qquad (4)$$

The dimensionless velocity is defined as:

$$V^* = V/\varpi Nd \qquad (5)$$

Experimental set-up

To perform the investigation, the computer software (CFX), which is based on the finite volume method, was used. However, the geometry and mesh of the computational domain (Fig. 2) were created with the computer tool Ansys ICEM CFD. The steady-state, three-dimensional, and laminar flows of an incompressible fluid were considered. The Navier-Stokes equations written in a rotating, cylindrical frame of references were solved. Due to the absence of baffles, the Rotating Reference Frame (RRF) technique was technique. The same approach has been used by many researchers, and satisfactory results were obtained [14-18]. To achieve the velocity-pressure coupling, a pressure-correction method of the type Semi-Implicit Method for Pressure-Linked Equations-Consistent (SIMPLEC) was used. Mesh tests were done by checking that additional cells did not change the velocity magnitude in the regions of high-velocity gradients around the impeller blades by more than 2.5%. After mesh tests, the final grid that was selected had about 0.8 million of cells.

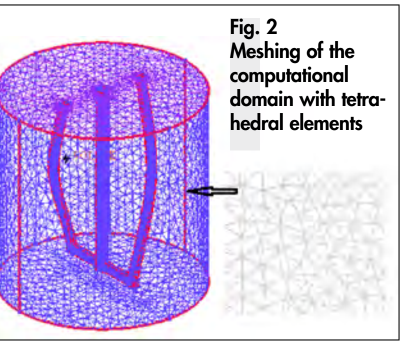


Fig. 2
Meshing of the computational domain with tetrahedral elements

With a machine (INTEL® i7 processor with 8 Gb RAM) and for a residual target 10^{-7}, the convergence was achieved after about 1700–1800 iterations, which corresponds to about 4–5 hours of CPU time.

Validation

To validate the numerical approach and to check the reliability of the computer software and the selected mesh, some predicted results were compared with available experimental data. The predicted values of power numbers are presented in Figure 3 against those obtained experimentally by Prajapati and Ein-Mozaffari [2]. The results provided in this figure were obtained with the same geometrical conditions and fluid characteristics as those used by Prajapati and Ein-Mozaffari. The comparison between both results shows a satisfactory agreement.

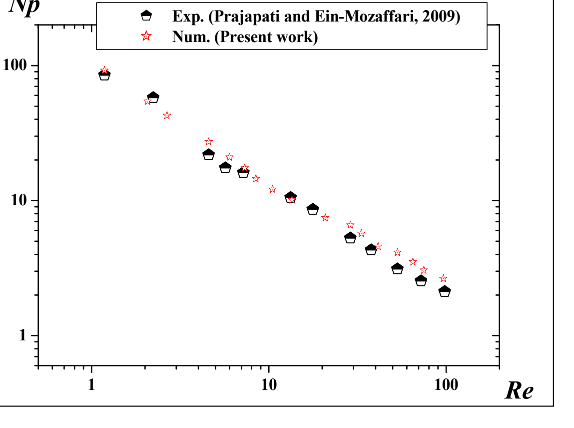


Fig. 3
Impeller power number versus Reynolds number

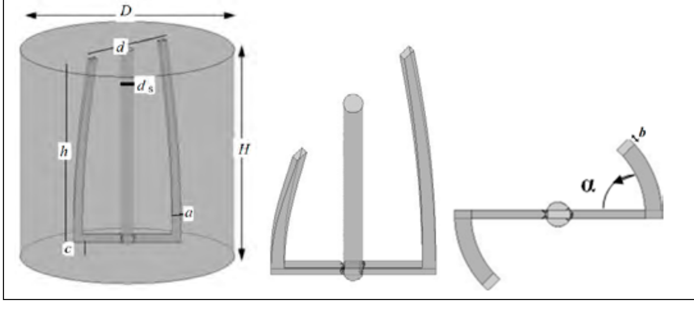


Fig. 1
The geometry of the stirred system

Results and discussion

Flow fields

In the first part of our investigation, the

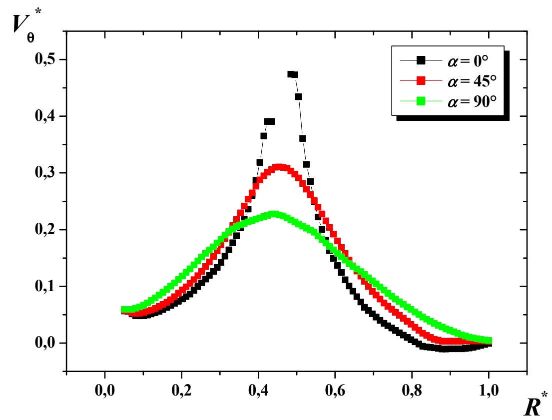


Fig. 4
Tangential velocity for Re = 50, Z* = 0.5, θ = 0°

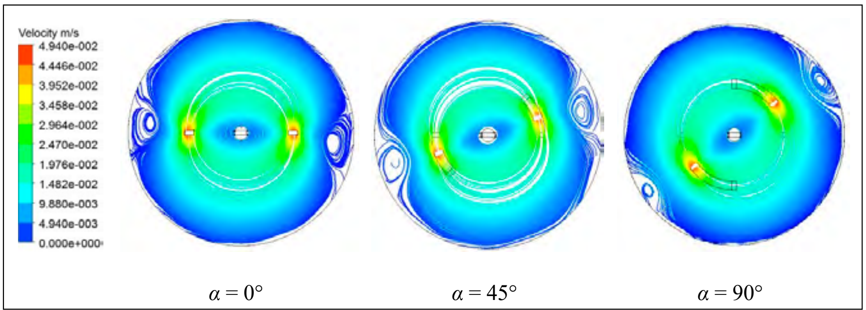


Fig. 5
Streamlines for Re = 50, Z* = 0.5

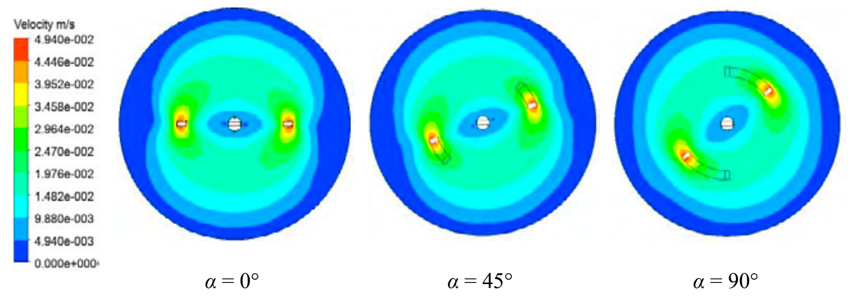


Fig. 6
Well-stirred region for Re = 50, Z* = 0.5

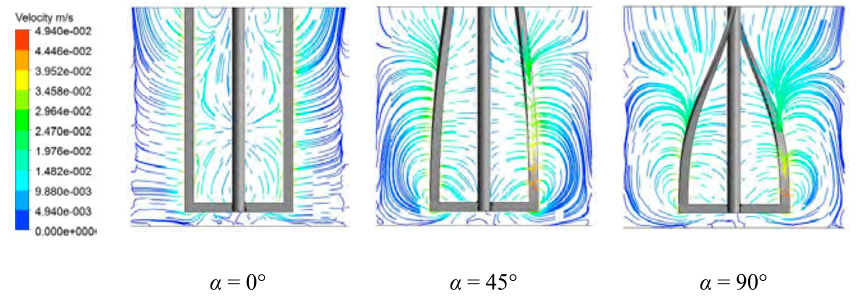


Fig. 7
Streamlines at Re = 50, θ = 0°

flow fields are presented under various plots and for different locations in the vessel volume. At the mid-height of the vessel ($Z^* = 0.5$) and for the angular position θ = 0°, the variation of the dimensionless tangential velocity (V_θ^*) along the vessel radius is given in Figure 4. Values of V_θ^* are provided for the three cases under investigation, i.e., α = 0°, 45°, and 90°. We note the line passing through the blade of the impeller is taken as a reference for the angular coordinate.

As observed in this figure, the tangential velocity increases gradually from the impeller shaft until reaching the highest values at the blade tip, and it decreases again until becoming negligible at the tank wall. The comparison between the three geometrical configurations reveals that the maximum amount of V_θ^* is reached at the blade tip, whatever the curvature of the blade.

The streamlines induced by the different impellers studied are plotted in Figure 5 at the mid-height of the vessel. A recirculation zone, where the fluid is less agitated, is formed near the tank wall in the area swept by the impeller. This is due to the wall effect. The size of theses loops decreases with the raise of blade curvature, resulting thus in a wider well-stirred region around the impellers, as observed in Figure 6.

For further insight into the hydrodynamic induced by the newly modified anchor impellers, the axial streamlines are plotted (Figure 7) on the vertical plane passing through the impeller (θ = 0°). For the classical anchor, the flow patterns are uniform in the whole vessel volume. However, the curved blade has yielded a significant change in the flow patterns. Considerable enhancement in the axial circulation of fluid particles is obtained with the raise of blade curvature (α). Figure 8, where the dimensionless axial velocity is followed along with the vessel height (Z^*), confirms this finding. We note that the negative values of velocity represent the existence of counter flows. However, the excessive increase in the blade curvature may result in reduced size of the well-stirred region near the free surface of the liquid, as illustrated in Figure 9.

Power consumption

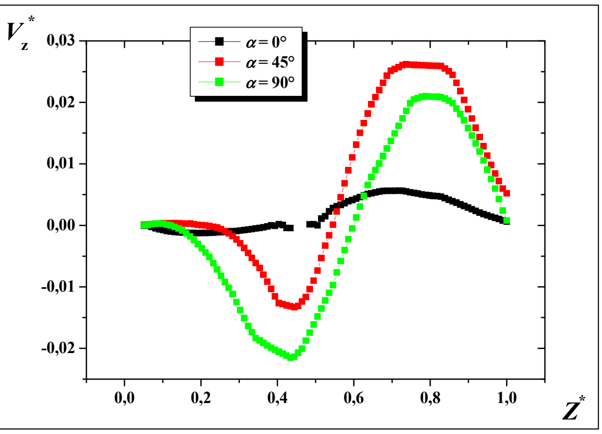
Variations of the power number (*Np*) for the different geometrical configurations under study are provided in Figure 10. Values of *Np* for the three cases α = 0°, 45°, and 90° are: 2.43, 2.41, and 2.37, respectively. As observed, the increase in the inclination angle of the vertical arm of the blade yields a reduction in power consumption. Compared to the classical anchor, the inclination by 45° and 90° provided a decrease in *Np* by about 0.8% and 2.5%, respectively.

Conclusion

Some modifications in the classical anchor impeller have been introduced to enhance the overall performances in cylindrical tanks. It concerned the curvature (α) of the upper part of the vertical arm of the blade. Three cases were considered, namely: α = 0° (which corresponds to the classical anchor), 45°, and 90°. The flow fields generated in the whole vessel volume, as well as the power requirements for the agitation of a viscous Newtonian fluid, were determined.

From the obtained results, the increased

Fig. 8
Axial velocity at Re = 50, R*=0.8, θ = 90°



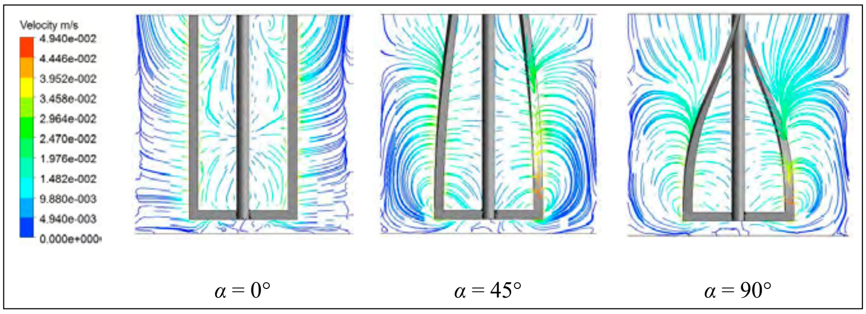
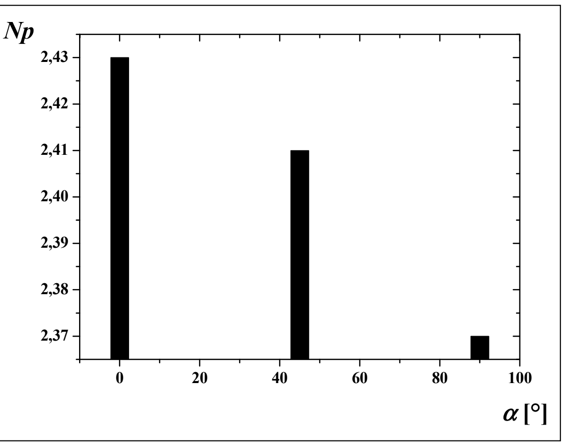


Fig. 9
Flow fields at Re = 50, θ = 0°

Fig. 10
Power number for the different cases studied, Re = 50



angle α has been found to be advantageous in terms of reduction in power consumption. Compared to the standard anchor, a decrease in power number by about 2.5% was reached with the case α = 90°. Furthermore, the size of the well-stirred region has been increased with the raise of α, which is due to the intensification of the movement of fluid particles.

Nomenclature

- *a* - Width of the blade arm, m
- *b* - Thickness of the blade arm, m
- *c* - impeller off-bottomed clearance, m
- *d* - impeller diameter, m
- *D* - tank diameter, m
- *h* - Blade height, m
- *H* - Vessel height, m
- *N* - Impeller rotational speed, s^{-1}
- *P* - Power, W
- *Np* - Power number, dimensionless
- *R* - Radial coordinate, m
- R^* - Dimensionless radial coordinate, $R^* = 2R/D$
- *Re* - Reynolds number, dimensionless
- V_z - Axial velocity, $m{\cdot}s^{-1}$
- V_θ - Tangential velocity, $m{\cdot}s^{-1}$
- *Z* - Axial coordinate, m
- Z^* - Dimensionless axial coordinate, $Z^* = 2Z/D$
- ρ - Fluid density, $kg{\cdot}m^{-3}$
- *μ* - Viscosity, Pa·s
- α - Blade curvature, degree.

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