Chin. J. Mech. Eng. (2017) 30:1008–1016
DOI 10.1007/s10033-017-0158-5

ORIGINAL ARTICLE

Effect of the Inclination of Baffles on the Power Consumption and Fluid Flows in a Vessel Stirred by a Rushton Turbine

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Received: 17 December 2015 / Revised: 17 May 2016 / Accepted: 27 November 2016 / Published online: 12 June 2017

Abstract The role of baffles in mechanically stirred tanks is to promote the stability of power drawn by the impeller and to avoid the fluid swirling, thus enhancing mixing. The present paper numerically investigates the baffles effects in a vessel stirred by a Rushton turbine. The geometric factor of interest is the baffle inclination which is varying between 25°, 32.5°, 45°, 70° and 90° at different impeller rotational speeds. The impeller rotational direction has also been varied. The vortex size and power consumption were evaluated for each geometrical configuration. It was found that the best configuration is the baffle inclination by $\alpha = 70°$ at a negative angular velocity.

Keywords Stirred tanks · Power consumption · Baffles · Rushton turbine · CFD simulation

Abbreviations

a	blade length, m
b	blade height, m
c	impeller off-bottomed clearance, m
C	Torque, N·m
d	impeller diameter, m
D	tank diameter, m
d_s	shaft diameter, m
H	liquid level, m
N	number of impeller revolution, rev/s
nb	number of baffles, dimensionless
Np	power number, dimensionless
P	power, W
Q_v	viscous dissipation function, 1/s^2
R	radial coordinate, m
Re	Reynolds number, dimensionless
S_l*	Vortex length, dimensionless
S_w*	Vortex width, dimensionless
V_r, V_z, V_θ	radial, axial; tangential velocity, m/s
w	baffle length, m

Greek symbols

ρ	fluid density, kg/m^3
μ	viscosity, Pa·s
θ	angular coordinate, degree
ω	angular velocity, rad/s
α	angle of the baffle inclination, (°)

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1 Introduction

The baffles are present in several industrial equipments, such as in the solar air heater, storage water heater, heat exchanger, stirred tanks [1–4].

In mechanically stirred tank reactors, the choice of the vessel and impeller geometry, the number and type of baffles can vary depending on the operation carried out. If no baffles are supplied in a stirred vessel filled with low viscosity fluids, the rotating impeller imparts a tangential motion to the liquid. The fluid moves along circular trajectories with high circumferential velocity creating poor mixing and a vortex is created at the free surface, whose depth depends on the agitation rate [5]. Installation of the baffles effectively destroys the circular fluid flows, inhibiting the vortex formation so that the liquid surface becomes almost flat. Moreover, axial flows become much stronger, leading to an improved mixing rate [6].

However, there are cases in which the use of unbaffled tanks may be preferred. Baffles are usually omitted in the case of very viscous fluids ($Re < 20$), where they, giving rise to dead zones, may actually worsen the impeller performance, and where vortex formation is inhibited by the low agitation rate and by the high friction on the cylindrical wall [7]. Unbaffled vessels give rise to higher fluid-particle mass transfer rates for a given power consumption, they are preferred also in crystallizers where the presence of baffles may promote the particle attrition phenomenon. Another situation where vessels without baffles are used is the mixing of highly viscous non-Newtonian fluids with close clearance impellers [8, 9]. Tatterson [10] reported that the swirling flow formed within the unbaffled vessel leads to lower power numbers. Assirelli, et al [11] reported that these lower values of power number, together with the need to limit the impeller rotational speed to that at which the central vortex reaches the impeller if gas ingestion is to be avoided, severely limits the energy that can be imparted to the fluid and which may be required to produce the necessary transfer and reaction rates. Assirelli, et al [11] reported also that the swirling flow and the unstable flow conditions found when the central vortex reaches the impeller can give rise to mechanical damage, especially at the larger scale.

During recent years, the study of the power consumption in mechanically stirred vessels has been continued by researchers for different impeller types. Ameur, et al [12] determined the power consumption for a Scaba 6SRGT impeller with baffled and unbaffled vessels. Iranshahi, et al [13] studied the effect of baffles on the power consumption for a Maxblend impeller. They noticed that the power consumption increases in the baffled stirred vessels. For several turbines, Strek and Karcz [14] studied the power consumption in a vessel equipped with short baffles. They reported that the shorter baffles located at a certain distance from the vessel base are an interesting solution for some applications as the production of suspension. Lu, et al [15] studied the effects of the width and the number of baffles in mechanically agitated vessels with standard Rushton turbine impellers. They reported that the insertion of the appropriate number of baffles improves the extent of liquid mixing. However, the excessive baffling (i.e., $nb > 8$ or $w/D > 0.2$) through the impeller would interrupt liquid mixing and lengthen the mixing time. For a Rushton turbine, Youcefi, et al [16] studied the flow fields and the power consumption for three types of vessels: unbaffled, baffled and a vessel with slots placed at the external perimeter of its vertical wall. These authors interested to the effect of the slot lenght.

Our review of the literature shows that no paper has been published on the effects of the baffle inclination in stirred tanks. Therefore, the purpose of this research is the determination of power consumption and vortex size in a vessel stirred by a Rushton turbine. Five geometrical configurations concerning the baffles inclination were realized.

2 Mixing System

The mixing system (Fig. 1) consists of a six-blades Rushton impeller in a flat bottomed cylindrical tank with a diameter D equal to its height ($D = H = 150$ mm). The impeller which has a diameter $d = D/3$ is mounted on a disc of a diameter and a thickness $g/d = 3/4$ and $x/d = 2/50$, respectively.

The shaft is placed concentrically with a diameter ratio $d_s/d = 1/5$. The blade is defined by a height and a width equal to $a/d = 1/4$ and $b/d = 1/5$, respectively. The clearance between the bottom of the vessel and the midsection of the impeller disc is $c = D/3$ (Table 1). Water at 25°C (density $\rho = 997$ kg/m^3, dynamic viscosity $\mu = 0.00089$ kg/(m·s)) is used as a working fluid.

The vessel is equipped with four equally spaced baffles with a width $w/D = 1/10$ and a thickness $e/D = 1/75$. The effects of baffles inclination were investigated by realizing four geometrical configurations and which are: α (angle of inclination) is 25°, 32.5°, 45°, 70° and 90°, respectively.

3 Theoretical Background

In this study, the Reynolds number is varying from 4×10^4 to 8×10^4. The standard k-ε model is used for modeling the turbulent flow. The Reynolds number for the flow in a stirred vessel is defined as:

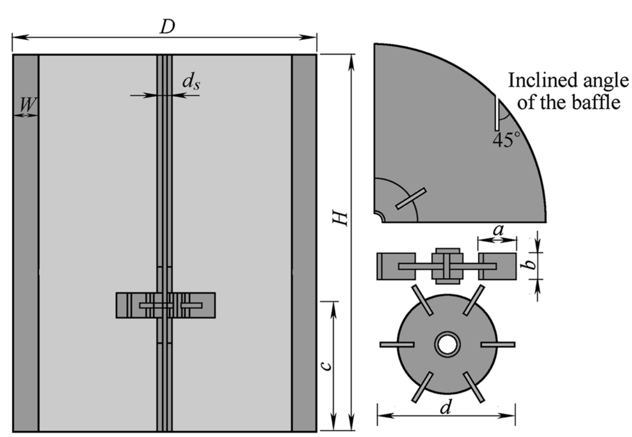

Fig. 1 Mixing system

$$Re = \frac{\rho N D^2}{\mu}, \quad (1)$$

where N is the number of impeller revolutions ($\omega = 2\pi N$, ω is the angular velocity), μ is the dynamic viscosity of the working fluid and Re is the Reynolds number.

The radial (R) and axial (Z) coordinates are normalized as: $R^* = 2R/D$, $Z^* = Z/D$. Velocities are normalized with the blade tip velocity ($V_{tip} = \pi N D$): $V^* = V/V_{tip}$. The power number is calculated according to this equation:

$$N_P = \frac{P}{\rho N^3 D^5}. \quad (2)$$

4 Numerical Simulation

The present study is performed with the help a CFD computer program (CFX 13.0). The Navier-Stokes equations written in a rotating, cylindrical frame of references are solved.

In the case of unbaffled vessels, the rotating reference frame technique is used. In this approach, the stirrer was kept stationary while the vessel walls were assigned an angular velocity, which was equal and opposite to the impeller rotational speed. Further details can be found elsewhere [17].

In the case of baffles vessels, the MRF (Multiple Reference Frame) technique may be used [18]. Here, the computational grid consists of two parts: an inner rotating cylindrical volume enclosing the turbine, and an outer, stationary volume containing the rest of the tank. However, the sliding mesh approach [19] is to divide the computational domain into two meshes, one moving with the impeller while the other one is fixed. For the unbaffled configuration and according to the finding of Deglon and Meyer [20], the MRF technique is considered in this paper.

With the help of the ICEM CFD 13.0 software, the domain was discretized using an unstructured tetrahedral mesh Fig. 2. A refined mesh has been created in the vicinity of impeller and near the vessel walls. The mesh size was selected basing to the details given by Haque, et al [21]. The convergence criterion on residuals was set to 10^{-5}, this limit was reached after 400 iterations.

5 Results and Discussion

5.1 Validation of the Predicted Results

As a first step, a comparison is made between our predicted results and the experimental data given by Wu and Patterson [22]. We note that the same geometry as that used by Wu and Patterson has been considered. Fig. 3 presents the variation of tangential velocity along the vessel height for a radial location $R^* = 0.185$. The evolution of the tangential component of velocity along the vessel height is also followed for other radial positions: $R^* = 0.222$ and $R^* = 0.285$ (Fig. 4 and Fig. 5, respectively). As observed on these figures, the comparison shows a satisfactory agreement.

The predicted results of Deglon et al. [20] are also depicted on Fig. 3. As remarked, our results are more close to the experimental data given by Wu and Patterson [22].

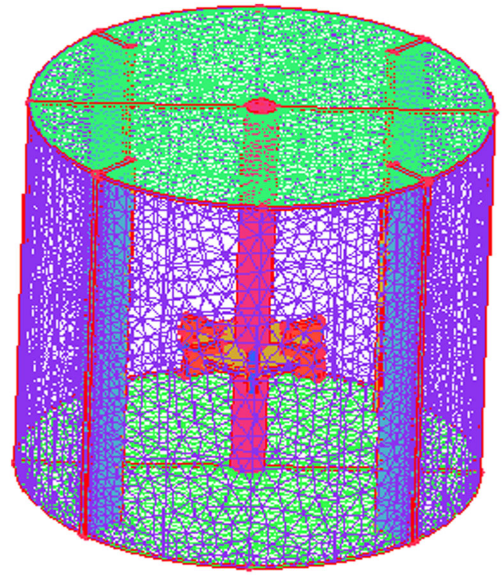

Fig. 2 Mesh generated (tetrahedral mesh)

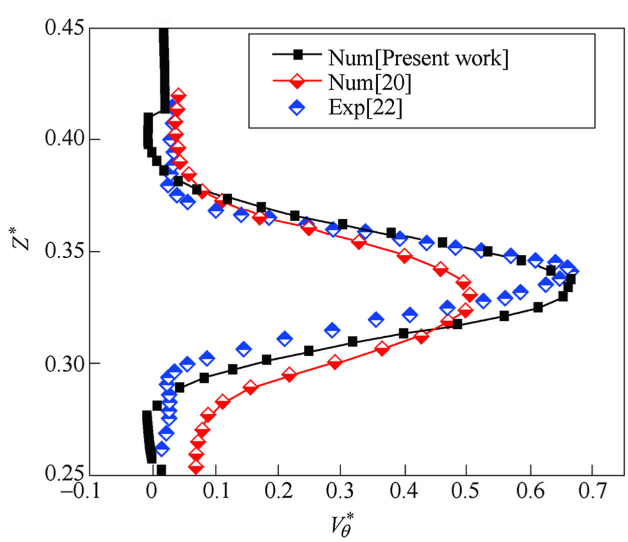

Fig. 3 Tangential velocity for $Re = 40000$, $R^* = 0.185$

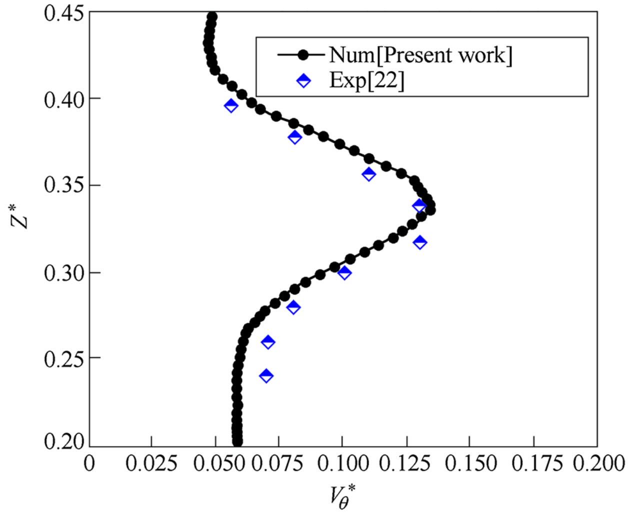

Fig. 4 Tangential velocity for $Re = 40000$, $R^* = 0.222$

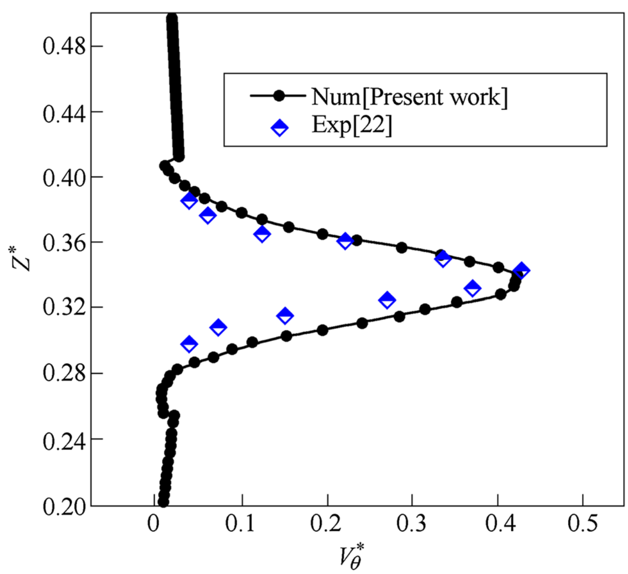

Fig. 5 Tangential velocity for $Re = 40000$, $R^* = 0.285$

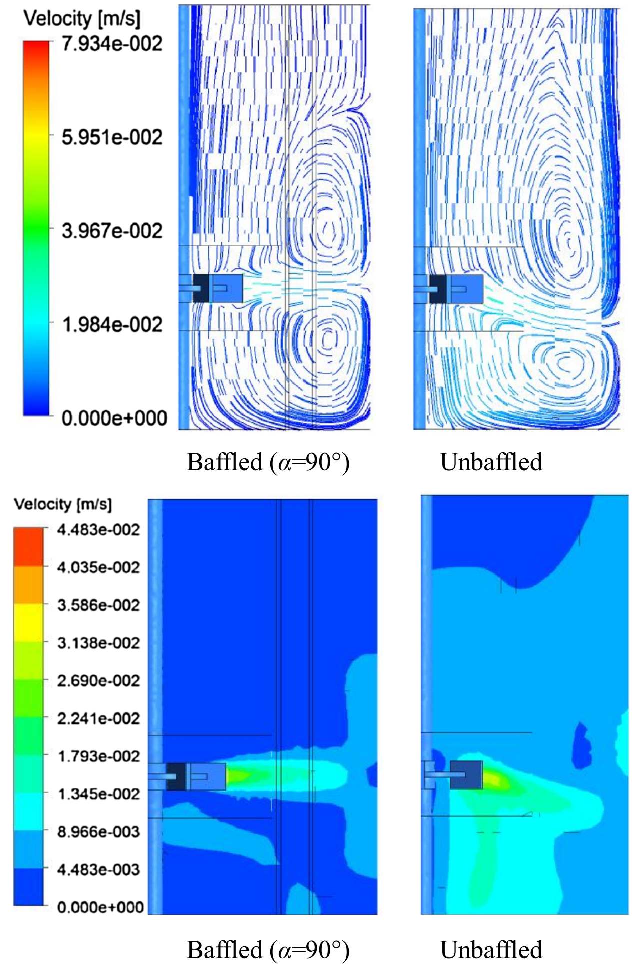

Fig. 6 Flow fields for $Re = 40000$

5.2 Effect of the Vessel Internals

In the present paper, a hydrodynamic investigation inside a vessel stirred by a Rushton turbine is presented in detail with the help of the CFD method.

As a first step, we have studied the effects of presence of baffles inside the vessel. It consists of four flat vertical plates, directed radially, spaced at 90° intervals around the vessel periphery, starting from the bottom tangent line of the lower vessel head and running the length of the vessel side to the top tangent line of the upper head.

As remarked on Fig. 6, the discharge flow from the Rushton turbine is characterized by two vortices, at the top and bottom of the blade and a high velocity radial discharge flow in the middle. In a comparison between the baffled and unbaffled configurations, the radial discharge for the unbaffled vessel is directed horizontally; however, the radial discharge is inclined toward the bottom for the baffled vessel. Another remark is that the upper vortex generated in the unbaffled vessel seems very higher and it reaches the free surface of liquid.

From these remarks, the baffled vessel is the best configuration for this kind of fluids and this range of Reynolds number. However, does the inclination of baffles have any effect on the mixing performance and energy consumption? This is the object of the following section.

5.3 Effect of Baffle Inclination

The fluid flows and power consumption depend strongly of the impeller design, impeller rotational speed and the baffling provided. The stirring effect is based on the interaction between the impeller and baffles. A certain volume flow is exchanged between the baffles leading to a transfer of angular momentum.

Here, we test the effect of baffle inclination on the flow structure and the power consumption. The vessel is equipped with four baffles which is often referred as a fully baffled condition. The insertion of extra baffles to obtain more heat transfer area is very used in large scale tanks. However, the excessive baffling may cause a reduction of mass flow and localizing flow within the system.

Five geometrical configurations are realized to test the effect of baffle inclination and which are: $\alpha = 25°$, 32.5°, 45°, 70° and 90°, respectively.

A particularly important feature of the flow field is the vortices generated by the blade impeller. Fig. 7 presents in vertical planes passing through the impeller blade the flow structure generated for different baffle inclinations and different rotational directions. In all cases, the discharge flow dissipates in the bulk and turns axially near the tank wall. Baffles increase the axial circulation and reduce the tangential velocities. Due to a split in the discharge flow, compartments are formed above and below the impeller. Galleti and Brunazzi [23] evaluated the energetic content of the two main vortices and showed that especially the upper vortex is rather strong with an energetic content up to 52% of the turbulent kinetic energy. This means that such vertical structures may have considerable effect on macro-mixing.

In a comparison between the five cases studied, the standard baffles ($\alpha = 90°$) seems to be the best configuration in terms of reducing the fluid vortexing near the free surface, thus greatly improving mixing.

In an attempt to describe more clearly this phenomenon, we present on Fig. 8 the evolution of the axial velocity along the radial coordinate of the vessel. On the other hand, when the impeller is rotating in the negative direction ($-\omega$), the upper vortex yields to be longer (as illustrated on Fig. 9).

Figs. 10 and 11 show the effect of the impeller rotational direction on the free surface of liquid for different values of α. As it is observed on these figures, the free surface of liquid is more disturbed in the case of $\alpha = 25°$ and ($-\omega$).

Since trailing vortices can have a potential benefit for mixing practice, it is necessary to study their characteristics (width, length and location). Fig. 12 presents the size of upper vortex (Fig. 12(a): vortex length, Fig. 12(b): vortex width) with respect to the baffle inclination.

5.4 Power Consumption

From a practical point of view, the power consumption is perhaps the most important parameter in the design of stirred vessels. In this section, we present the effects of baffles on the power consumption. But first, we checked the validity of our predicted results. Table 2 resumes the values of power number Np found by other researchers for baffled and unbaffled vessels. As remarked on this table, the comparison between our results and the other available data shows a satisfactory agreement.

In the present study, we interest to the effect of baffle inclination on the power consumption. However, in our knowledge, no papers have been published yet and a limited space has been reserved to this subject. Power consumption for a stirred tank equipped with the short baffles was tested by Strek and Karcz [14] only, Karcz and Major

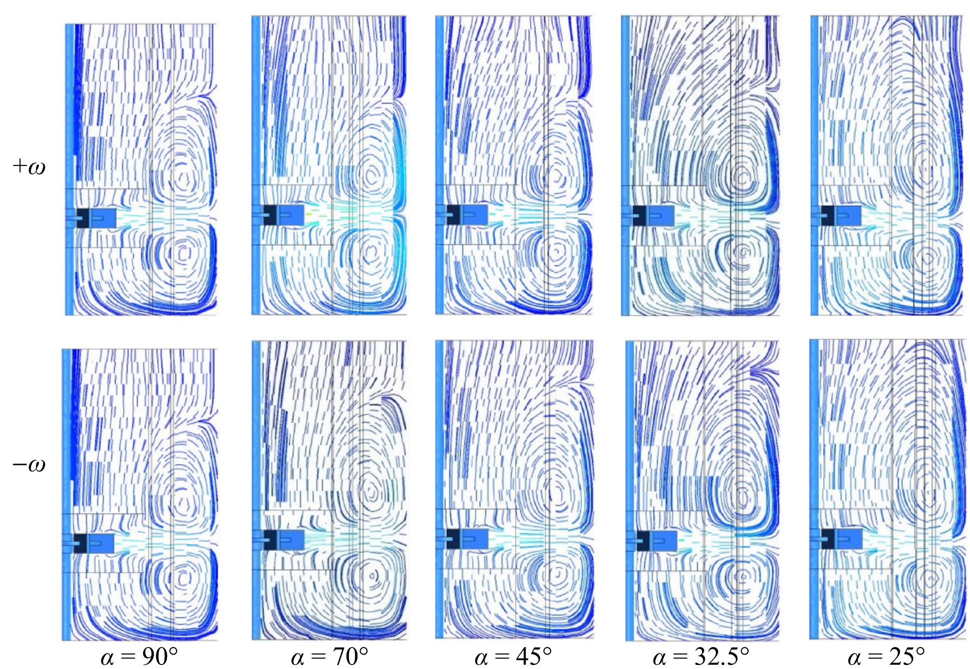

Fig. 7 Effect of the baffle inclination on the flow behavior, for $Re = 40000$

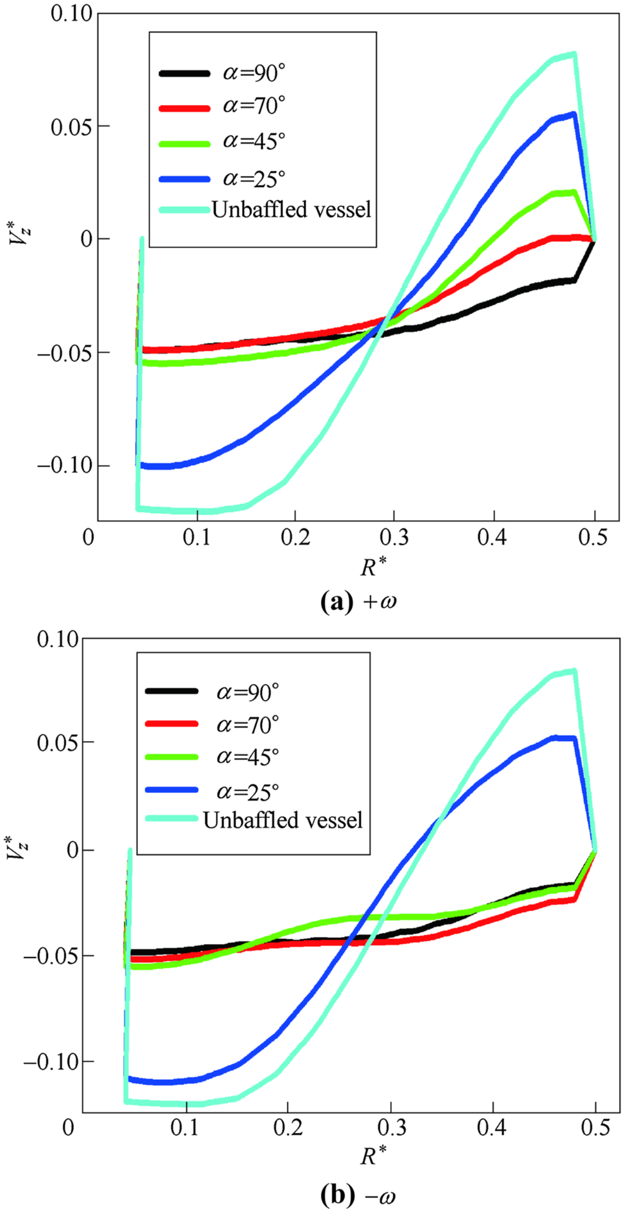

Fig. 8 Axial velocity for $Re = 40000$, $Z^* = 0.8$

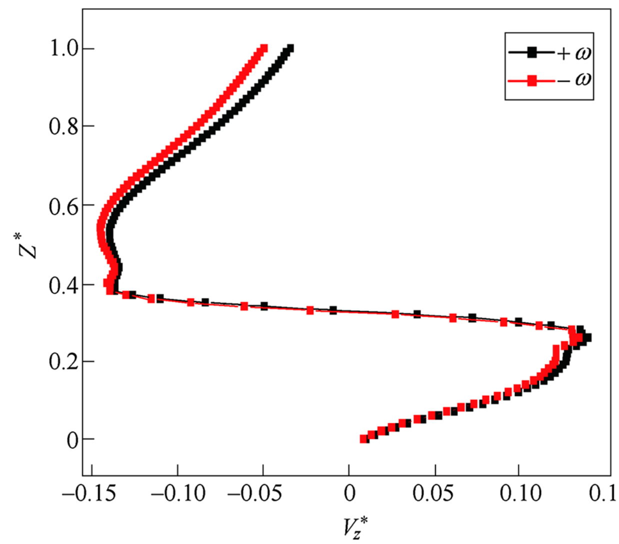

Fig. 9 Axial velocity for $Re = 40000$, $R^* = 0.185$, $\alpha = 25°$

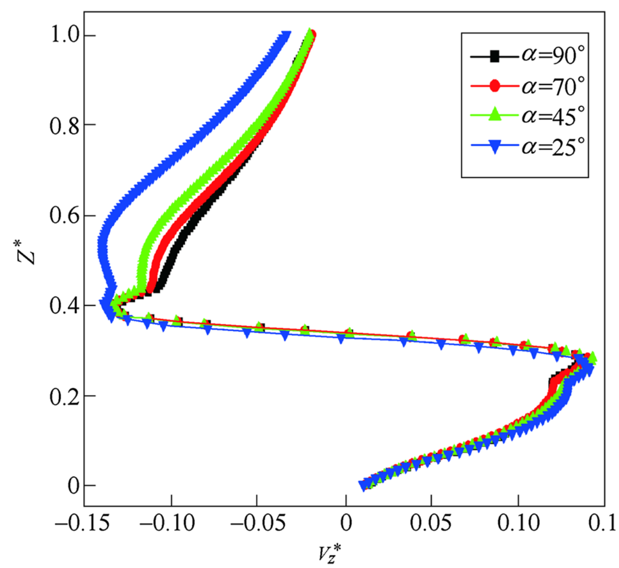

Fig. 10 Axial velocity for $Re = 40000$, $R^* = 0.185$, $+\omega$

[24] and Ammar, et al [25] studied the effect of baffle length. Strek and Karcz [26] examined the influence of the geometrical baffle parameters (number, width, length and distance between the lower edge of the baffle and the bottom of the vessel) upon both power consumption and heat transfer for an agitated vessel.

Our predicted results concerning the effects of baffle inclination on the power number are summarized on Table 3. The data presented in this table show that the greatest power numbers *Np* are obtained for the agitated vessels equipped with standard baffles ($\alpha = 90°$), whereas, the least values *Np* correspond to the systems without baffles. Moreover, the reduction in power number following the baffle inclination ($\alpha = 70°$, 45°, 32.5° and 25°) is 20%, 25%, 45% and 48%, respectively (compared with standard baffles $\alpha = 90°$). On the other hand, the impeller rotation in the positive direction ($+\omega$) yields a considerable increase in power number, and this is due to the resistant force caused by the baffle which is also responsible of the formation of small eddies at the tank wall (Fig. 13).

The optimization criterion should take into account the type of process which occurs in the stirred tank. The consequence of employing optimal geometrical parameters is the minimum power consumption for the required operating conditions of the agitated vessel. According to the predicted results presented in this paper, the best geometrical configuration seems to be 70°.

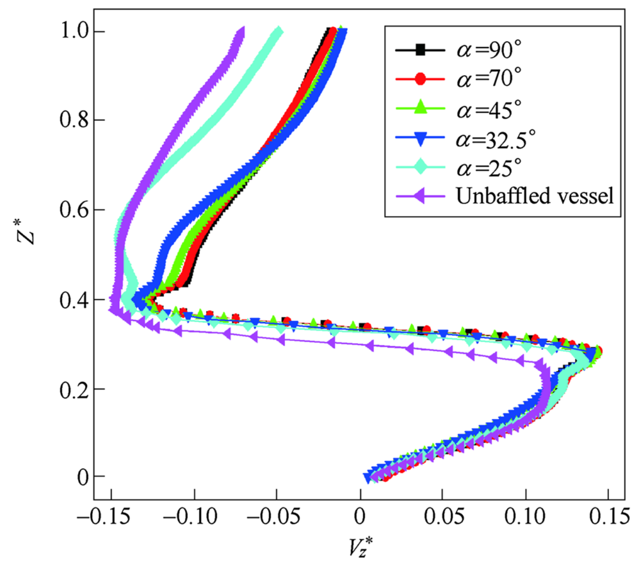

Fig. 11 Axial velocity for $Re = 40000$, $R^* = 0.185$, $-\omega$

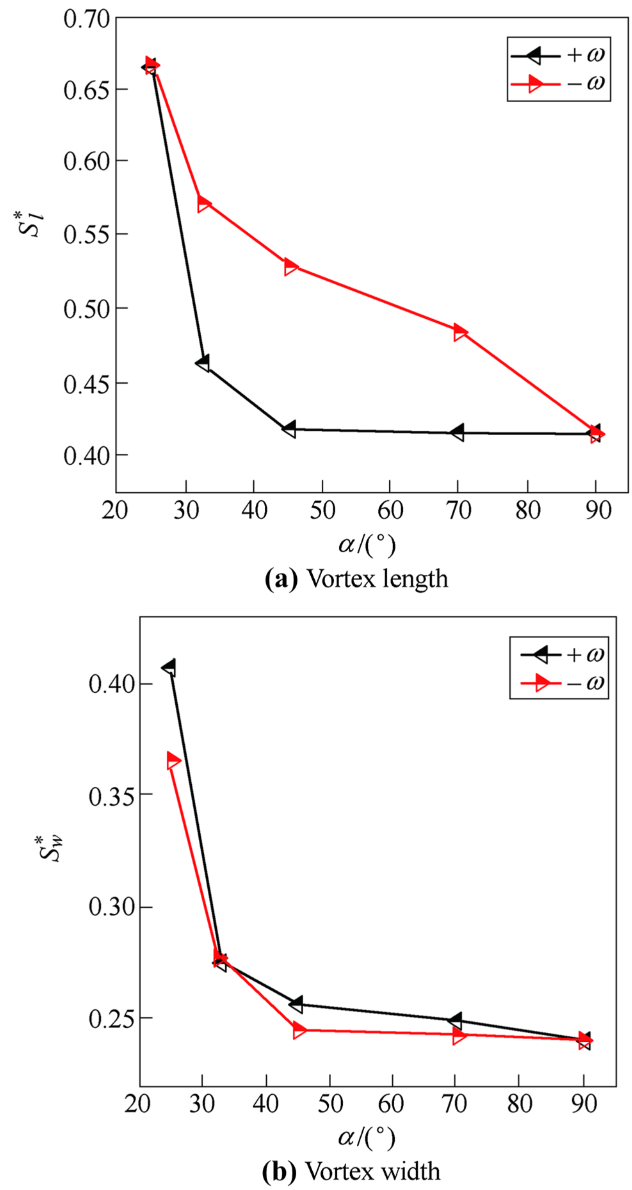

Fig. 12 Effect of the baffle inclination on the vortex size for $Re = 40000$

5.5 Effect of Reynolds Number

The following figures present the effects of Reynolds number on the flow structure. Three values of Reynolds number are chosen and which are: $Re = 40000$, 60000 and 80000.

For all cases (Fig. 14), the fluid flows off radially from the impeller with a circumferential component, and flows towards the tank wall where it divides into two streams: one toward the vessel base and the other toward the free surface of liquid. There they are deflected toward the axis and once more drawn in axially by the impeller. Thus, a double vortex is formed in the vessel volume. The mixing occurs mainly in the flow passing through the vortex system and where the discharge flow meets the bulk flow[10].

Fig. 14 presents the effect of Reynolds number on the shape of the upper vortex. The higher value of Re yields the higher vortex with respect to the vertical plane. The presence of the lower vortex is also discernable.

The direction of impeller rotation has also an important effect on the vortex size with respect to the Reynolds number (Fig. 14). At the same Re, the positive angular velocity ($+\omega$) yields the wider vortex when compared with the negative angular velocity ($-\omega$).

6 Conclusions

A mixing system equipped with a Rushton turbine and a Newtonian fluid is numerically investigated. Predicted results produced a clear insight into the physics of vortex formation and the energy required for such systems.

Table 1 Vessel and impeller characteristics

H/D	c/D	w/D	d/D	d_s/d	a/d	a/d
1	1/3	1/10	1/3	1/5	1/4	1/5

In the first part, we have compared the baffled and unbaffled configurations: the baffles promote the stability of power consumption and limit the swirling or vortexing fluid near the free surface.

Reduction of power consumption and swirling fluid near the free surface of liquid was the main purpose of the present paper. Therefore, the baffle inclination technique is proposed to attend the objective. Five cases concerning the

Table 2 Power number (*Np*) for $Re = 40000$ (comparison between our results and other available data)

	Present work	Ref. [20]	Ref. [27]	Ref. [24]
Baffled vessel	6.41	5.40	–	6.0
Unbaffled vessel	0.82	–	1.2	0.85

Table 3 *Np* for different values of α, for $Re = 40000$

Direction of rotation	90°	70°	45°	32.5°	25°
$-\omega$	6.41	5.13	4.83	3.51	3.30
$+\omega$	6.41	6.38	–	–	–

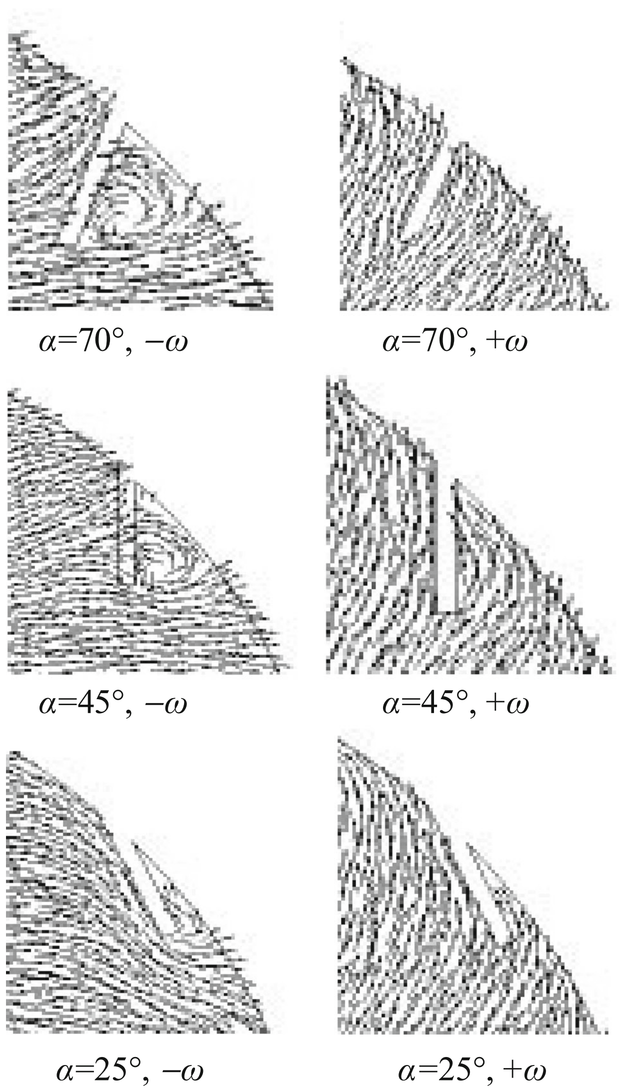

Fig. 13 Velocity vectors for $Re = 40000$

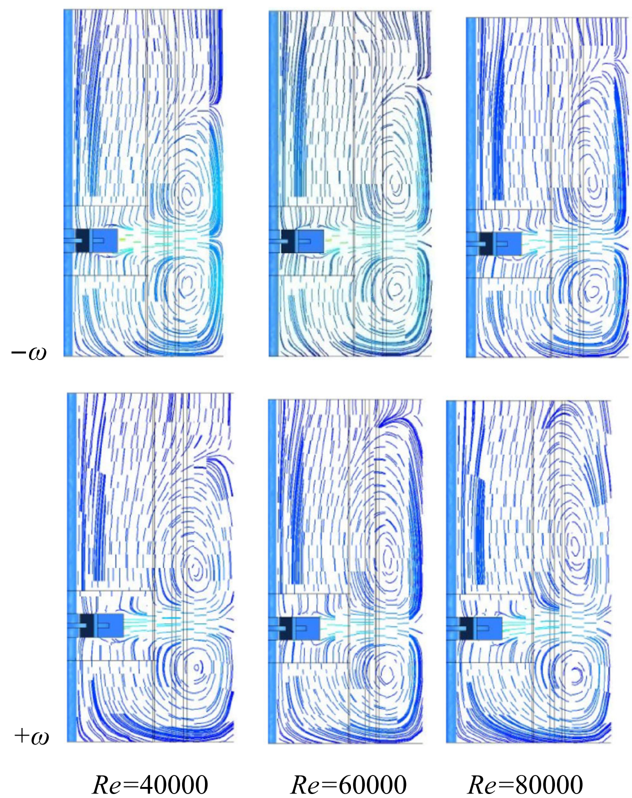

Fig. 14 Streamlines for different Reynolds numbers, $\alpha = 70°$

baffle inclination (α) are studied and which are $\alpha = 25°$, 32.5°, 45°, 70° and 90°, respectively. The increase of α showed a reduction in the size of the upper vortex formed near the free surface of liquid, but with an increase in power consumption. The impeller rotational direction is also investigated, and the clockwise direction ($+\omega$) was found to yield an increase in power consumption and swirling size.

Finally, the best compromise between the two criteria (i.e., power consumption and swirling fluid) is obtained when $\alpha = 70°$ operating in the opposite clockwise direction ($-\omega$).

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