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Numerical Study of Bottom Shape Effect on the Mixing for Stirred Tank

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Abstract: In this work, computational fluid dynamics (CFD) was used to investigate the effect of the bottom shape on the flow field and mixing characteristics in an agitated vessel stirred by six-pitched blade turbine (PBT6). The simulation was based on the resolution of the Navier-Stokes equations using standard k-ε turbulence model. Hydrodynamic behavior of the stirred vessel with four types of bottom shapes was investigated, a flat bottom and three different semi-elliptical bottoms. The results show reasonably satisfactory agreement with the experimental data. The CFD simulation also showed that the semi-elliptical bottom shapes had a significant influence on the velocity profiles and on the turbulent kinetic energy distributions of the local flow generated at the bottom region of the vessel.

Keywords: Bottom shape, computational fluid dynamics (CFD), hydrodynamic, tank height, turbulent flow.

1. Introduction

Mechanical agitation occurs in several industrial processes. Its field of application is very wide, from the mixing of miscible fluids to the manufacture of pharmaceutical products. Stirring techniques are parameters to take into account when optimizing a process.

In the literature, the study of agitation systems has been initiated in several works. We can mention the work of Hao et al. [1] who studied the influence of bottom shape on hydrodynamics and particle suspension in a DTB crystallizer. The effect of eccentrically located position of the impeller on the mixing time was investigated by Koji et al. [2] in agitated vessels of different bottom shapes. They concluded that the bottom shapes do not affect the mixing time but give a significant influence on power consumption. Experimental studies have been performed by Ghionzoli et al [3] and Kondoo et al. [4] to evaluate the influence of bottom roughness and optimum bottom shape on solid particle dispersion in stirred vessels. They concluded that the distribution of the solids concentration in the tank was significantly influenced by the local flow formed at the vessel base.

The comparative study has been carried out by Foukrach et al. [5] on the influence of the vessel shape on the hydrodynamic performances in a tank mechanically agitated by a Rushton turbine and by Ammar et al. [6] on the design effect for three different vessel shapes: a flat-bottomed cylindrical vessel, a dished bottomed cylindrical vessel and a closed spherical vessel. Gong et al. [7] studied the effect of different geometric parameters in stirred vessels with a flat square base equipped with four blades impeller on the particles concentration in a solid-liquid system. Binxin. [8] evaluated six turbulence models of a non-Newtonian fluid in a mechanically stirred anaerobic digester with inclined turbine blades (PBT) by using (standard k-ε, realizable k-ε, RNG k-ε, Standard k-ω, SST k-ω and Reynolds Stress Model). He found that the standard turbulence models k-ω and the realizable k-ε performed better than the other models. Numerical and experimental studies carried out by Antonija et al. [9] investigated the mobile type effect of agitation and its position in a cooling catalyst on the enhancement of the kinetic of the crystal borax decahydrate. The used geometry was a cylindrical flat bottom tank equipped with four baffles placed at 90° with a distance ratio between the impeller and the bottom which varies from 0.1 to 0.5 for three types of turbines and four different blades. For a low viscous Newtonian fluid and turbulent flow regime, Taca and Paunescu [10] studied experimentally the power input in a spherical closed vessel stirred by a Rushton turbine or six pitched blade impeller. A comparative study was conducted by Jie et al. [11] on the influence of the bottom shape and of the baffles' length on the velocity distribution in transitional and turbulent flow, in two agitated tanks (flat bottom and dished bottom), equipped with a Rushton turbine. They found that the shapes of the bottom tank have significant effect on the flow pattern, as well as on the velocity profiles below the impeller.

LDV method was used by Aubin et al. [12] to measure the one single phase turbulent flow in a tank stirred by a down and an up-pumping modes using two different turbines. They observed the circulation efficiency and it was shown to be clearly superior for up-pumping impellers (especially for the PBT) than for the down-pumping or reverse mode operations. Using a PIV and LDA systems, Aubin et al. [13], Gabriele et al. [14] and Petrícek et al. [15] studied the effect of the down and up-pumping direction of the impeller in a stirred tank. From these anterior studies, it is clear that the design investigation of the bottom shape for stirred tank is very useful.

The present work aims to determine the influence of geometrical parameters of the stirred vessel with down pumping direction from a pitched blade turbine (PBT 45°) on the hydrodynamic structure of the flow. Moreover, we are interested in moving the lowest point of the tank located at the center dished bottom towards the turbine by reducing the bottom height with the same distance.

2. Geometry model

As presented in *Fig. 1*, four geometrically scaled vessels are chosen with different tank heights equal to: $H+h_3$=0.190 m named case 1, $H+h_2$=0.177 m named case 2, $H+h_1$=0.164 m named case 3 and H=0.152 m named case 4. The first system configuration is similar to the one presented by Aubin et al. [12]. In these conditions, the tank height is equal to the diameter $H=T$ for each tested geometry, and is completely filled with water. In each case, a six pitched blade turbine PBT45° has been used, with diameters d_1=0.095m, d_2=0.088m, d_3=0.082m, d_4=0.076m, respectively.

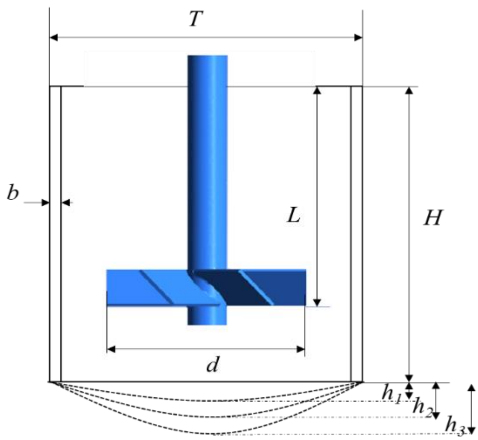


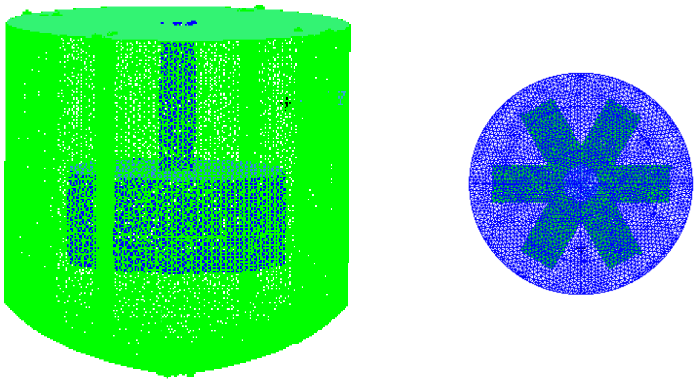
Figure 1: Vessel configuration

3. CFD simulation

Three-dimensional computational fluid dynamic modeling was carried out. to investigate, with the help of a CFD software (Ansys CFX), the flow field in an agitated vessel stirred by six-pitched blade turbine (PBT6). The computer tool Ansys ICEM CFD is used to mesh the computational domain by tetrahedral cells

(*Fig. 2*). The domain is divided into two distinct zones. Tank walls and baffles constitute the stationery zone (*Fig. 2a*) discretized with 530208 nodes. A rotating zone (*Fig. 2b*) describes the rotational motion of the fluid around the impeller. This zone is discretized with 188773 nodes. The boundary conditions are introduced in ANSYS CFX-Pre, using the multiple referential approach (MRF).

In this approach, the interface between the two regions is treated by the method called frozen rotor and the flow fields are connected at the interior surfaces (interface) separating the two domains.



a. Stationary zone *b. Rotating zone*

Figure 2: Tetrahedral mesh generation

4. Equation

The power Number (*Np*) is an essential parameter to estimate agitated tank. It is given as:

$$N_P = \frac{P}{\rho N^3 d^5} \tag{1}$$

In (1), *P* is the power consumption, *d is* turbine diameter and *N* is the impeller rotational velocity. The Reynolds number Re is the ratio between the viscous and inertia forces:

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

In (2), ρ and μ are the density and dynamic viscosity of the working fluid.

The dimensionless radial and axial coordinates *r** and *z** are defined respectively as:

$$r^* = {}^{2r}/_{T} \text{ and } z^* = {}^{z}/_{T} \tag{3}$$

In (3), r is radius of the tank, z is axial coordinate and T is vessel diameter. The velocity at the edge of the blade is defined as:

$$V_{tip} = \pi N d \tag{4}$$

The dimensionless radial velocity component is

$$V^* = \frac{V}{V_{tip}} \tag{5}$$

5. Numerical results

5.1 Validation

First, we considered necessary to validate the CFD model, for this purpose we have referred to the work of Aubin et al. [12]. With the exactly same geometrical conditions we predicted the variation of radial profile of turbulent kinetic energy k^* along the vessel dimensionless radius r^* (*Fig. 3*) for Reynolds number equal with 4.5×10^4. At axial position $z/H = 0.057$, it can be seen that predicted profiles have a similar form to the experimental one and there the agreement is quite good. As observed on this figure, the maximum wake of the dimensionless turbulent kinetic energy extended with the up-pumping direction flow is caused by the inclined angle of the blade impeller.

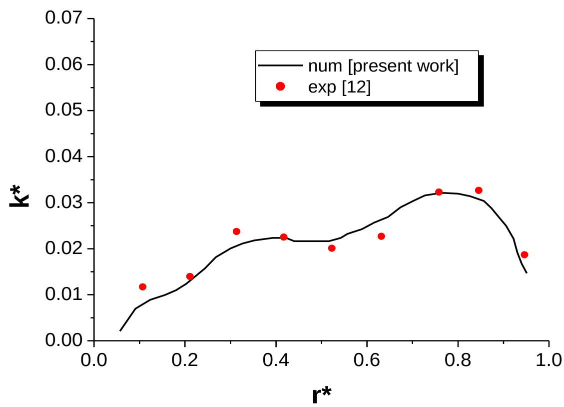


Figure 3: Radial profiles of dimensionless turbulent kinetic energy at axial position *z/H*=0.057

5.2 Effect of the bottom shape of tank

5.2.1 Tangential Velocity

The distribution of the turbulent viscosity is presented in the r–z plane (*Fig. 4*). In the two configurations corresponding to case 1 (*Fig. 4a*) and case 4 (*Fig. 4d*), the wake of the maximum values of the turbulent viscosity appears on the mechanical source and develops within the fluid to reach the sidewall of the tank. Indeed, reducing the height of the convex bottom creates larger amplitude circulation loops in the upper part of the tank with a dished bottom, for both systems case 2 and case 3 (*Fig. 4b* and *4c*, respectively).

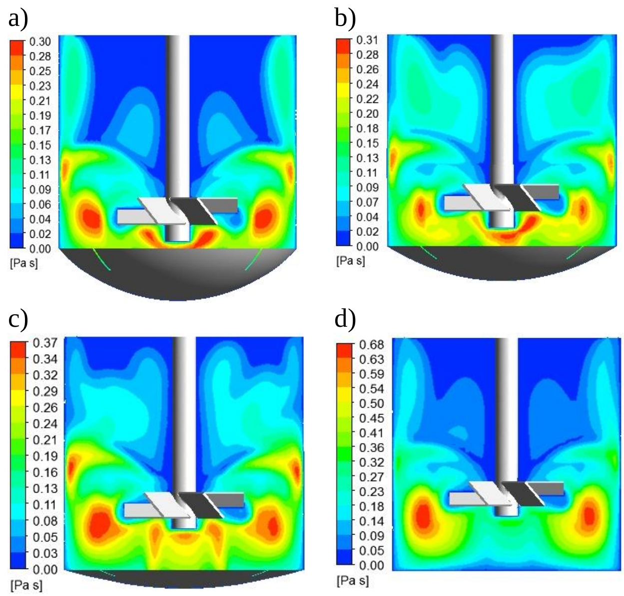


Figure 4: Velocity contours in the r-z plane

5.2.2 Turbulent kinetic energy

The distribution of the turbulent kinetic energy is shown in *Fig. 5*, on the vertical plane. The turbulent kinetic energy keeps a high value at the proximity of the side wall of the tank for the 3rd and 4th configurations (*Fig. 5c* and *5d*). This is explained by the reduction of the distance between the impeller and the bottom center of tank. In the first configuration with dished bottom corresponding to case 1 (*Fig. 5a*), the turbulent kinetic energy is very low with 0.07 m^2/s^2 compared to the three other cases. It can be noted that as the vessel diameter decreases, there is a continuous increase in turbulent kinetic energy between the impeller blade tip and vertical wall of the tank.

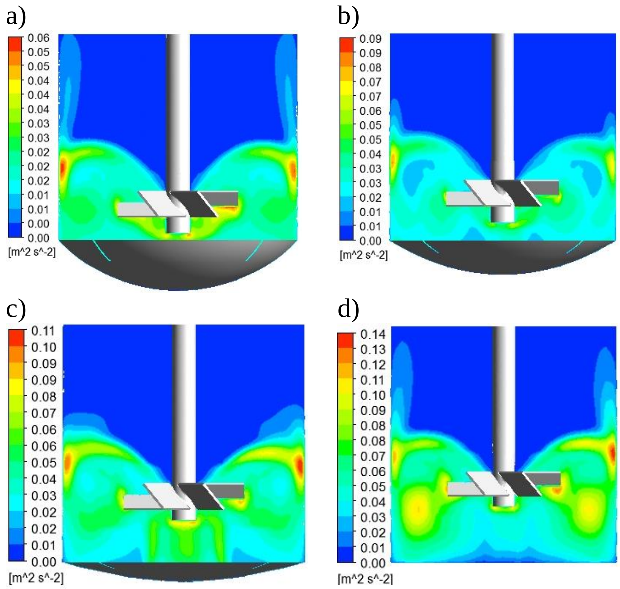


Figure 5: Turbulent kinetic energy contours r-z plane

5.2.3 Radial profiles of the dimensionless turbulent kinetic energy

For a location just below the pitched blade turbine at z=15mm, the profiles of dimensionless turbulent kinetic energy are plotted on *Fig. 6* for four cases. Particularly, in case 4 corresponding to a tank with flat bottom, the height values of turbulent kinetic energy are obtained along the vessel radius. This is due to the small distance between the impeller and effects of the flat bottom shape of the tank. But in the other three tank configurations with dished bottom, the turbulent kinetic energy profile decreases gradually and becomes negligible at sidewall. The magnitude of *TKN* increases with respect to the decrease of tank diameter and close turbine to the vessel base with a small ratio of *d/T*.

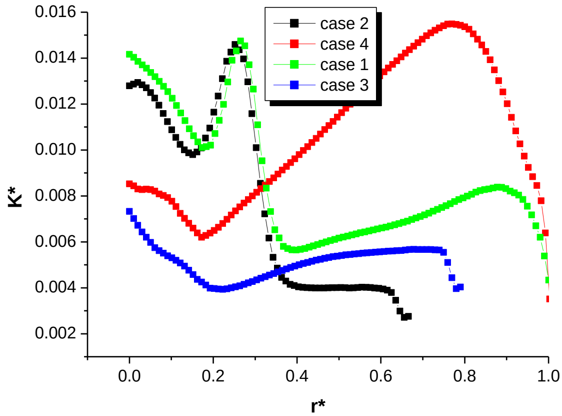


Figure 6: Dimensionless turbulent kinetic energy at z= 15mm, *N*=300 rpm

5.2.4 Flow patterns

The flow velocity vectors generated for all studied configurations are shown in *Fig. 7*. These figures indicate the dominance of a radial jet originating from the turbines which divides into two jets when it reaches the side wall of the tank. The descending jet creates an intense recirculation zone at the bottom, while the ascending jet decreases gradually in the configurations corresponding to case 1, 2 and 4 (*Fig. 7a*, 7b and *7d* respectively).

A very larger circulation loop is formed near the vertical solid wall in the tank with a dished bottom i.e. case 3 (*Fig. 7c*). This can be explained by higher down-pumping flow effects of the pitched blade turbine and the shape of vessel base.

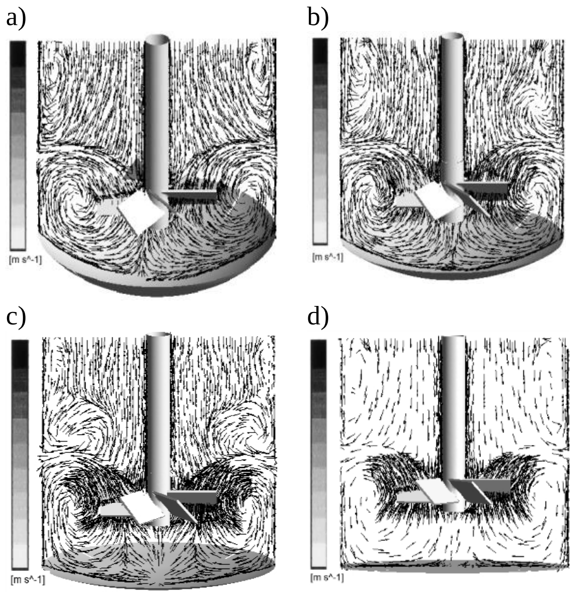


Figure 7: Flow patterns in r-z plane

5.3 Dimensionless velocity profiles

5.3.1 Axial velocity component

The profiles plotted on *Fig. 8* give the distribution of dimensionless axial velocity for four cases studied at $z^*= 0.13$. We can distinguish two different zones: negative and positive zone of the axial component. This dynamic phenomenon is due to the down pumping effect of the six pitched bade turbine toward the bottom of the tanks. In the first configuration (case 1), the axial component is very low compared to the other configurations (cases 2, 3 and 4 respectively), because of the bottom shape effect of each tank and the large distance between the impeller and vessel base. Arguably, the axial velocity component is influenced by the impeller's clearance from the tank bottom.

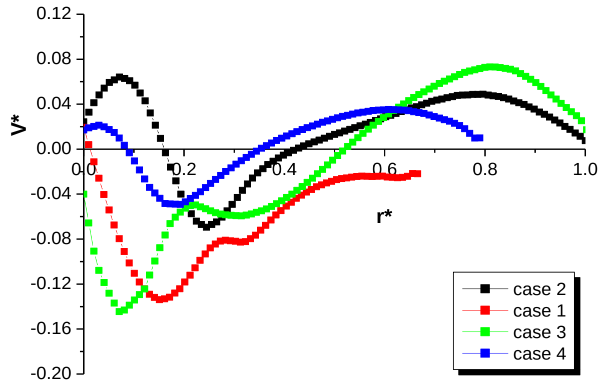


Figure 8: Axial velocity at axial position z*= 0.13 (below the impeller), *N*=300 rpm.

5.3.2 Radial velocity component

Fig. 9 shows a parabolic shape of the dimensionless radial component along the vessel's radius (in the space between shaft and vertical side wall). At *z**= 0.13, the profiles of the radial velocity are distributed according to the configurations studied in decreasing way: case 3, 1, 4 and 2 respectively. This velocity profile is due to the reduction of the bottom height of the tank. The radial component is more significant for two configurations: case 1 and case 3, both with a dished bottom tank. In the case 4 with flat bottom of the tank the velocity is very low. The negative values of the velocity indicate the existence of recirculation loops.

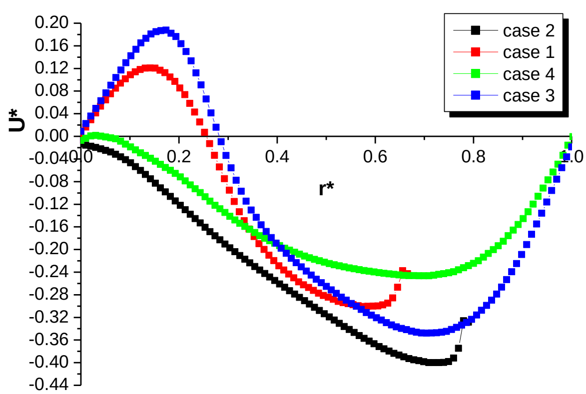


Figure 9: Radial velocity at axial position z*= 0.13 (below the impeller), *N*=300 rpm.

6. Conclusion

The goal of the investigation in this work was to determine the effect of the distance between the turbine and the bottom of the tank with different geometries. From the presented results the following conclusions can be deduced.

In planes r-z the reduction in bottom clearance for all tank configurations leads to significant growth in the parameters of turbulent viscosity and turbulent kinetic energy. A closer bottom to the turbine results in the intense movement of turbulent viscosity towards the solid walls of the tank and a notable improvement in the upper part for both configurations, namely case 2 and 3. It minimizes the stagnation of the turbulent kinetic energy at the vessel base. It has been clearly noticed that the axial and radial velocities are directly affected by impeller size and tank design. The impeller clearance from the bottom tank with the down pumping direction of pitched blade turbine plays also an important role by improving the operating conditions of stirring and mixing.

We can conclude that the design of the bottom shape of the cylindrical tank with down pumping direction of a pitched blade turbines is a very important parameter in optimizing the mixing systems.

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