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Agitation of Complex Fluids in Cylindrical Vessels by Newly Designed Anchor Impellers

Bingham-Papanastasiou Fluids as a Case Study

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Abstract

The fluid flows and power consumption in a vessel stirred by anchor impellers are investigated in this paper. The case of rheologically complex fluids modeled by the Bingham-Papanastasiou model is considered. New modifications in the design of the classical anchor impeller are introduced. A horizontal blade is added to the standard geometry of the anchor, and the effect of its inclination angle (α) is explored. Four geometrical configurations are realized, namely: $\alpha = 0°$, 20°, 40°, and 60°. The effects of the number of added horizontal blades, Reynolds number, and Bingham number are also examined. The obtained findings reveal that the most efficient impeller design is that with (case 4) arm blades inclined by 60°.This case allowed the most expansive cavern size with enhanced shearing in the whole vessel volume. The effect of adding second horizontal arm blades (with 60°) gave better hydrodynamic performance only with a slight increase in power consumption. A significant impact of Bingham number (Bn) was observed, where Bn = 5 allowed obtaining the lowest power input and most expansive well-stirred region.

Keywords

anchor impellers, bingham-papanastasiou model, power consumption, fluid flows

1 Introduction

Agitation is a fundamental procedure used in different main industrial processes such as field of industrial chemistry, crystallization, polymerization, paint, metallurgy, gas dispersion, petroleum products. This operation is necessary to achieve the intimate contact between different phases by acceleration chemical reactions, either to cause them to react or to cause the transfer material or heat transfer, and make uniform concentration in this final product.

The viscoplastic fluids are an important kind of non-Newtonian fluids .These fluids are only able to flow when shear stress reaches a certain value greater than that of its own, which forms dead zones, and this reduces the mixing efficiency.

To obtain a high product quality, it is needed to eliminate difficulties of complex rheology that form stagnant regions, poor heat exchange, and increased consumption of power. Fewer dead zones are necessary for effective homogenization.

The industry encountered many problems in implementing the mixing process (such as polymer solutions, melted polymers, detergents, petroleum products, biological fluids, food products). These complex rheology proprieties such as high viscosity, which formed dead zones (called cavern) during the mixing process, low thermal exchange, and high cost of power consumption are a challenge for many researchers in this field to resolve it or reduce it to improve the mixing process [1].

For this reason, many researchers worked to resolve this issue with studies guided towards viscoplastic, which included changing design systems.

Belhadri [2] investigated experimentally the flow of threshold fluids in pipes through convergent and divergent singularities at shallow Reynolds number values using LDV. Threshold fluids were made using a mixture of distilled water and Carbopol 940 powders regarding flow through an agitation system. In work performed by Marouche et al. [3], the analysis was done with Newtonian fluid (glucose solution) and viscoplastic fluid with Carbopol solutions. The sliding impact seen with a

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smooth wall is reduced with the use of a rough coating on the tank. The velocity calculations are presented, and significant variations and differences are illustrated between Newtonian fluid and viscoplastic fluid.

Anne-Archard et al. [4] discussed the distributions of shear rates and their link to the power consumed when mixing power-law fluids with helical and anchor impellers. They established a Metzner–Otto correlation for mixing in power-law fluids (Bingham, Herschel-Bulkley, and Casson fluids). Mebarki et al. [1] discussed the hydrodynamic characterization of a mixing system equipped with a circular anchor agitator that contains a viscoplastic fluid model (Bercovier and Engelman). They reported that various rheology parameters and design geometry have an influence on the flow field, enhancing and reducing power consumption. For a viscoplastic fluid (Bingham model), Rahmani et al. [5] conducted a comparative study of power consumption in stirred vessels between various impellers (anchor agitator, gate agitator, two-blade agitator). The results obtained showed that the anchor agitator has the benefit of low energy consumption compared with the rest. Ameur [6] added a number of blades (horizontal and vertical) in the classical anchor impeller. Their results revealed that the anchor impeller with four blades has the best performance in this mixing system. Ameur and Ghenaim [7] used a stirred vessel with a modified impeller design, including a curved blade turbine (CBT) placed on a classical anchor impeller (CAI). They focused on the influence of mixing system design and curvature of the anchor on the fluid flow, power consumption, and shearing zone.

Triveni et al. [8] investigated the effect of impeller speed on the elimination of dead zones in mixing vessels. Rahmani et al. [9] performed a 2-D thermal study of stirred tanks with Bingham fluids. They discussed the variations of the Nusselt number versus the Reynold number. Savreux et al. [10] simulated the viscoplastic fluid flows in stirred vessels. They observed that the dead zones were eliminated with the decrease of the impeller rotational speed. Tanguy et al. [11] and Bertrand et al. [12] studied the same geometry configuration of anchor impellers. They examined the variation of power number versus Bingham number and determined the Metzner and Otto concept. Prajapati and Ein-Mozaffari [13] studied (with the CFD technique) the effect of impeller clearance to diameter ratio (c/D) and width impeller to diameter ratio (w/d) in a stirred tank that contains Xanthan gum solution. They observed that the optimal value of c/D and w/d is 0.012 and 0.079, respectively. They reported also that the effect of four anchor impeller blades is more effective than two anchor impeller blades.

Espinosa-Solares et al. [14] investigated the effect of both bottom-clearance and wall-clearance on the power consumption rate. They suggested a numerical correlation and declared that the power consumption decreases as the bottom and wall clearances increase, which is because of the change in the flow pattern. Jamshidzadeh et al. [15] discussed the power consumption for gas dispersion in power-law fluid with a new agitator design called coaxial mixer that consisting of an anchor impeller and two central impellers. Other interesting works on the classical and other anchor impellers may be found in [16–18].

Several studies were conducted to simulate the viscoplastic fluid, but none addressed the 'Papanastasiou' fluid in the stirred tank. Therefore, we conducted research directed at making the studies 3D and more precise. We focus also on the design of anchor impellers. A new blade was added to the classical anchor impeller, and its inclination was changed to enhance the overall performance.

2 Stirred system

Our system is a flat bottom tank equipped with an anchor impeller (Fig. 1). This impeller is positioned at the central position of the vessel. The required details on geometrical parameters are provided in (Table 1). Many specification criteria have been modified, such as the inclination of the blade and the number of blades added.

The first configuration is a classical impeller fitted with a straight blade. Then, adjustments were introduced in the blades with different angles α. The effect of blade inclination is explored by considering these two geometrical configurations (Fig. 2):

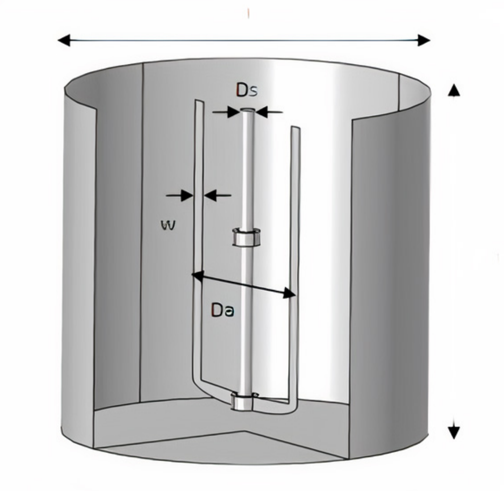


Fig. 1 Stirred system

Table 1 Vessel parameters

D	H	Da	w	Ds
0.3	0.3	0.15	0.03	0.02

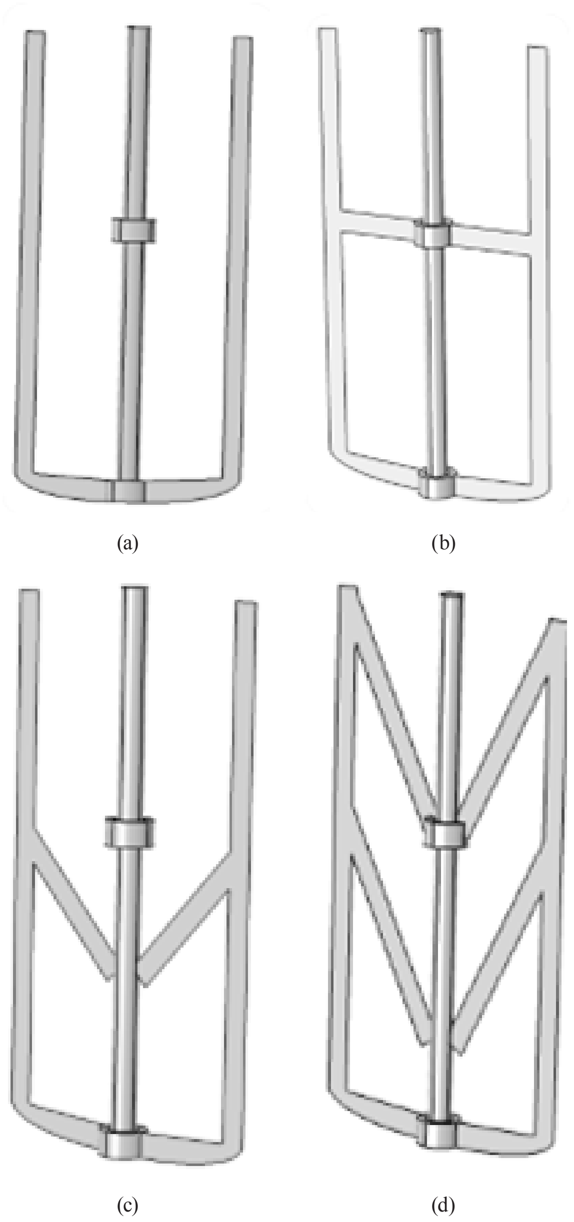


Fig. 2 Geometrical configurations of the impellers under study; (a) Case1; (b) Case2; (c) Case3; (d) Case4

1. Variation of angle degrees of the blades towards the vertical position (yz plane) ($\alpha = 0°. 20°.40°. 60°$).
2. Additional blades follow the same procedures as the first configuration.

3 Theory

The viscoplastic fluid Bingham-Papanastasiou prescribes the following relation:

$$\mu = \mu_0 + \frac{\tau}{\dot{\gamma}} \exp\left(1 - m\dot{\gamma}\right). \tag{1}$$

To model the stress-deformation behavior of yield stress fluids, the Bingham constitutive equation has been modified by Papanastasiou [19].

In simple shear flows, it takes the following dimensional form where μ_0 is a constant viscosity, denotes the yield stress, τ is the shear stress and m is the stress growth exponent and also called a regularization parameter.

The shear rate is expressed as:

$$\dot{\gamma} = \sqrt{s : s}. \tag{2}$$

With s is the rate-of-deformation tensor given by:

$$s = \frac{1}{2}\left[\nabla u + (\nabla u)^T\right], \tag{3}$$

where u is the velocity.The Reynold number is defined as:

$$\mathrm{Re} = \frac{\rho N D^2}{\mu}. \tag{4}$$

ρ is the density, N is the impeller rotational speed, Re is varying from 1 to 500.

The Bingham number is defined by:

$$\mathrm{Bn} = \frac{\tau D}{\mu N}. \tag{5}$$

P is the power consumption defined by:

$$\mathrm{P} = \int_A \Omega \cdot \Gamma \cdot dA, \tag{6}$$

the integral is taken over the surface of the impeller. Ω is the rotational speed, Γ is the torque applying on a point r = {x, y, z}, defined by:

$$\Gamma = \mathrm{r} \cdot \mathrm{F}. \tag{7}$$

That F is force applying on all point of this surface.

The calculation of the power consumption with Eq. (8):

$$\mathrm{P} = \int 2\pi N\left(xF_Y - yF_X\right), \tag{8}$$

when $\Omega = 2\pi N$ and $\Gamma = (xF_y - yF_x)$, and Eq. (6) become :

$$\mathrm{P} = \int_A 2\pi N \cdot \left(xF_y - yF_x\right) \cdot dA. \tag{9}$$

The power number is expressed as:

$$Np = \frac{\mathrm{P}}{\rho N^3 D_a^5}. \tag{10}$$

4 Numerical method

The 3D flow of viscoplastic fluid in a stirred tank by different geometrical designs of anchor impellers was analyzed numerically by the software package COMSOL multiphysics 5.4. This computer tool was utilized to solve numerically the Navier-Stokes equations with the finite volume method. The incompressible, laminar flows were considered. An unstructured grid (tetrahedral mesh) was used for discretization of the computational domain (Fig. 3). The Free Tetrahedral operation builds surface meshes on unmeshed faces before it builds the volume meshes. The surface mesh must conform with the geometry boundaries, but the surface mesh nodes can be moved around within the faces during element quality optimization [20]. After mesh tests, the 3D mesh had about 248.277 elements (Fig. 3). The simulations were run by setting the residual convergence to 10^{-6}.

5 Results and discussion

5.1 Validation

It is necessary to check the reliability of the computer software and the numerical method adopted. In present numerical study, we have referred to the work of Marouche et al. [21], and we used the same geometrical and rheological characteristics (Da =0.288; D = 0.3; τ =1 Pa; μ_0=0.1 Pa·s) (i.e., a classical anchor impeller and Bigham fluid). The results given in Fig. 4 illustrate the similarities between our products and those of Marouche et al. [21]. The comparison shows a very good relatedness.

Fig. 3 Tetrahedral mesh elements of the computational domain

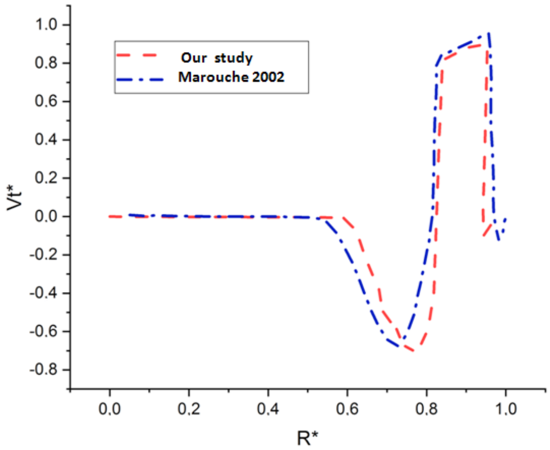


Fig. 4 Tangential velocity on the impeller plan for Re = 13.8

5.2 Influence of inertia

Different parameters have been investigated in our research; the effects of impeller rotational speed were studied. Fig. 5 and Fig. 6 present the velocity tangential in different positions (median and impeller plane) with range Reynold number from 1 to 500.

It is noticed that the tangential velocity reached maximum degree at the impeller edge tip and started to decay continuously until becoming negligible at the immediate contact with the sidewalls of the vessel.

The presence of a non-sheared zone coinciding with the low Reynold number and vanishing at a high Reynolds number value. Therefore, it increases the influence of rotational speed on the fluid flow.

The streamlines presented in Fig. 7 show the formation of vortices at the blade tip at low Reynold number (1–50). These vortices are detached from the blade tip going away to the vessel wall with increasing Reynold number (from 200 to 500). In addition, an expansion of moving zone is observed with increasing inertia in the vessel.

5.3 Effect of impeller design

The primary role of the mixing operation is to achieve maximum homogeneity within this mixing system that means getting a high-quality product. To investigate this, we must be familiar with all the factors related to this mixing system, such as fluid flow pattern and impeller design.

A new geometrical model was put to the test and compared its efficiency to classical models in order to eliminate the zone rigid in a stirred tank that had an extra anchor impeller which enlarged the non-sheared zone along with the tilted blade that offered more appealing results.

The influence of impeller design on the cavern zone is presented in Figs. 8–10. demonstrates the effect a different

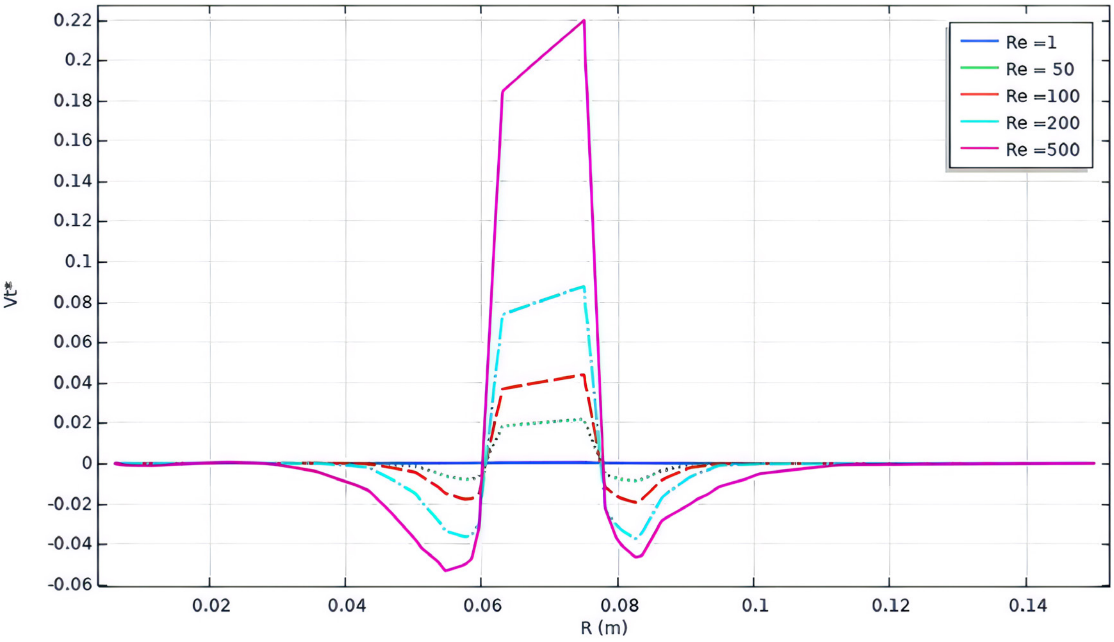


Fig. 5 Tangential velocity at the impeller plane

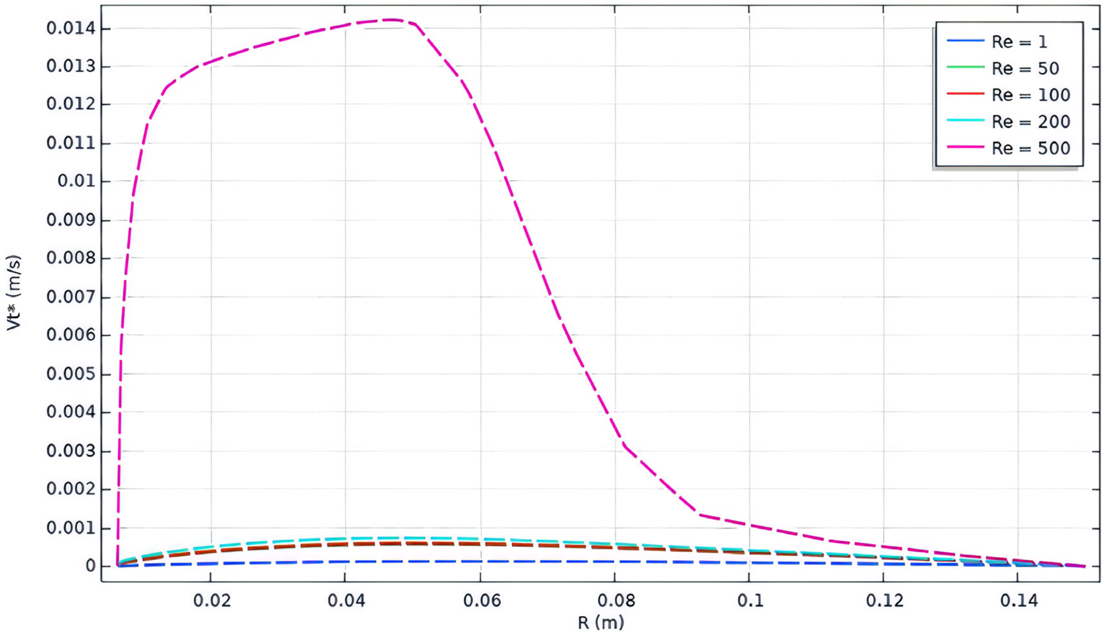


Fig. 6 Tangential velocity at the median plane

impeller design, such as a tilted blade, can have on the velocity distribution inside the mixing vessel. Despite the addition of extra blades, power consumption did not increase exponentially. It was approximatively heightened in all four cases.

The results of Figs. 11 and 12 correspond to the range of angles studied (α =20, 45, 60).We note the existence of a large non-sheared zone for the first case (anchor impeller with a straight blade).This is explained by a stagnant zone of null speeds, and the shear is only perceptible in the vicinity of the blades .But with an increasing degree angle of the arm blade, the shear zone was expanded in the rest of the vessel, and the fluid turns first to a shear thinning behavior to eventually be similar to a Newtonian fluid. The curved blade offered a significant change in the flow patterns.

A considerable enhancement in the axial circulation of fluid particles is obtained with the raise of blade angle. In which the tangential within the median plane is the dominant one. The horizontal velocity's effect was high and

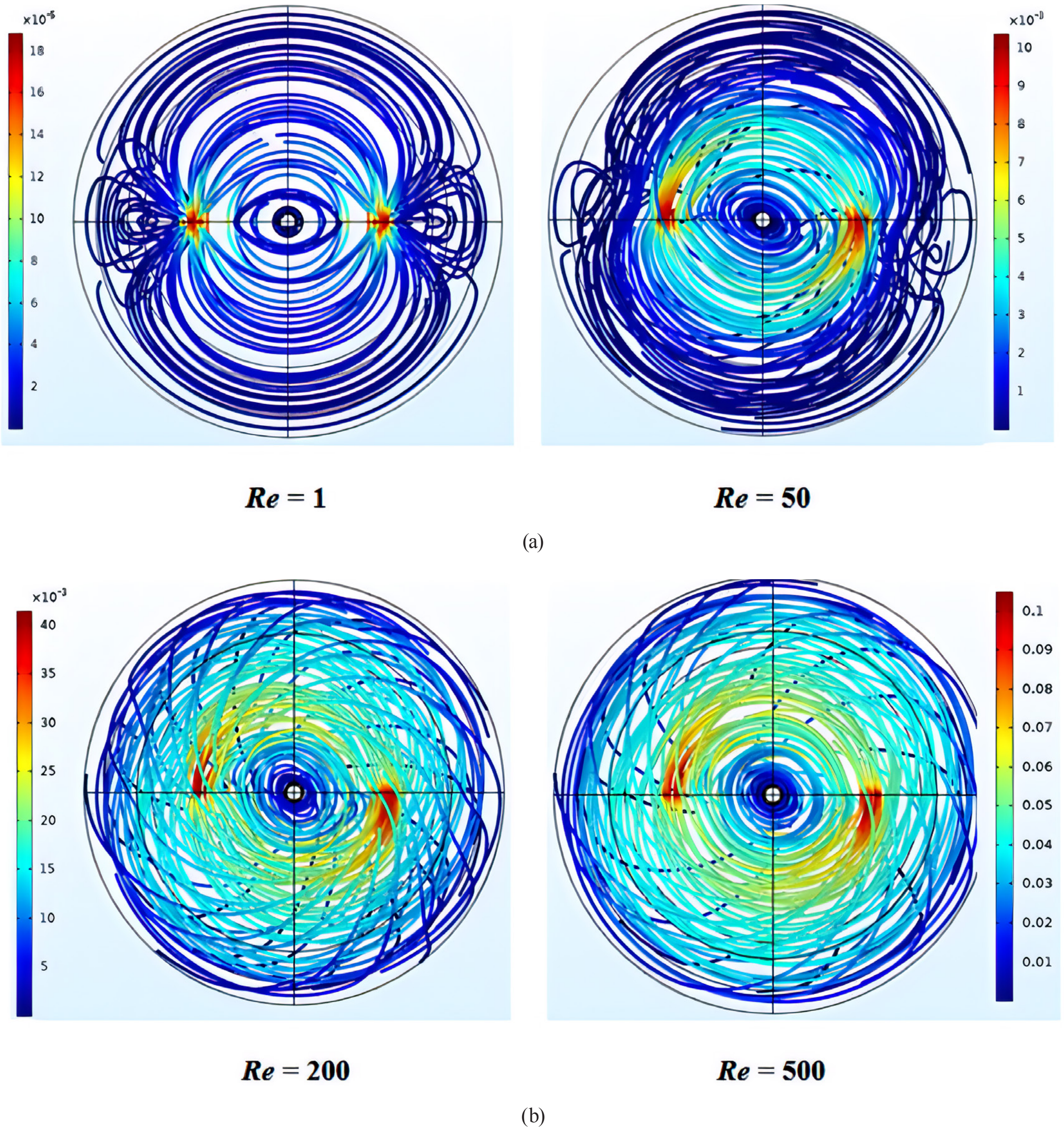


Fig. 7 Streamlines distribution at the mid-height of the stirred tank; (a) streamlines distribution for low inertia value (Re = 1; Re = 50); (b) streamline distribution for high inertia value (Re = 200; Re = 500)

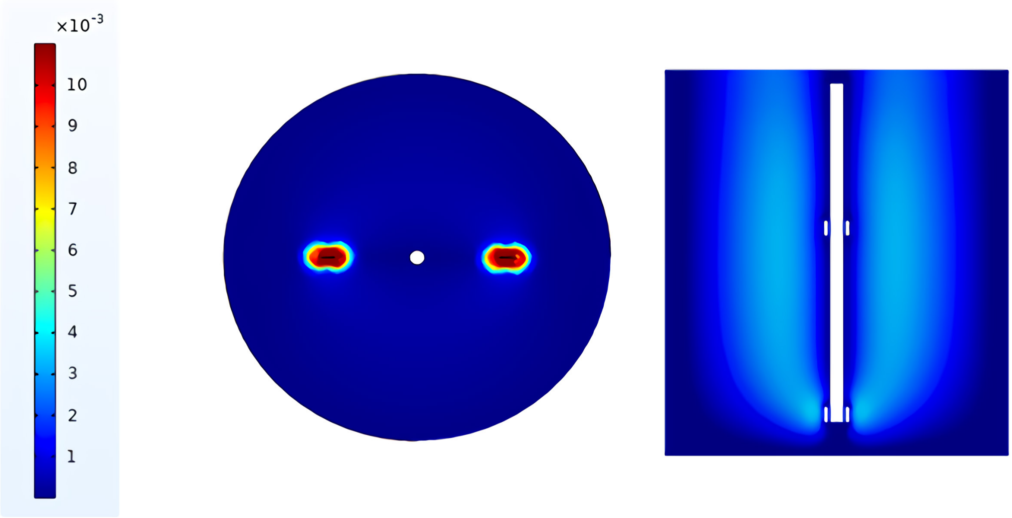
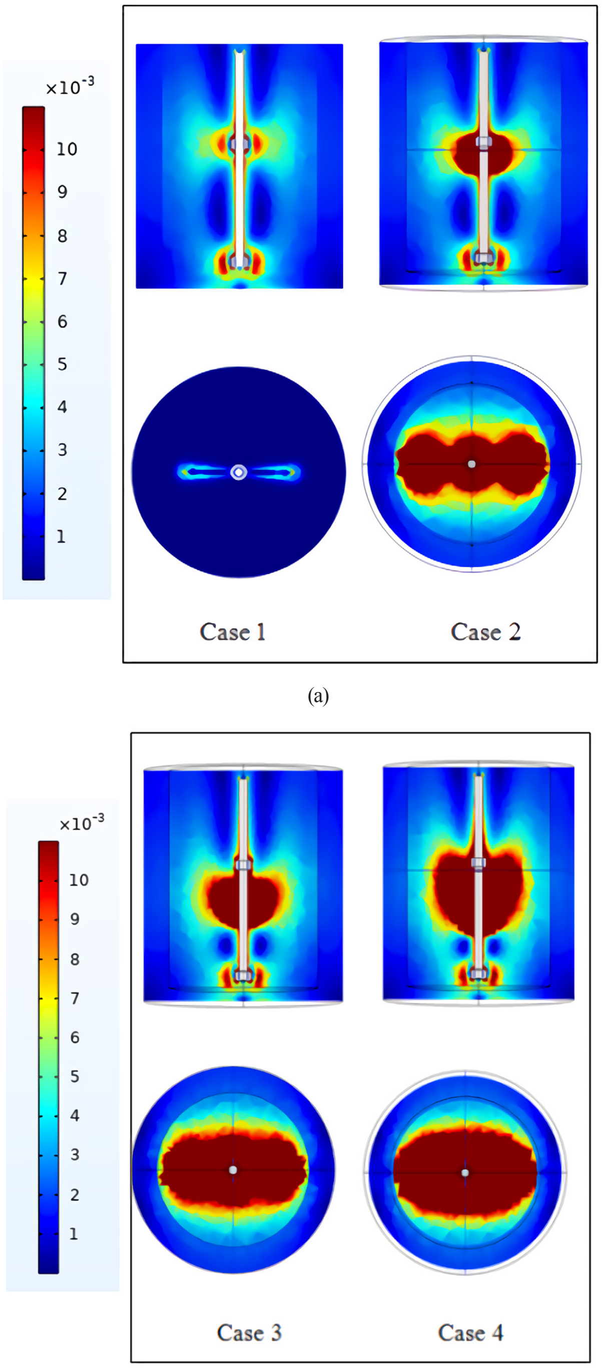


Fig. 8 Shear rate distribution with classical anchor impeller



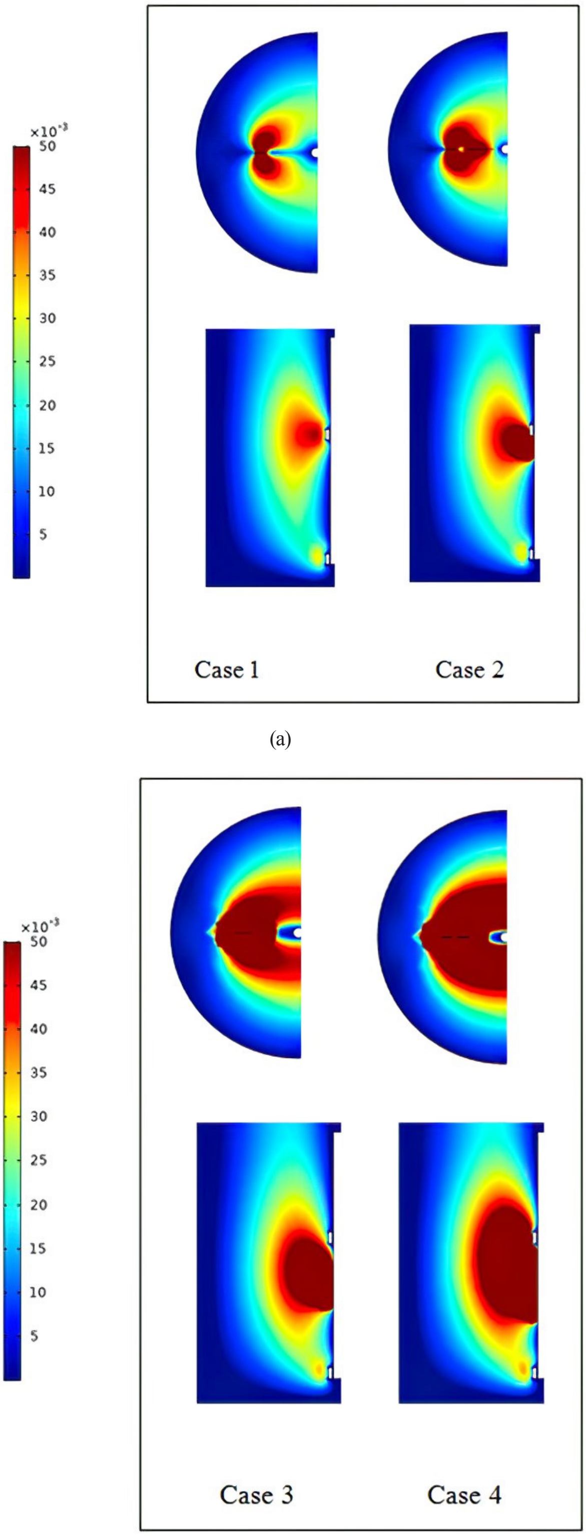
(a)

(b)

Fig. 9 (a) Shear rate distribution. Case1: Anchor impeller with straight arm blade. Case2: Anchor impeller with inclined arm blade $\alpha = 20°$; (b) Shear rate distribution. Case3: Anchor impeller with inclined arm blade $\alpha = 45°$. Case4: anchor impeller with inclined arm blade $\alpha = 60°$.

reached up to α =60 degrees due to the tilted blades, and the best illustration is Case4.

This type of Anchor impeller make a dominanace tangential flow on vessel, that explain a existence of high velocity along impeller plane and very low on the median plane.



(a)

(b)

Fig. 10 Velocity distribution for different impeller design in the stirred tank at $Z^* = Z/D = 0.5$; (a) Velocity distribution on vessel, Case1: Anchor impeller with straight arm blade, Case2: Anchor impeller with inclined arm blade $\alpha = 20°$; (b) Velocity distribution on vessel, Case3: Anchor impeller with inclined arm blade α = 45°, Case4: Anchor impeller with inclined arm blade $\alpha = 60°$.

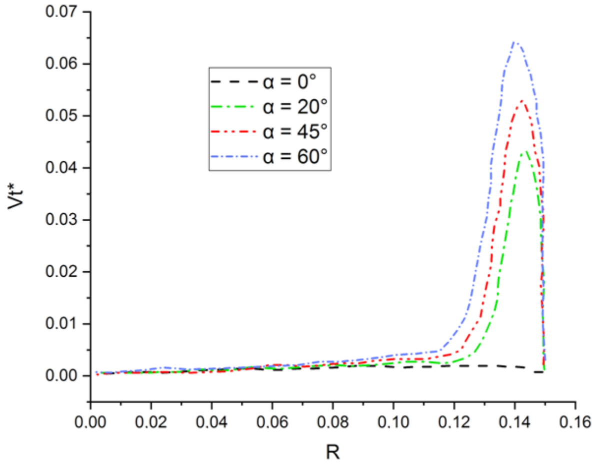


Fig. 11 Tangential velocity at the median plane

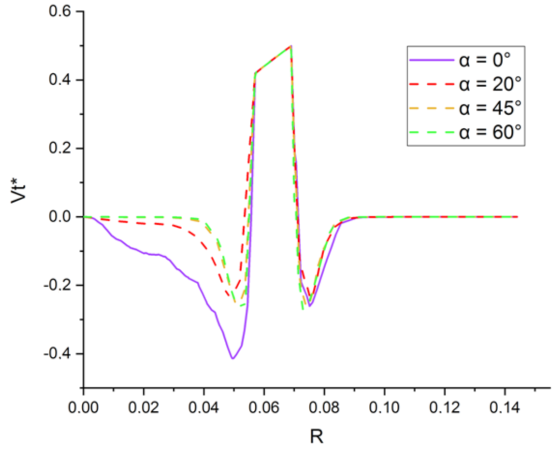


Fig. 12 Tangential velocity profiles on the impeller and median planes

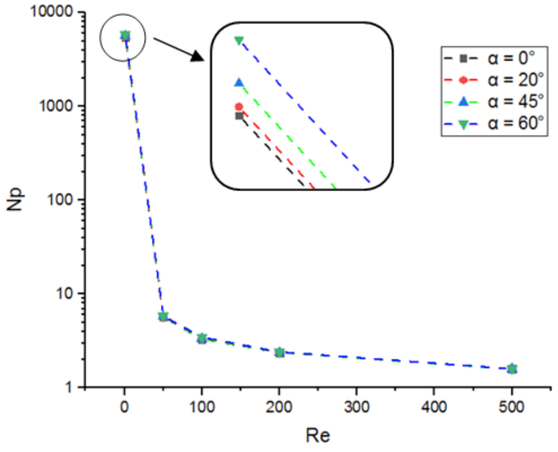


Fig. 13 Power consumption versus Reynolds with different angles inclinaison (*α*)

The result obtain of Puissance number versus angle inclinaison (Fig. 13) shown that the diference is very small. After zooming in first zone we find that the power consumption increase slightly with increasing angle and becomes approximately the same with increasing Reynold number.

With the improvement made by anchor impeller modified (*α* = 20°, 45°, 60°) in the previous result, this considered positif because we didn't need a big power consumption to achieve desired result .

5.4 Influence of rheology

As a case study, only an *α* = 60° anchor impeller was taken as a reference (Fig. 14). The influence of rheology parameters which is measured by Bn (Bingham number) was studied and showed that the more it is increased, the more velocity is necessary to produce more fluid flow with relativity to Bingham and Reynolds numbers (Bn = 5, 50, 500, and 5000) to see what Reynolds number it takes to reach homogeneity.

It is observed that in the case of Bn = 5, only Re =100 is needed to have a total non-sheared zone. However, the higher Bn is, the higher the Reynolds number is obligatory.

The results presented in Fig. 15 show the power consumption along with Reynolds number with added factor parameters (Bn number). It was conducted by increasing the Reynolds number in velocity as Bn was raised or lowered to see if it influences the mixing rate to test whether power consumption is increased as the rate does or not. As a result, the lower Bn is, the lower power consumption is needed because the residue isn't thick.

As an observation, rheology, in general, has a significant impact on the necessity of power consumption.

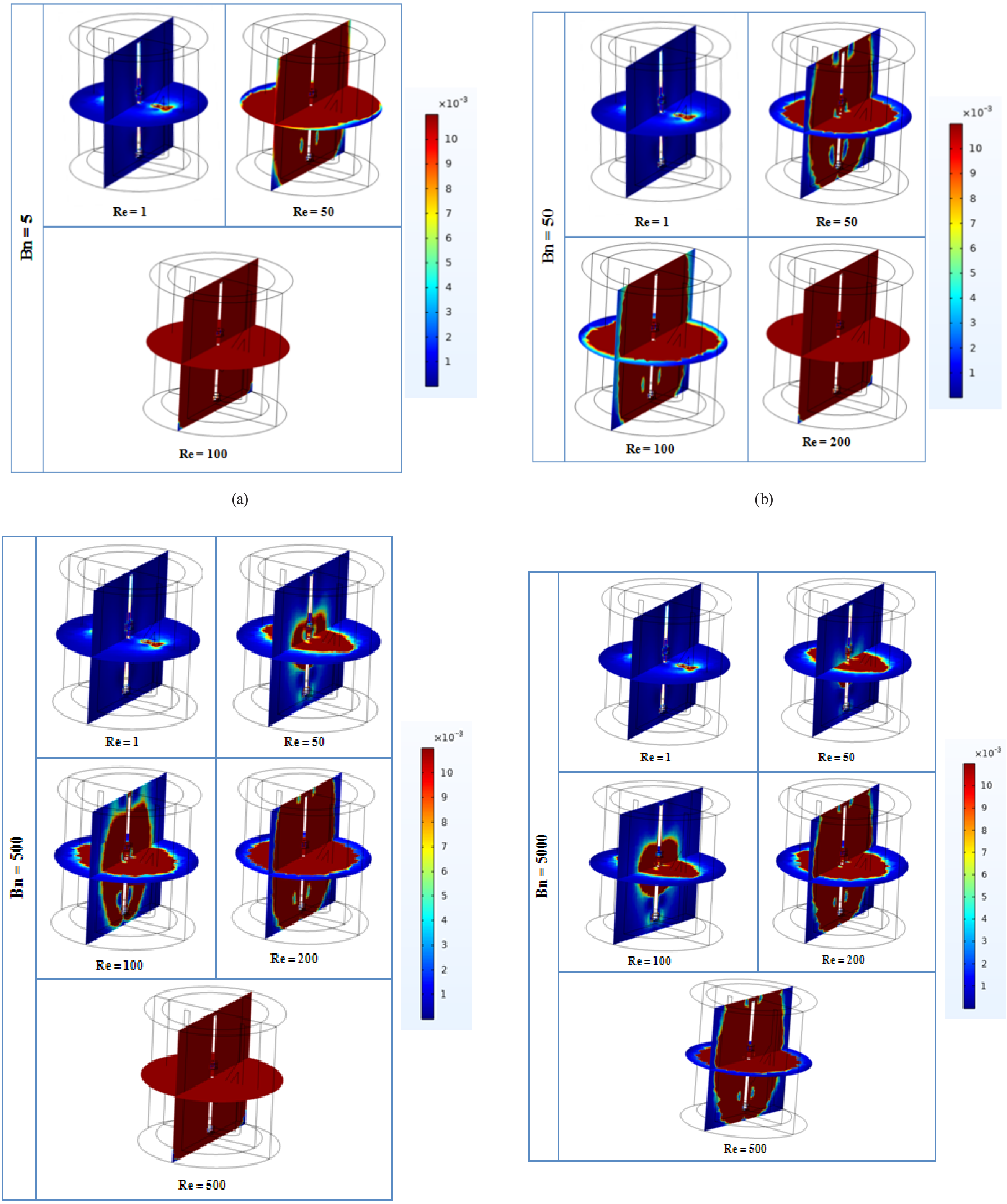
5.5 Effect of the blade number

An additional study that was conducted with the addition of another blade offered tremendous positive results with doubled effects on enlarging the non-shearing zone. Plus, as it was tilted, it provided even more outstanding results (Figs. 16 and 17).

6 Conclusion

The agitation of Bingham-Papanastasiou fluids in cylindrical vessels by introducing new designs in the anchor impeller was numerically investigated in this paper. The effect of the new design by introducing four geometrical cases (anchor impellers with horizontal straight blade), and three cases with varying inclination angles of the added arm (α = 20°, 45° and 60°) was explored.

From the computed results, the case with 60° inclination of the added arm was found efficient in expanding cavern zone, with a small energy cost compared with the classical impeller. By adding a second arm blade, this result was more improved. Moreover, the variation of Bingham number had a good impact on enlarging the shearing zone and reducing



(a)

(b)

(c)

(d)

Fig. 14 (a) Sheared zone on vessel with Bn = 5; (b) Sheared zone on vessel with Bn = 50; (c) Sheared zone on vessel with Bn = 500; (d) Sheared zone on vessel with Bn = 5000

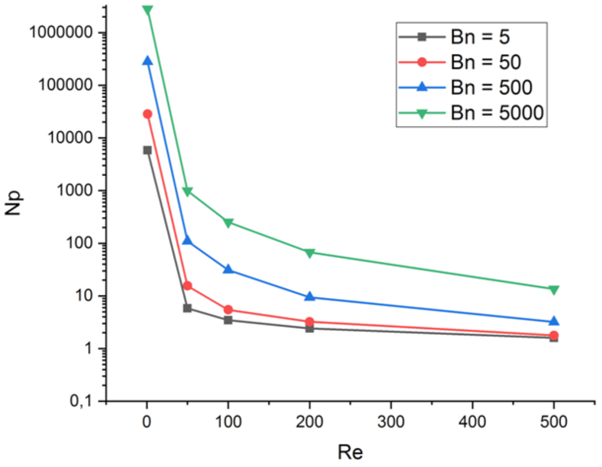
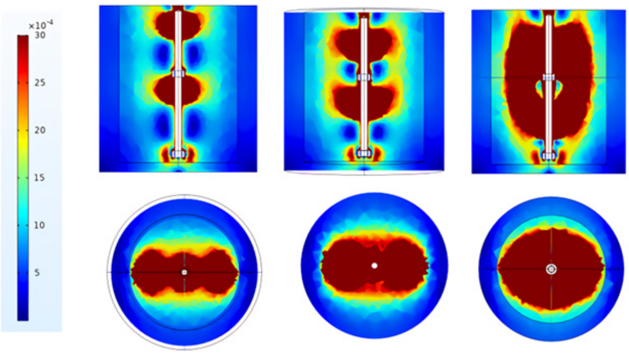
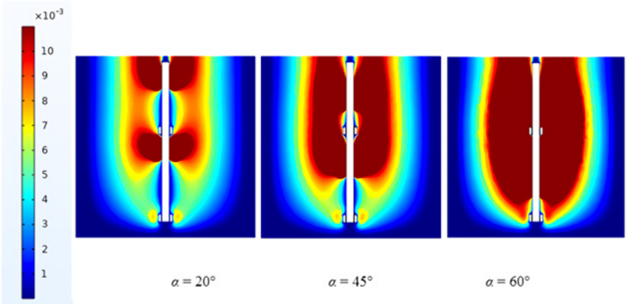


Fig. 15 Power consumption versus Reynolds with different Bingham numbers



$\alpha = 20°$ $\alpha = 45°$ $\alpha = 60°$

Fig. 16 Shear rate distribution with the double arm blade



$\alpha = 20°$ $\alpha = 45°$ $\alpha = 60°$

Fig. 17 Velocity distribution with the double arm blade

the power required. The well-stirred region was totally expanded when Bn = 5 with the lowest power consumption.

The correlation between the best results obtained from each side of the design (case 4 with $\alpha = 60°$) and rheological parameter (Bn = 5) may be selected at the best geometrical and rheological parameters to achieve the best performances. Further studies are needed on this new technique to economize the power consumption of impellers in stirred vessels with preserving the product quality.

Nomenclature

D	Tank diameter (m)
Da	Anchor diameter (m)
H	Vessel height (m)
Ds	Shaft diameter (m)
w	Width of the blade (m)
N	Rotating impeller (m/s)
Re	Reynold number (dimensionless)
Bn	Bingham number (dimensionless)
Vt^*	Dimensionless velocity ($V^* = V/\pi ND$)
Np	Power number (dimensionless)
R^*	Dimensionless Radius ($R^* = 2R/D$)
Z^*	Dimensionless Height ($Z^* = Z/D$)
R	Tank radius (m)
S	Rate-of-deformation tensor
Fx	Force vector direction x (N)
Fy	Force vector direction y (N)
m	Stress growth parameter (s)
A	Surface around the impeller (m^2)

Greek letters

α	Angle degree inclination (degree)
μ	Dynamic viscosity (Ps·s)
μ_0	Constant viscosity (Ps·s)
γ	Shear rate (1/s)
τ	Yield stress (Pa)
ρ	Fluid density (kg/m^3)
Ω	Rotational speed vector (1/s)
Γ	Torque (N·m)

References

[1] Mebarki, B., Draoui, B., Rahmani, L., Bouanini, M., Rebhi, M., Benachour E. H. "Numerical Study of Mechanical Stirring in Case of Yield Stress Fluid with Circular Anchor Impeller", Sensors and Transducers Journal, 132(9), pp. 108–121, 2011. [online] Available at: https://www.sensorsportal.com/HTML/DIGEST/september_2011/P_858.pdf [Accessed: 11 February 2020]

[2] Belhadri, M. "Ecoulements des fluides à seuil au travers de singularités convergentes et divergentes" (Flows of yield stress fluids through contractions and expansions), Doctoral Thesis, Grenoble Institute of Technology, 1996. (in French)

[3] Anne-Archard, D., Boisson, H. C., Marouche, M. "Etude expérimentale d'une cuve agitée en fluide viscoplastique" (Experimental study of a stirred tank in viscoplastic fluid), In: 18éme Congrès Français de Mécanique, Grenoble, France, 2007, Article ID: 9556. [online] Available at: http://documents.irevues.inist.fr/bitstream/handle/2042/16617/CFM2007-0842.pdf?sequence=1 [Accessed: 11 February 2020] (in French)

[4] Anne-Archard, D., Marouche, M., Boisson, H. C. "Hydrodynamics and Metzner-Otto correlation in stirred vessels for yield stress fluids", Chemical Engineering Journal, 125(1), pp. 15–24, 2006. https://doi.org/10.1016/j.cej.2006.08.002

[5] Rahmani, L., Draoui, B., Mebarki, B., Bouanini, M., Benachour, E., Allaoua, B. "Comparison of power consumption for viscoplastic fluid in a rotating vessel with anchor, gate and two blades impellers", International Review of Mechanical Engineering, 3(4), pp. 627–631, 2009. [online] Available at: https://www.epjconferences.org/articles/epjconf/pdf/2018/15/epjconf_efm2018_02089.pdf [Accessed : 05 January 2019]

[6] Ameur, H. "Effect of some parameters on the performance of anchor impellers for stirring shear-thinning fluids in a cylindrical vessel", Journal of Hydrodynamics, 28, pp. 669–675, 2016. https://doi.org/10.1016/S1001-6058(16)60671-6

[7] Ameur, H., Ghenaim, A. "Mixing of Complex Fluids in a Cylindrical Tank by a Modified Anchor Impeller", ChemistrySelect, 3(26), pp. 7472–7477, 2018. https://doi.org/10.1002/slct.201801047

[8] Triveni, B., Vishwanadham, B., Venkateshwar, S. "Studies on heat transfer to Newtonian and non-Newtonian fluids in agitated vessel", Heat and Mass Transfer, 44, pp. 1281–1288, 2008. https://doi.org/10.1007/s00231-007-0364-2

[9] Rahmani L, Draoui B, Bouanini M, Benachour E. "CFD Study on Heat Transfer to Bingham Fluid During with Gate Impeller", International Review of Mechanical Engineering, 7(6), pp. 1074–1079, 2013.

[10] Savreux, F., Jay, P., Magnin, A. "Viscoplastic fluid mixing in a rotating tank", Chemical Engineering Science, 62(8), pp. 2290–2301, 2007. https://doi.org/10.1016/j.ces.2007.01.020

[11] Tanguy, P. A., Thibault, F., Brito De La Fuente, E. "A new investigation of the metzner-otto concept for anchor mixing impellers", The Canadian Journal of Chemical Engineering, 74(2), pp. 222–228, 1996. https://doi.org/10.1002/cjce.5450740207

[12] Bertrand, F., Tanguy, P. A., Brito-De La Fuente, E. "A new perspective for the mixing of yield stress fluids with anchor impellers", Journal of Chemical Engineering of Japan, 29(1), pp. 51–58, 1996. https://doi.org/10.1252/jcej.29.51

[13] Prajapati, P., Ein-Mozaffari, F. "CFD Investigation of the Mixing of Yield-Pseudoplastic Fluids with Anchor Impellers", Chemical Engineering and Technology, 32(8), pp. 1211–1218, 2009. https://doi.org/10.1002/ceat.200800511

[14] Espinosa-Solares, T., Brito-De La Fuente, E., Thibault, F., Tanguy, P. A. "Power consumption with anchor mixers effect of bottom clearance", Chemical Engineering Communications, 157(1), pp. 65–71, 1997. https://doi.org/10.1080/00986449708936683

[15] Jamshidzadeh, M., Kazemzadeh, A., Ein-Mozaffari, F., Lohi, A. "Analysis of power consumption for gas dispersion in non-Newtonian fluids with a coaxial mixer: New correlations for Reynolds and power numbers", Chemical Engineering Journal, 401, Article number: 126002, 2020. https://doi.org/10.1016/j.cej.2020.126002

[16] Ameur, H. "Energy efficiency of different impellers in stirred tank reactors", Energy, 93, pp. 1980–1988, 2015. https://doi.org/10.1016/j.energy.2015.10.084

[17] Kamla, Y., Ameur, H., Karas, A., Arab, M. I. "Performance of new designed anchor impellers in stirred tanks", Chemical Papers, 74, pp. 779–785, 2020. https://doi.org/10.1007/s11696-019-00902-x

[18] Ameur, H., Kamla, Y. "Geometrical modifications of the anchor impeller to enhance the overall performances in stirred tanks", Instal, 6, pp. 42–45, 2020. https://doi.org/10.36119/15.2020.6.5

[19] Papanastasiou, T. C. "Flows of Materials with Yield", Journal of Rheology, 31(5), pp. 385–404, 1987. https://doi.org/10.1122/1.549926

[20] Wollblad, C. "Your Guide to Meshing Techniques for Efficient CFD Modeling", [online] Available at: https://www.comsol.com/blogs/your-guide-to-meshing-techniques-for-efficient-cfd-modeling/ [Accessed: 07 April 2021]

[21] Marouche, M., Anne-Archard, D., Boisson, H. C. "A Numerical Model of Yield Stress Fluid Dynamics in a Mixing Vessel", Applied Rheology, 12(4), pp. 182–191, 2002. https://doi.org/10.1515/arh-2002-0010