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The Rheological and Energy Study of the Blade Torsion Effect in a Vessel Stirred by Two- Blade Impeller

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ABSTRACT

This work presents a comprehensive numerical study on the hydrodynamic behaviour and power consumption of a cylindrical vessel stirred by a two-blade impeller, employing the simulation by the RRF method (Rotation Reference Frame). The study focuses on addressing the issue of power consumption in the context of blade orientation referring to different values equal to α=15°, α=30°, α=45°, α=90°, α=135°, and α=180°. The primary objective is to identify a novel design that promotes effective fluid circulation and exhibits lower energy consumption compared to standard geometries. By employing the commercial CFD code ANSYS CFX 14.0, the research delves into the impact of fluid rheology and blade curvature on mixing efficiency. The validation of the results, achieved by comparing them with data from existing literature, demonstrated a satisfactory agreement. According to our obtained results, it has been observed that the energy consumption decreases when the blade orientation exceeds 90°. This study contributes valuable insights into both blade orientation and Reynolds number effects (ranging from 1 to 100 for laminar flow), with the ultimate goal of proposing innovative designs that optimize fluid mixing efficiency while minimizing the consumed energy.

Keywords:
Mixing; Rheological; Curvature; Power consumption; Impeller

1. Introduction

Mixing of liquids by mechanical agitation occurs in a number of industries such chemical and polymer processing applications. Several of challenging still exists for improving the mixing efficiency and suitable configuration stirred vessel.

To study the characteristics of a machine used in an engineering application, previous studies using the CFD (Computational Fluid Dynamics) method [1-6].

The geometry of an impeller plays the key role in optimum design. For this purpose, various types of impellers are used in order to satisfy the different aims of the mixing operation. As know the two-

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blade impeller is commonly impellers used mixing of highly viscous fluids at low Reynolds numbers [7], for this purpose [8] proposed a new correlation in order to predict the power required for agitated non Newtonian fluids. YOUCEFI *et al.,* [9] studied the effect of blade height on the power consumption and mixing times for viscoelastic fluids, KOMODA *et al.,* [10] proved that change on geometrical configuration of impeller can generate optimal operation and enhance the quality of mixture. LIU *et al.,* [11] studied the performance of a new large two-bladed impeller configuration, which is based on the Maxblend and Fullzone impellers. GABRIELE *at al.,* [12] used the CFD simulations to study the effect of the modified blade attack angle on the flow prediction generated on a stirred tank equipped with pitched blade agitators in a stirred tank. AMEUR *et al.,* [13] investigated the effect of blade attack angle and shear-thinning behavior for flat and pitched bladed impellers, AMEUR *et al.,* [14] investigated the effect of rhelogical behavior, agitator speed, impeller clearance blade configuration on the fluid flow and power consumption. The performance of newly designed impellers in stirred tanks is studied by several researchers [15, 16]. NOVIA *et al.,* [17] examined the hydrodynamic characteristics of a fermenter using ANSYS FLUEN. As well previous studies [18-20] designed a new type of the stirrer of the cylindrical to improve the mixing efficiency of this type of agitator. The effect of the design and optimization of WAG injection operations is also studied by previous researcher [21].

The use of twin blade mixers in industry is of great importance, especially when mixing viscous liquids and powders. These mixers play an essential role in many applications, helping to optimize manufacturing processes.

The main objective is to explore the influence of Reynolds number, fluid properties, and curvature blade on the flow fields, power number.

There is a wide range of mixing geometries available for viscous fluids and the selection of an appropriate design for a given application is not an easy task Ameur *et al.,* [22], in 2011. ANNE *et al.,* [23] studied numerically the flow of non-Newtonian fluid in a tank stirred by a double helical ribbon and an anchor agitator. The effect of the geometric configuration of a propeller agitator on thermal performance has been experimentally studied by Mahir *et al.,* [24], in 2021.

2. Methodology

2.1 Simulation Model

Figure 1 shows all dimensions of the agitation system studied. The stirred vessel consists of a cylindrical flat bottom unbaffled tank of diameter (D) and height (T). The impeller consists of two blades with diameter (d), fixed on a shaft of diameter (ds/D=0.05). The impeller shaft is concentric with the axis of the vessel, the impeller clearance from the tank bottom is (C/D=0.05). The effects of the Reynolds number, rheological behavior, blade curvature and the blade diameter have been analyzed. The different degrees of blade curvature were considered and which are: α = 15°, 30°, 45°, 90°, 135° and 180° respectively.

Study is restricted to the laminar regime, the Reynolds number is varying in the range from Re= 0.1 to 32. A series of shear thinning fluids obeying the power-law model are considered: the consistency index is m= 8 Pa s, and the power law indices range from n= 0.2 to 1. In all the computations, the fluid density is 1394 kg/m3.

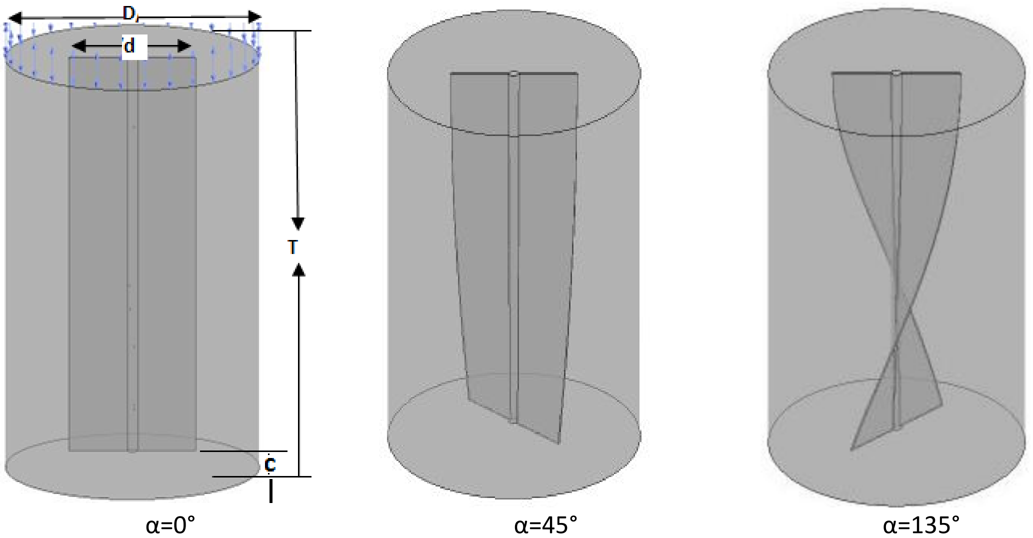


Fig. 1. Schematic of the agitated system

2.2 Mathematical Equations

The following continuity and momentum equations describe the laminar flow of a fluid agitated by a two-blade mechanical agitator:

$$\frac{\partial \rho}{\partial t} = -\nabla.\rho v \tag{1}$$

$$\frac{\partial (\rho v)}{\partial t} = -\nabla.(\rho v v) - \nabla p + \nabla.\tau + \rho g + F \tag{2}$$

With: ρ, p, v, g, F and τ respectively are: fluid density, pressure, velocity, gravity, force, and the stress tensor given by:

$$\tau = \mu\left[(\nabla v) + (\nabla v)^T - \frac{2}{3}(\nabla v)I\right] \tag{3}$$

In Eq. (4), (μ) represents the dynamic viscosity, and (I) is the unit tensor. For an incompressible fluid, the stress tensor is given by the following equation:

$$\tau = \mu\left[(\nabla v) + (\nabla v)^T\right] \tag{4}$$

The shear thinning fluid behavior is modeled by the Ostwald de Waele model according to the following equation:

$$\tau = m.\gamma^n \tag{5}$$

With: (n) is the fluid behavior index and (m) is the consistency index whose unit is a function of (n) are both positive; for a shear thinning fluid, (n) is less than 1

The Reynolds number is given by the following relation Eq. (6) for a shear thinning fluid (Ostwald model):

$$\mathrm{Re}_g = \frac{\rho N^{2-n} D^2}{m} \tag{6}$$

The power number is an important parameter which characterizes the stirring system, it is calculated in this numerical study by:

$$Np = \frac{P}{\rho N^3 D^5} \tag{7}$$

In the above equation: (N) is the speed of the agitator, (P) is the power consumed by the agitator.

3. Results

3.1 Model Validation

In order to check the validity CFD model, similar geometrical conditions to those chosen by Bertrand *et al.,* [25] were considered. Which we have validated with their experimental and numerical study as shown in Figure 2, good agreement is demonstrated.

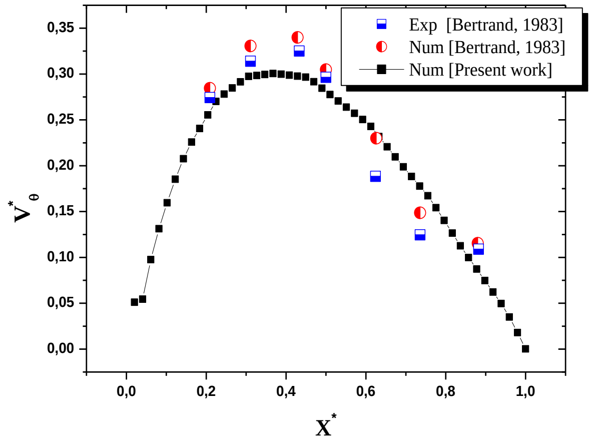


Fig. 2. Tangential velocity for Re = 37.86

3.2 Effects of the Blades Orientation

The impeller design is an important parameter for enhancing quality, capacity, process efficiency and energy efficiency of a mixing system. For meeting these objectives, it is imperative that the relationship between the flow pattern and the design objective is understood. One of the flow characteristics affecting the impeller flow efficiency is the presence of trailing vortices generated at the tip of the impeller blades.

The effect of blade curvature on the flow patterns and power consumption has also been studied. To perform this test, four geometrical configurations have been realized, which are: d/D= 0.535, 0.625, 0.75 and 0.937 respectively.

For a location below the impeller (Z*= 0.5) and along the vessel radius (Figure 3), the tangential velocity is plotted for the four cases studied. As illustrated, the increase of the balde curvarture can agitate the motion of fluid particles. Figure 4 shows the variation of radial velocity along the height of vessel, with variation of angle curvature blade.

The maximum value the radial velocity is reached for α=90°, so, we can deduce that curvature of blade have effect of radial flow.

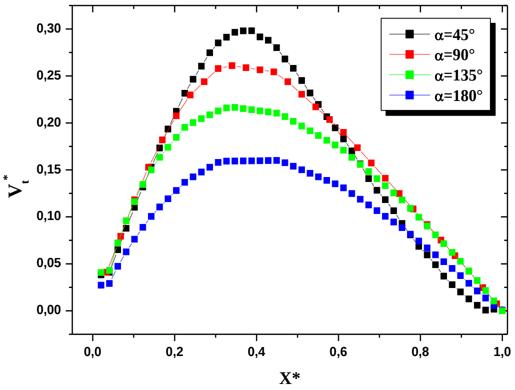


Fig. 3. Tangential velocity for Re = 10, d/D = 0.5 and Z* = 0.5

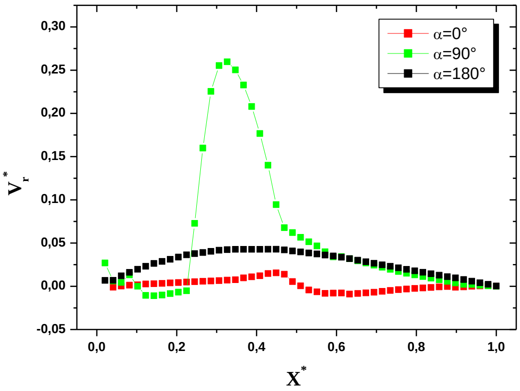
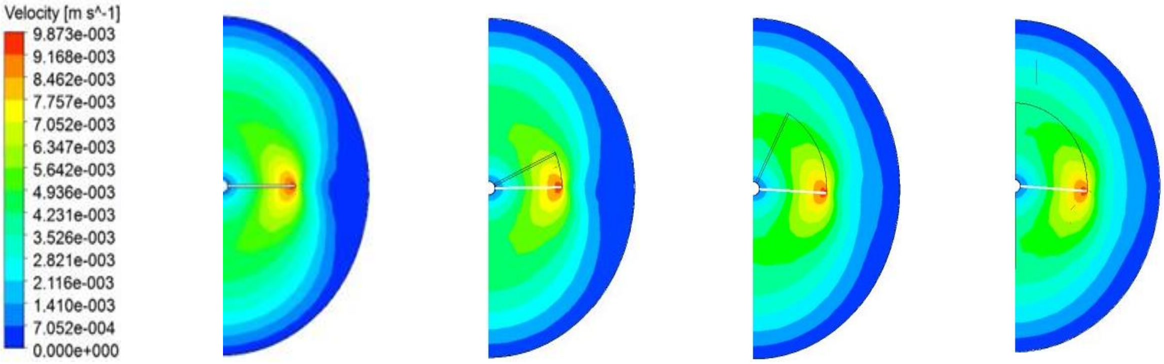


Fig. 4. Radial velocity for n = 0.4, Re =10, d/D = 0.5 and Z* = 0.5

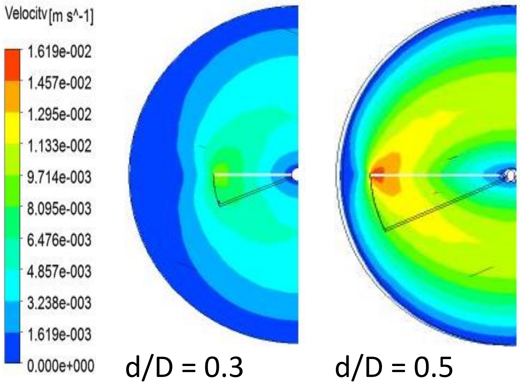
The velocity is presented for the four geometries (Figure 5).It can be seen that the maximum value of velocity is reached at the tip of the each blade. Moreover, we find that the area swept by the impeller becomes greater with the increase in blade curvature, the cavern size become larger in size. Thus, we deduce that the blade curvature have a significant effect on the cavern size.

The diameter of blades is another parameter that can strongly influence the size of the cavern, a comparison of the two slices permits to obtain the following figure 6.



α = 0° α = 45° α =135° α = 180°

Fig. 5. Velocity distribution for Re = 10, d/D = 0.5, Z*=0.5



d/D = 0.3 d/D = 0.5

Fig. 6. Velocity distribution for different diameters, α = 45°

3.3 Power Consumption

The effect of blade width on the flow patterns and power consumption has also been studied. For this purpose two geometrical configuration have been used which: d/D =05, 0.82 respectively. The results show that the increasing on blade width enlarges the well-stirred region and ensures mixing in the whole vessel volume, but the power required is greater (table 1).

Table 1
Power number for Re=10

Orientation angle [°]	45	90	135	180
d/D = 0.5	22.99	22.23	21.96	21.71
d/D = 0.82	113.4	112.7	111,90	111.0

3.4 Effect of the Power Law Index

The rheological properties of the fluid have significant effect on the flow structure. For this purpose, four values of the structural index (n) were chosen (0.2, 0.4, 0.8 and 1). The variations of the tangential velocity component along the vessel radius and for the four cases studied are plotted on figure 7 at the mid height of the impeller blade, Along the lines corresponding to the curvature radius α=90°, the evolution of the tangential velocity is followed for different structural indices, it has been noted that at the mid-height of the impeller blade, show a maximum at the blade tip for any value of the structural index and become negligible, but when the structural index n is more lower, the momentum transfer become less intense, due of the viscous forces, which explains the speed decay curves (for solutions n= 0.2 and 0.4).

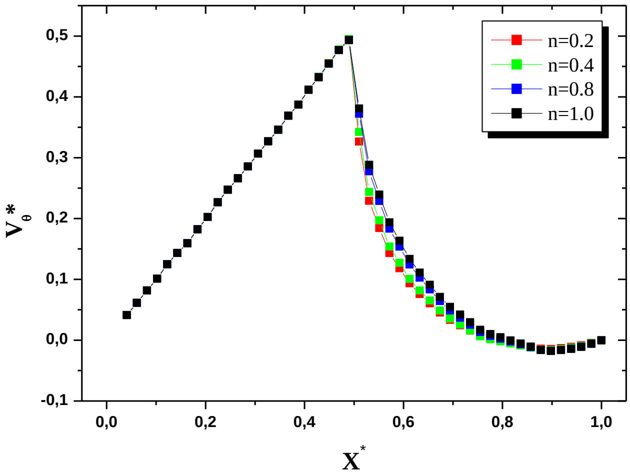


Fig. 7. Tangential velocity, Re=10, α=90°

The variation in the radial velocity component along the vessel radius as a function of the rheological behavior is presented in Figure 8. It has been noted that within the area swept by the blades of the stirrer, the velocity gradients are stronger when compared to the rest of the vessel volume; this phenomenon is illustrated in Figure 10.The maximum absolute value is reached for n = 1.

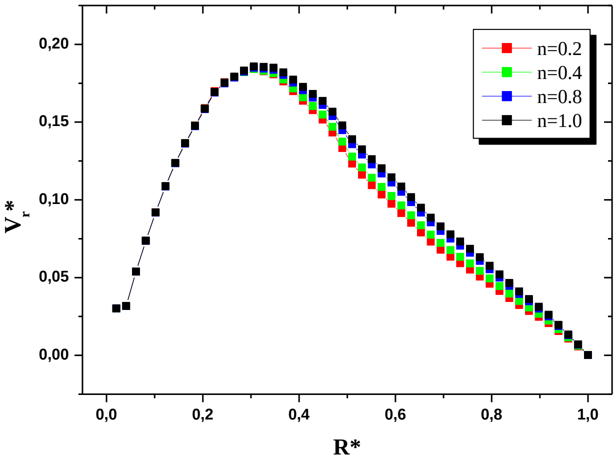


Fig. 8. Radial velocity for Re = 10, Z* = 0.001, α = 135°

In order to illustrate the effect of the rheological behavior on the vortex size, the axial and radial velocities have been followed as a function of the structural index n figure 9 and 10. The results shows that at the immediate contact with the side wall and at the stirrer axis, the velocity is negligible whatever the value chosen for n, on the other hand, it's clear that increasing the structural index increases the axial flow in the area between the tips of the turbine blades and the walls of the tank.

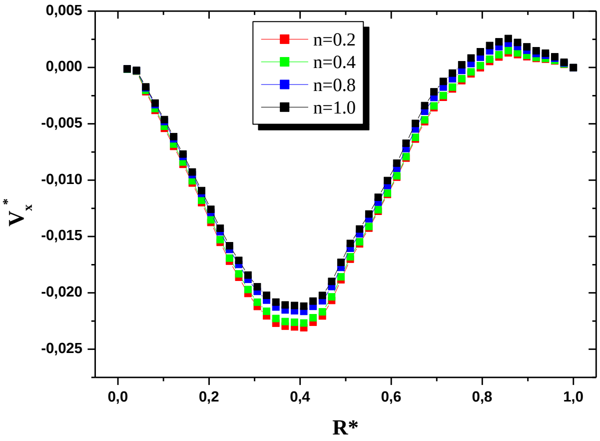


Fig. 9. Axial velocity for Re = 10, Z* = 0.001, α = 135°

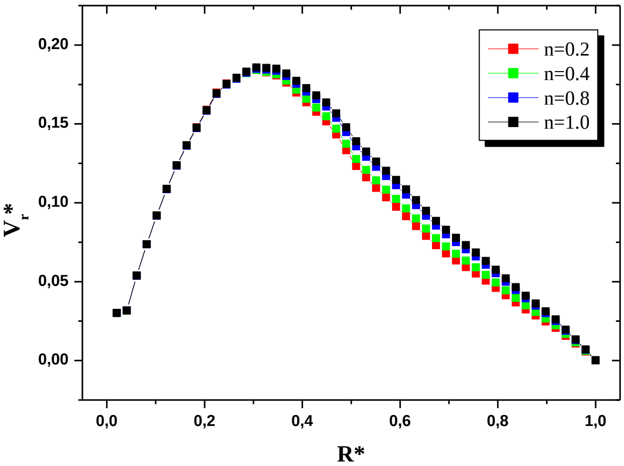


Fig. 10. Radial velocity for Re = 10, Z* = 0.001, α = 135°

Power consumption is the most important parameter to describe the performance of a mixing system. Here, the power requirements for different structural index and different curvature angles are presented (Table 2) and figure 11, it has been observed that the increasing of flow behavior index requires higher power consumption due to the viscous forces. On the other hand reduction of Np is obtained with increasing blade curvature. So we can deduce, that blade orientation have significant effect on the power consumption.

Table 2
Place power number for two blade impeller, Re=10

	α = 0°	α = 45°	α = 90°	α = 135°	α = 180°
n = 0.2	8.63	8.40	8.35	8.28	8.21
n = 0.4	10.28	10.31	10.30	10.20	10.06
n = 0.8	16.60	16.66	16.55	16.36	16.21
n = 1	22.33	22.35	22.20	21.94	21.68

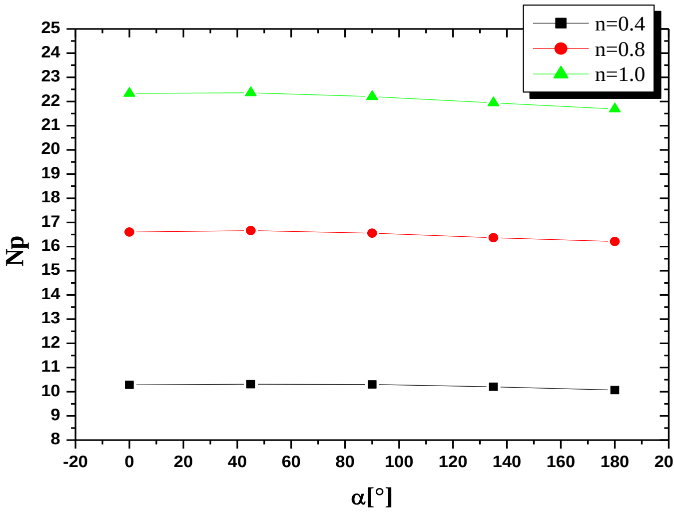


Fig. 11. Power number vs. many impeller curvature angle α = 0°, 45°, 90°, 145°, 180°, Re = 10

4. Conclusions

In this paper, a numerical characterization of laminar flow and power consumption in agitated vessel with curved blade agitator has been developed in order to provide a physical analysis of mixing in Newtonian fluid. For each configuration, the power consumption was calculated. From the obtained results, it has been proven that the size of the impeller plays an important role on the flow structure. The increase in the blade curvature is beneficial to enhance radial flow and enlarge wide cavern size with longer blade diameter which provide new approach on as well as this new blade configuration requires less power consumption. This study has demonstrated that the parametric analysis of laminar flow for viscous fluid in geometrics involved in industrial process, such as agitated tanks, can be efficiently handled through CFD.

These outputs will be considered for the design of the stirred tanks and improving of the energy efficiency.

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