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NUMERICAL STUDY OF BAFFLE PARAMETERS EFFECT ON FIELD FLOW AND POWER CONSUMPTION

NUMERIČKA STUDIJA UTICAJA PARAMETARA PREGRADE NA POLJE PROTOKA I POTROŠNJU ENERGIJE

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Keywords
- power consumption
- computational fluid dynamics (CFD)
- stirred mechanism
- Rushton turbine

Abstract

The current state of research in the field of stirred tanks across diverse industrial sectors places significant focus on the design of stirred tanks, turbine blades, and baffles. This research involves a numerical investigation which focuses on examining the velocity field in a tank subjected to mechanical agitation through a Rushton turbine, particularly in turbulent flow conditions. The study utilises a Newtonian fluid as the working medium and explores the influence of various factors, including the number and placement of baffles. The investigation employs a specialised calculation code called CFX 18.0. The numerical results are analysed to determine and discuss the impact of geometrical parameters, such as the number two, three and four shape, and spacing between vertical tubular baffles, on the power characteristics obtained for each impeller type.

Ključne reči
- potrošnja energije
- računarska dinamika fluida (CFD)
- mehanizam za mešanje
- Rašton turbina

Izvod

Trenutno stanje istraživanja u oblasti rezervoara sa mešanjem u različitim industrijskim sektorima stavlja značajan fokus na dizajn rezervoara sa mešanjem, lopatica turbina i pregrada. Ovo istraživanje uključuje numeričko istraživanje, koje se fokusira na ispitivanje polja brzina u rezervoaru koji je podvrgnut mehaničkom mešanju kroz Raštonovu turbinu, posebno u uslovima turbulentnog strujanja. Studija koristi njutnovsku tečnost kao radni medijum i istražuje uticaj različitih faktora, uključujući broj i postavljanje pregrada. Istraživanje koristi specijalizovani računski program pod nazivom CFKS 18.0. Numerički rezultati su analizirani da bi se odredio i razmotrio uticaj geometrijskih parametara, kao što su oblik broj dva, tri i četiri, kao i razmak između vertikalnih cevastih pregrada, na energetske karakteristike dobijene za svaki tip radnog kola.

INTRODUCTION

The technology of agitation and mixing is widely employed in a diverse range of industrial sectors, including mining, petroleum, chemical, biological, pharmaceuticals, food processing, wastewater treatment, and processing industries. In recent times, a prominent research focus within the realm of mechanical agitation has centred on the hydrodynamic analysis of fluid flow and power consumption in stirred tanks. The aim of this paper is to increase their efficiency by introducing geometric modifications both to the diameter and configuration of the bottom of the tank. Also, we focus our attention on the location and design of the agitator and internal elements, such as the presence and baffle configuration.

Wan et al. /1/ tested the effect of baffles on power consumption in a tank agitated by a Rushton turbine. Tanks with vertical tubular baffles arranged in groups of four, six or eight where studied. They confined that the number of tubular baffles favoured an increase in power consumption. In the same thematic, Major-Godlewska et al. /2/, studied the effect of tubular baffles on power number. These parameters were studied also by Karcz et al. /3/, Kato et al. /4/, Foukrache et al. /5, 6/, Zhou et al. /7/ for the gas-Newtonian and solid-Newtonian liquid applications. Kamla et al. /8/ achieved the evolution of the baffle curvature on the power consumption. They confined that power consumption decreases with increase in the radius of baffle curvature. The same authors in /9/ investigated the influence of baffle inclination, which varies between 25°, 32.5°, 45°, 70°, and 90° on power consumption. They found that the best configuration for minimising energy consumption is the tank with a 70° baffle inclination at negative angular velocity. Fan et al. /10/ conducted an experimental study of baffle impact on power consumption and the flow field stirred by pitched blade turbine (PBT). Several experimental and numerical studies on the effect of baffles on power number and mixing time were developed by Karcz et al. /11/, Major Godlewska et al. /12/, Youcefi et al. /13/, and Kamla et al. /8/. Xiong et al. /14/ compared energy consumption and flow field instability in a stirred tank equipped with different structures of baffle. They found that the punched baffle stirred tank (Pun-BST), and Isolated baffle stirred tank (Iso-BST) systems consume less energy than Traditional baffled stirred tank (Trad-BST) system, and that flow field instability is lower than that of the TradBST system. Houcine et al. /15/ studied the effect of bottom shape of the tank on power number and mixing time, such us flat, conical, rounded, and profiled bottoms. The results obtained experimentally confined that the TTP propeller equipped by rounded tank bottom is the most efficient in degree of mixing. Tacă et al. /16/ compared the performance of agitated fluid using a Rushton turbine and a radial blade impeller. This comparison shows that the energy consumption is very low in the case of radial blade impeller. Foukrach et al. /5/ conducted a numerical investigation into the impact of tank geometry on the hydrodynamic characteristics of a tank agitated by a six-bladed Rushton turbine in one cylindrical tank. The other configuration consists of a polygon of 64 sides with different shapes of baffles (VB, CHB, and CHCB). Mokhefi et al. /17/ studied the effect of wavy tank wall on the hydrodynamic, thermal, and energetic behaviour in laminar regime of mechanical agitation. This investigation presented an exceptional thermal efficiency with a high cost due to the increase of energy consumption. Major-Godlewska et al. /18/ studied the effect of blade inclination ($\beta = 45°$, $60°$, and $90°$) of a radial turbine on bubble residence time and energy consumption. The obtained results confirmed that the energy consumption of gas-liquid agitation systems does not depend on the ability of bubbles to coalesce. It depends solely on the inclination of turbine blades. Driss et al. /19/ used a numerical simulation of hydrodynamic structure of flows in a stirred tank equipped with pitched blade impeller with inclination angles 45°, 60°, and 75°. They found that power consumption increases with increasing of the angle pitch blade. The same authors in /20/ investigated the effect of different configurations of stirred tank equipped by one, two, and three impellers. They found that the multi-stage system meets the needs of every industrial application. The same results were confined also by Gelves et al. /21/ and Ameur et al. /22/. Wood et al. /23/ examined the importance of impeller type, including the Rushton bladed disk turbine, the inclined blade turbines (up and down), the Lightning A310 hydrofoil, and the sawtooth impeller. Several studies have also shown the impact of the agitator on the power number, such as the work of Driss et al. /20/, Yang et al. /24/, Jenish et al. /25/, Devi et al. /26/. The identification and characterisation of tip vortices of Rushton turbine flows is presented in the study of Sharp et al. /27/. For modelling the turbulence flow in a vessel mixing, Wójtowicz et al. /28/ investigated the distribution of energy dissipation rate for Rushton and pitched blade turbine, by using different model turbulence. On the other hand, mixing time is an important parameter that must be known to characterise the efficiency of a stirring system. Zhu et al. /29/, Duan et al. /30/, and Heidari /31/ confirm that the diameter and speed rotation of impeller have an effect on the quality of mixture.

The aim of this work is to examine how fluid properties and power consumption are influenced by design, positioning, and number of tank baffles to attain the desired optimal mixture.

STIRRED MECHANISM AND THEORICAL CONTEXT

The mixing system under investigation is depicted in Fig. 1, comprising a hydraulic tank of cylindrical shape and a flat bottom. The tank boasts an internal diameter of T_d = 300 mm and is completely filled with water up to a height H, which equals diameter T_d. To influence the flow within this enclosure, tubular baffles of varying numbers and positions are vertically installed, as illustrated in Fig. 1.

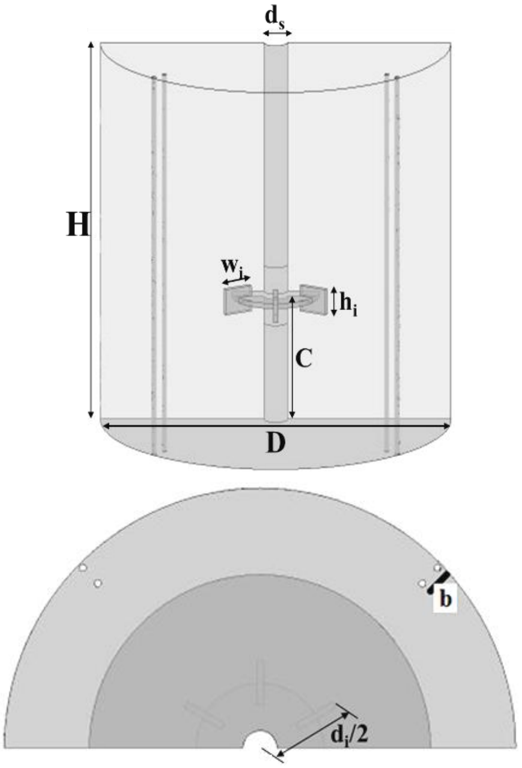

Figure 1. Geometries of the simulated mixing systems.

In our current study, we characterise the flow state inside the agitated vessel by the Reynolds number, $Re = \rho N D^2/\mu$, with a specific Re value of 40000. The tank is equipped with a standard six-blade Rushton turbine having a diameter $D = T_d/3$, and the turbine is positioned in the downward orientation. Essential parameters are summarized in Table 1.

Table 1. Main geometric parameters of the stirred tank.

T_d	H	C	h_i	w_i	D	d_s	d_d
300 mm	T_d	$T_d/3$	$D/4$	$D/5$	$T_d/3$	$T_d/15$	$3D/4$

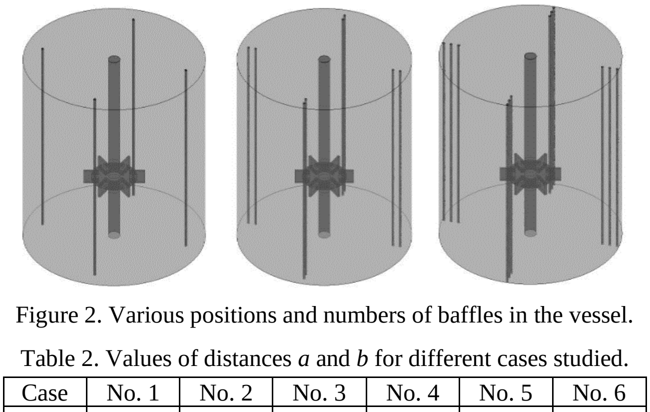

Figure 2. Various positions and numbers of baffles in the vessel.

Table 2. Values of distances *a* and *b* for different cases studied.

Case	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
N_b	1	2	2	2	3	2
a	0	$D/20$	$D/10$	0	$D/20$	0
b	0	0	0	$D/20$	$D/20$	$D/20$

The values of distances *a* and *b* for the different cases studied are summarized in Table 2, where *a* is the distance between the baffle and cylinder wall, and *b* is the distance between the baffles.

GLOBAL CHARACTERISTICS

The CFD model is developed to determine optimal parameters for the total power absorbed in the stirred mixing tank. The electrical consumption (*P*) depends on all parameters characterising the external geometry of the vessel, the geometry of the agitator, the flow regime and rotation speed of the turbine. In particular, two parameters are calculated, the power number N_P and the pumping number N_Q.

In a constant and continuous rotation at steady state, the power due to impeller and shaft torque is expressed as:

$$N_P = \frac{2\pi NT}{\rho N^3 D^5}\,, \tag{1}$$

$$P = 2\pi NT\,. \tag{2}$$

So, the power number (N_P) is then calculated as follows:

$$N_P = \frac{P}{\rho N^3 D^5}\,. \tag{3}$$

The flow number N_Q is a vital parameter for assessing the effectiveness and functionality of an agitator. It can be determined using the following formula:

$$N_Q = \frac{Q}{ND^3}\,. \tag{4}$$

RESULTS AND DISCUSSION

Figure 3 illustrates streamlines in various cases studied under turbulent operating regime characterised by a Reynolds number Re = 40,000. Streamlines typically provide a visual representation of fluid flow patterns. In this case, they appear to represent flow patterns induced by Rushton turbines, known for their generation of radial flows.

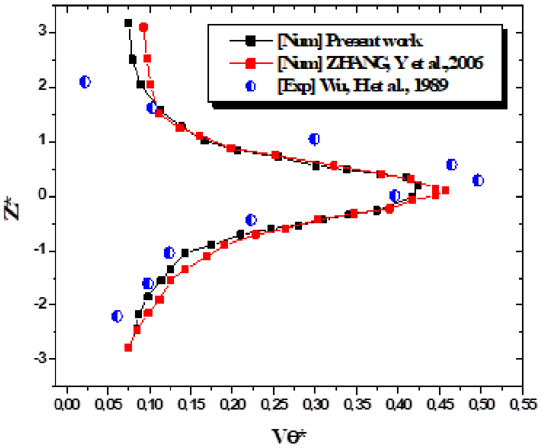

Figure 3. Tangential velocity for Re = 40000.

Tanks equipped with flat baffles include Rushton turbines that generate a radial flow, as shown in Fig. 4. On the other hand, in case no.3, where tubular baffles are used, we observe that they generate a semi-radial flow. This new geometric configuration helps to improve the quality of mixing of the agitated fluid. Figure 5 shows the streamlines for various cases where we modified the number of tubular baffles as well as the spacing between them. It is observed that, for all cases, there are two recirculation loops which are formed, one at the upper part and the other at the lower part of the stirring mobile. Regarding the standard geometry and cases No. 4, 5 and 6, we also note that the recirculation zones do not reach the free surface of the agitated fluid compared to the other cases studied (cases no. 1, 2, and 3). This keeps the free surface stable. These results show that the shape of the baffles influences the structure of the flow generated by this type of stirring mobile, as confirmed in the work of Kamla et al. /8/.

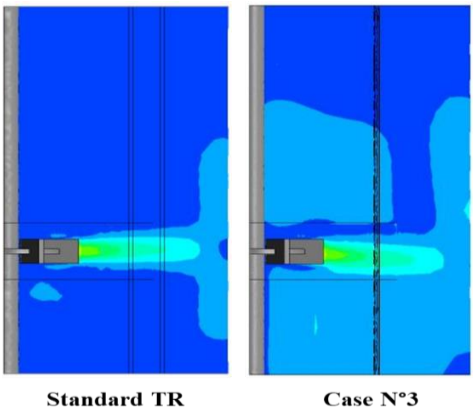

Figure 4. Streamlines for standard geometry and case no.3.

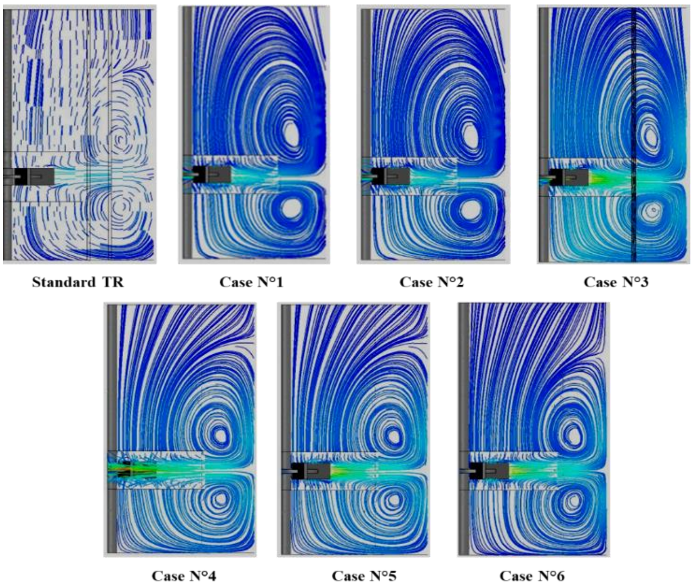

Figure 5. Streamlines for various cases.

The analysis of velocity fields of different explored geometric configurations allows for the delineation of zones characterised by both maximum and minimum speeds (see Fig. 6), as well as regions exhibiting increased turbulence. We notice that the fluid velocity reaches its maximum near the turbine wall. However, it gradually decreases as the distance from the wall increases and reaches zero near the tank wall.

Various factors influence the efficiency of mixing in stirred tanks, with system geometry being a significant parameter. Figure 7 presents the flow structure obtained and observed across six different geometric configurations studied at Re = 40000. It is noted that the flow intensity peaks at the blade tips, indicating the radial flow pattern generated by this type of agitation impeller. Such radial-flow turbines divide the flow into two streams: one directed towards the bottom of the tank and the other towards the liquid's free surface, resulting in the formation of two vortices above and below the turbine, as illustrated in Fig. 7.

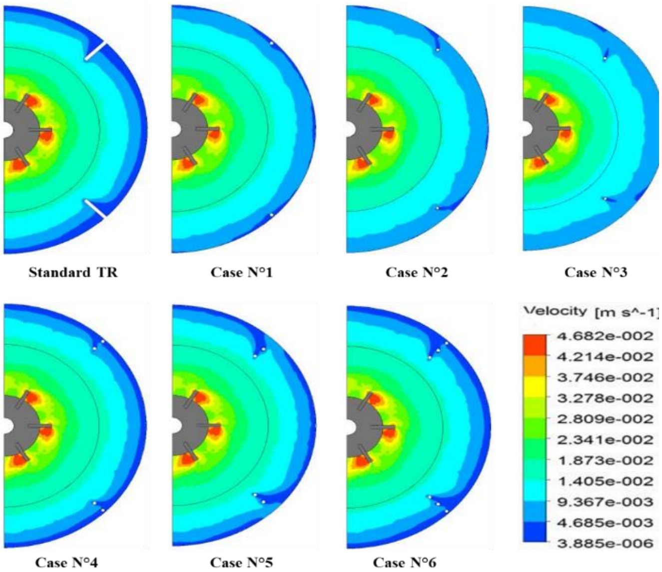

Figure 6. Velocity fields for $z^* = 0.5$; Re = 40000.

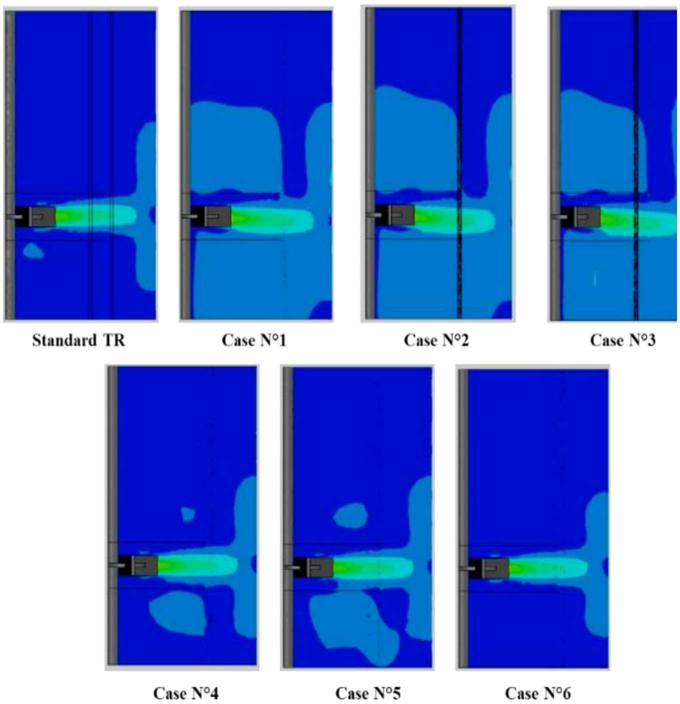

Figure 7. Velocity fields.

Figure 8 illustrates the size of vortices in the upper region of the stirring mechanism, highlighting the impact of baffle geometry on the length of these recirculation zones. The results indicate that the tubular configuration of baffles contributes to the formation of vortices with particular dimensions in the upper part of the Rushton turbine. This observation implies that the shape of baffles not only affects the presence of recirculation zones but also significantly determines their lengths, particularly in the upper section of the stirring mobile. Figures 9. and 10 depict the radial velocity distribution of a Rushton turbine operating at a Reynolds number of Re = 40000, at positions x equal to 0.0375 and 0.02775. The maximum velocity intensity is observed near the central region of Rushton turbine blades. This indicates that the fluid velocity reaches its maximum near the centre of the turbine blades, but as one moves away from this central area, the velocity gradually decreases. In other words, the arrangement of the Rushton turbine blades generates a radial velocity pattern peaking near the central region, showcasing how fluid velocity varies at different distances from the blade centre. The same trend is depicted in Fig. 8, which illustrates the tangential velocity. Figure 11 shows the tangential velocity for different cases, and we notice that this velocity is more intense in case no.2 than in the other cases.

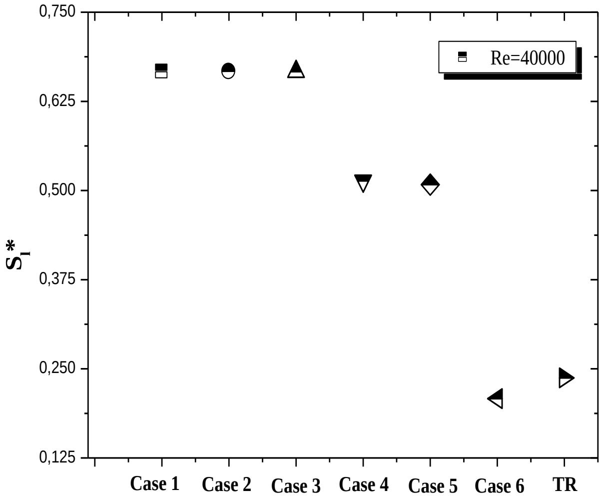

Figure 8. Vortex size for Re = 40000.

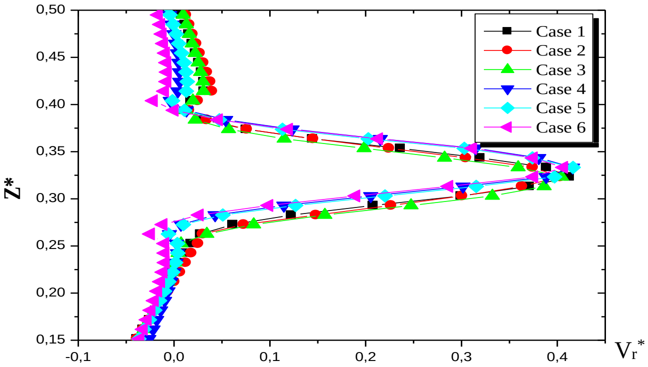

Figure 9. Radial velocity for Re = 40000, $x = 0.0375$.

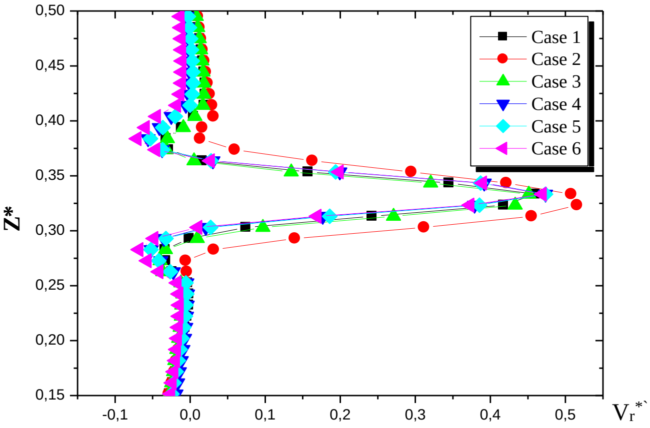

Figure 10. Radial velocity for Re = 40000, $x = 0.02775$.

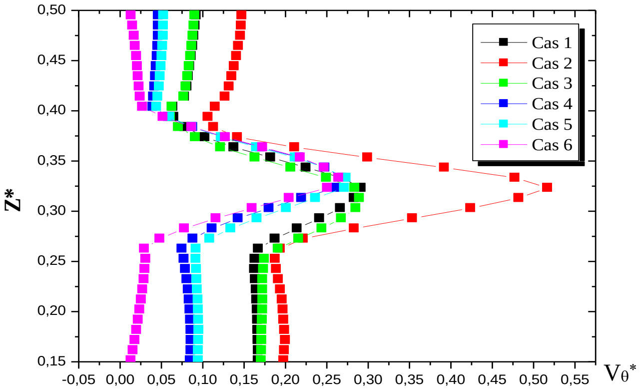

Figure 11. Tangential velocity for Re = 40000 and x = 0.0375.

The analysis of radial velocity distribution for various geometric configurations at z = 0.05, as shown in Fig. 12, reveals that the increase in radial velocities near the axis along the bisector is faster than those near the blades to reach their peak. However, this maximum speed gradually decreases towards the tank wall.

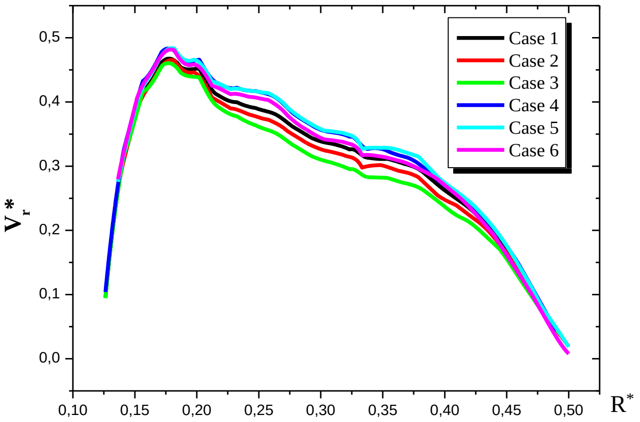

Figure 12. Radial velocity for Re = 40000 and z = 0.05.

Figures 13 and 14 show the axial velocity for z^* = 0.65 and 0.85, respectively. We can see that this velocity has both positive and negative values, indicating the formation of recirculation zones. This is particularly evident in Fig. 10. However, in Fig. 11 we see that these recirculation zones at z^* = 0.85, close to the free surface of the tank, are not present in cases no. 5, 6 and in the case of the standard geometry. This suggests that the free surface is more stable for these geometries than for the other geometries, /32, 33/.

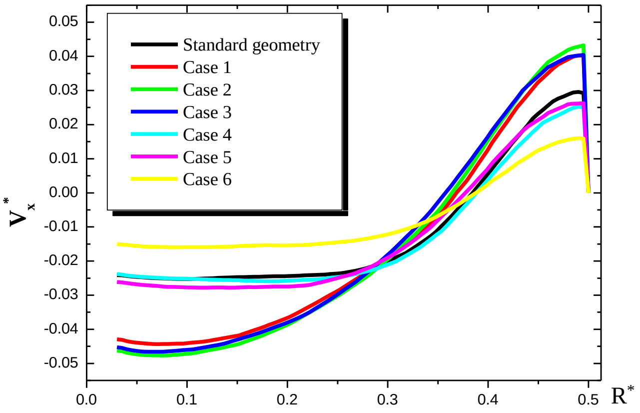

Figure 13. Axial velocity for Re = 40000, z^* = 0.65.

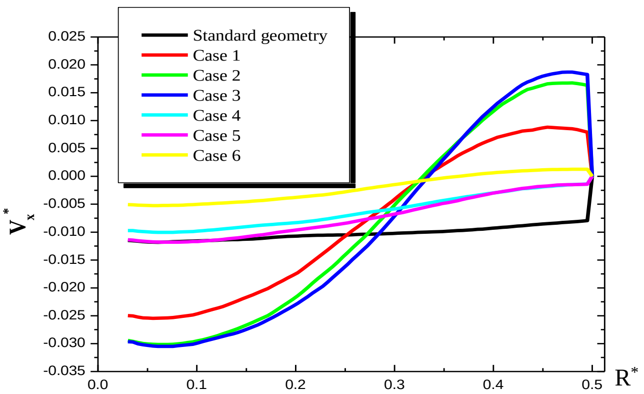

Figure 14. Axial velocity for Re = 40000, z^* = 0.85.

Table 3 represents the power values for different configurations studied. We notice that the consumed power is lower in cases 1, 2, 3, 4, 5, and 6 compared to the standard geometry. This is explained by the tubular shape of baffles that reduces fluid friction with baffle wall compared to flat baffles. A significant observation in this study is a 66 % decrease in energy consumption by the agitator in case no.3 compared to the standard geometry.

Table 3. Power number (N_P) for Re = 40000.

Case N°	Case N°1	Case N°2	Case N°3	Case N°4	Case N°5	Case N°6	TR standard
N_P	1.8	2.1	2.18	3.73	4.94	6.5	6.41

CONCLUSION

The results obtained from in-depth numerical analyses, illustrated by flow and energy consumption figures in a tank stirred by a Rushton turbine are significant. By examining key parameters such as the shape, number, and position of baffles, the study demonstrates the notable advantages of the new geometric configuration presented in case no. 3. This case generates a semi-radial flow pattern, leading to improved mixing quality and a substantial 66 % reduction in energy consumption compared to the standard geometry. These findings highlight the significant potential for energy savings and operational cost reductions in industrial processes by optimising parameters such as baffle geometry. In conclusion, this study provides valuable insights into stirred tank design, flow dynamics, and energy consumption, underscoring the importance of a tailored approach to achieving optimal performance and efficient resource utilisation in stirred tank applications.

List of symbols (nomenclature)

a	distance between baffle and cylinder wall (mm)
b	distance between two baffles (mm)
C	impeller clearance (mm)
D	tank diameter (mm)
d_i	impeller diameter (mm)
d_d	disk diameter (mm)
d_s	shaft diameter (mm)
H	liquid height in the tank (mm)
h_i	impeller blade height (mm)
N	impeller rotational speed (rpm)
N_b	baffles number
N_P	power number
N_Q	flow number
P	power consumption (W)

Q	volumetric flow rate swept by the impeller
R^*	radial coordinate (mm)
Re	Reynolds number
T	blade torque
w_i	impeller blade width (mm)
z^*	axial coordinate (mm)
Greek letters	
ρ	fluid density (kg·m^{-3})
μ	viscosity (Pa·s)
β	blade inclination
Abbreviations	
CFD	computational fluid dynamics
CHB	circular horizontal baffle
CHCB	circular horizontal cut baffle
Iso-BST	isolated baffle stirred tank
PBT	pitched blade turbine
PIV	particle image velocimetry
Pun-BST	punched baffle stirred tank
Trad-BST	traditional baffled stirred tank
VB	Vertical baffles

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