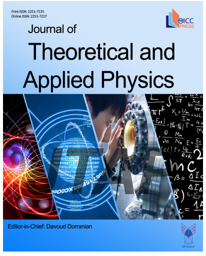

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Effects of different parameters on performance metrics in a vertical axis agitator: A CFD approach

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Original Research

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Abstract:

In this paper, a vertical axis agitator with four rectangular blades is studied numerically and performance metrics such as the mixing power and power consumption are presented. Effects of diameter, rotational velocity, and the twist angle of the blades on power consumption and maximum velocity are studied extensively. Results are compared with theoretical formula to mark the discrepancy and express the reasons. The effect of rotational speed on the maximum velocity magnitude is more pronounced at higher diameters which means that if you double the rotational speed of two mixers, the one with a larger diameter will experience a more significant effect of velocity enlargement. There is a threshold for the rotational speed of mixers beyond which the power consumed by it will increase in a way that there is no justification for diameter enlargement. It is worth mentioning that the twist angle has negligible influence over the maximum velocity value but installing the blade at some specified inclination leads to lower levels of power consumption; a promising solution to be used in designing efficient vertical agitators.

Keywords: Vertical axis agitator; Power consumption; Rotational speed; Blade angle; Mixer

1. Introduction

Mixing plays a crucial role in various production processes across fields such as chemistry, food, biology, and pharmaceuticals. A key objective has always been to develop innovative mixing equipment that enhances mixing efficiency without increasing power consumption. The effectiveness of fluid mixing depends on the flow field characteristics of the stirrer, making stirrer design optimization and the exploration of new stirrer types essential research areas [1–4].

Numerous studies have investigated the impact of geometric parameters on agitator performance. For instance, Foukrach et al. [5] employed computational fluid dynamics (CFD) to analyze a curved blade turbine (CBT) when mixing Newtonian fluids in a cylindrical tank. Comparing the efficiency of a standard Rushton turbine with that of a CBT revealed that power consumption decreases as blade curvature increases. In another study by Foukrach et al. [6], the hydrodynamic flow in an agitated tank was examined for different agitator types. Using the Navier-Stokes equations and the RNG $\kappa-\varepsilon$ turbulent model, they explored four agitator designs: Rushton turbine (RT), circular blade turbine (CBT), diverging triangular blade turbine (DTBT), and converging triangular blade turbine (CTBT). The simulations, conducted via the Multi Reference Frame (MRF) method, highlighted that the CTBT agitator significantly reduces power consumption, while the DTBT effectively minimizes vortex size caused by impeller angles.

Sun et al. [7] conducted a PIV test and CFD model validation in a cylindrical tank with a stirrer. Their results highlighted that increasing impeller diameter and rotational speed positively influence the anticipated flow field. Chupshev et al. [8] explored the energy consumption model for mixing using a vertical paddle mixer. They discovered that exceeding a stirrer rotation frequency of 350 min^{-1} slows down the rate of mixing time reduction. Reducing the mixture volume contributes to energy cost savings. Smaller mixers are more energy-efficient but may have lower productivity levels.

Zhao et al. [9] investigated agitator parameters in a baffleless stirred reactor during quaternary ammonium chitosan synthesis. Decreasing the bottom clearance reduces particle

accumulation, although it may create stagnant areas disrupting fluid flow. Increasing paddle diameter enhances axial fluid circulation. Gu et al. [10] used computational fluid dynamics to study solid-liquid suspension in a stirred tank with various impellers. Higher impeller speeds improved solid-liquid homogeneity. Smaller impeller gaps hindered solid particle suspension in the upper region, leading to less uniform dispersion for larger particles.
In this study, a generic agitator with vertical axis is investigated and its mixing power, power consumption and the effects of diameter, rotational velocity, and twist angle of the blades on power consumption are studied. A cylindrical tank with 15 meters diameter and 10 meters depth full of water is assumed to model a general water reservoir. A 4-blade propeller with rectangular cross section (180 mm height and 20 mm width) is modeled in different diameters and installation angles. Control volumes made in SolidWorks for the tank and propeller are shown in the Figure 1.
Further information regarding geometry, mesh creation and physics setup are presented in the following sections.

2. Analysis

Simulations are performed in the CFX module of ANSYS package since it has outstanding capabilities for analyzing rotary equipment in industrial context. A ring of fluid around the mixer propeller is considered according to its diameter and placed in another control volume of fluid

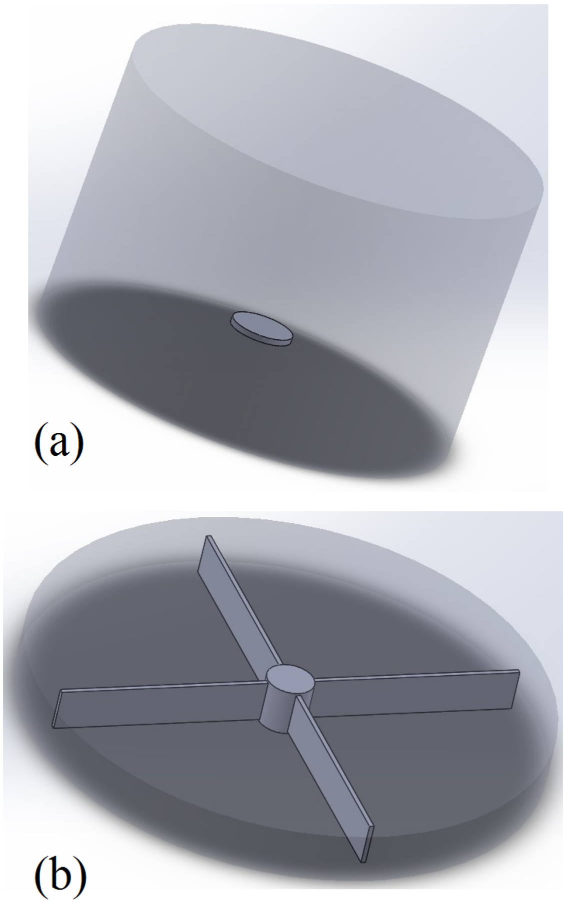

Figure 1. 3D models used in this study. (a) tank (b) propeller.

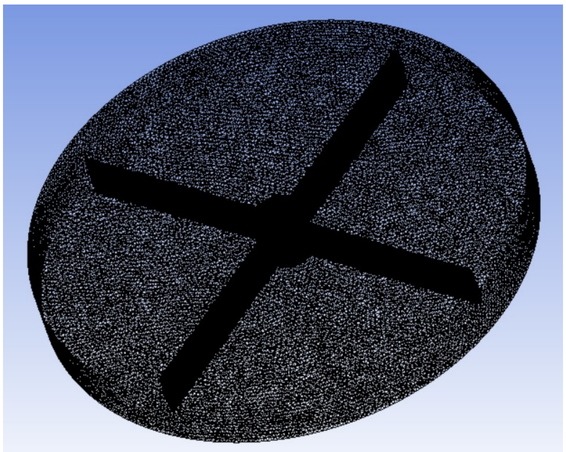

Figure 2. Mesh generation.

called a tank or reservoir at 8 meters depth. Three different diameters namely 2000, 1800 and 1600 mm are investigated in order to study the effects of propeller diameter on power consumption. Also, three different rotational speeds; namely 1, 2 and 4 rad/s are considered along with blades installed at 0, 22.5 and 45 degrees to take care of speed and angle effects.
A mesh dependency study resulted in a patch conforming method with different element sizing for named selections in the model. The edges of the blades are set to a maximum of 5 mm while the surrounding surfaces of the propeller control volume are set to 2 cm. Interface surfaces in both the tank and the propeller control volume have similar mesh sizing. These actions lead to a mesh with almost 600000 elements for the propeller control volume and around 800000 elements for the tank. Figure 2 shows a magnified view of a sample mesh in the simulation.
The surrounding walls and bottom surface of the tank are defined as rigid walls while its surface is defined to have zero shear stress. Three interface surfaces are defined for transferring numerical fluxes between the blade control volume which is rotating and the tank control volume which is stationary. The two enveloping surfaces of the tablet around the blade is considered to be a mixing layer type of interface while the circumferential ring is set to the frozen type. Solver options are set as high resolution for the advection scheme and a first order type for turbulence using k-epsilon model while timescale setting is set to auto. Simulations are performed on a laptop with 16 Gigabytes of RAM and a Corei7 CPU with 6 cores. Each simulation run needs almost 1 hour for 500 iterations to meet convergence criteria.

3. Results

Firstly, contours of velocity distribution in the tank and different planes intersecting the propeller are presented as general results to see the overall characteristics of a mixing process in a reservoir.
It should be noted that for most applications in water treatment pools, an average velocity magnitude of $0.3-0.5$ m/s is sufficient to avoid water sedimentation and to have a proper flow of water in the reservoir. As it is observed from Figure 3, the generic agitator considered here has succeeded

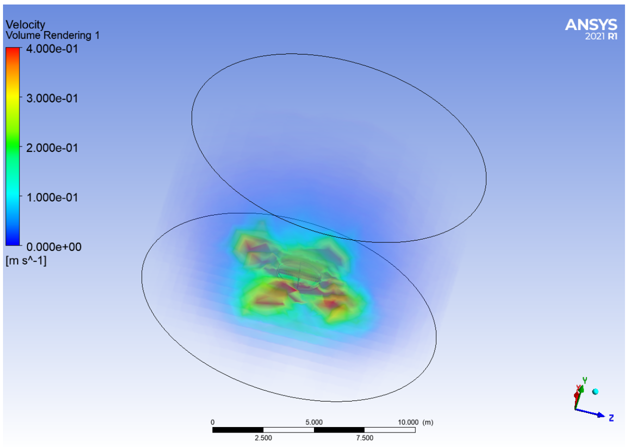

Figure 3. Velocity distribution in the tank in range $0-0.4$ m/s.

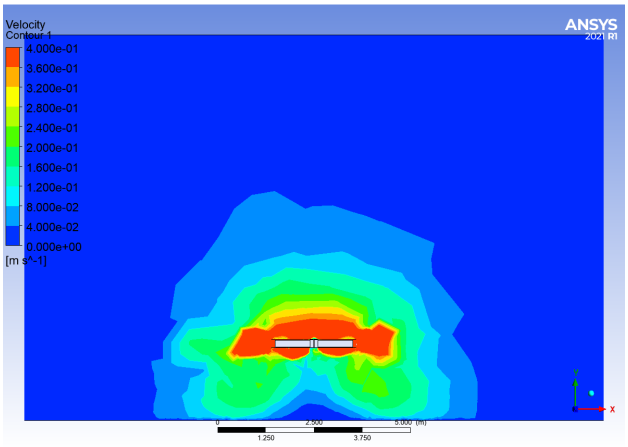

Figure 4. Velocity distribution in the vertical plane intersecting the propeller in range $0-0.4$ m/s.

to make a reasonable flow agitation in a 15-meter diameter tank.
The depth at which the mixer is mounted plays an important role in the final velocity distribution in the reservoir. In case of large tanks with more than 6 meters depth, multistage agitators are promising solutions but since the main concentration of this study is to consider the effects of diameter, blade angle, and rotational speed on its performance, we have skipped to study the staging effect.
As it is evident, although the tank diameter is considerable (15 meters); a 2-meter blade agitator with simple blade profile is able to cover a significant part of the reservoir and agitates the flow properly. One of the most important indices to use as a performance metric for a mixer is the maximum velocity the flow can reach in the tank which presents the agitation power of the mixer. Results for this index are summarized in the Tables 1, and 2.
Referring to natural wisdom and references for fluid dynamics of mixers guide us to expect higher velocity values for larger blades at higher rotational speed which is verified by Table 1. The interesting fact from the tables above is that the effect of rotational speed on the maximum velocity

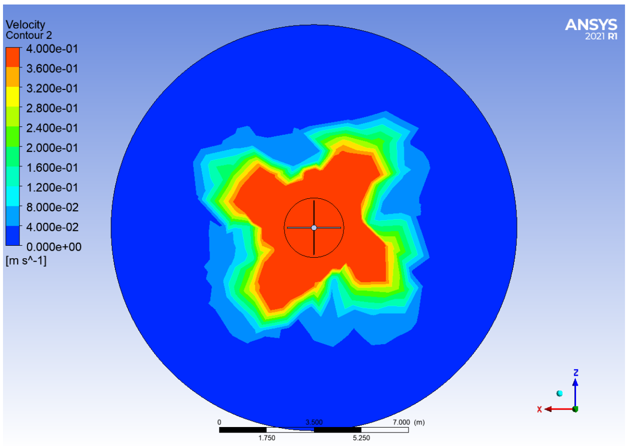

Figure 5. Velocity distribution in the horizontal plane intersecting the propeller in range $0-0.4$ m/s.

Table 1. Maximum local velocity in the tank for different propeller diameters.

Diameter (m)	V_{max} (m/s) @ omega = 1 rad/s	V_{max} (m/s) @ omega = 2 rad/s	V_{max} (m/s) @ omega = 4 rad/s
1.6	0.8773	1.72	3.417
1.8	0.966	1.931	3.833
2	0.9969	1.99	4.115

Table 2. Ratios of the maximum local velocity in the tank for different diameter ratios.

Diameter Ratio	Omega = 1 rad/s	Omega = 2 rad/s	Omega = 4 rad/s
$1.8/1.6 = 1.125$	1.1	1.12	1.12
$2/1.8 = 1.11$	1.032	1.03	1.07
$2/1.6 = 1.25$	1.14	1.16	1.2

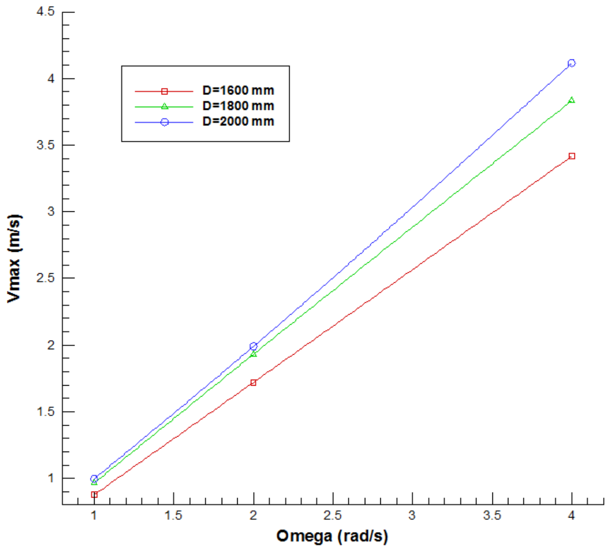

Figure 6. Effect of diameter on maximum local velocity in the tank.

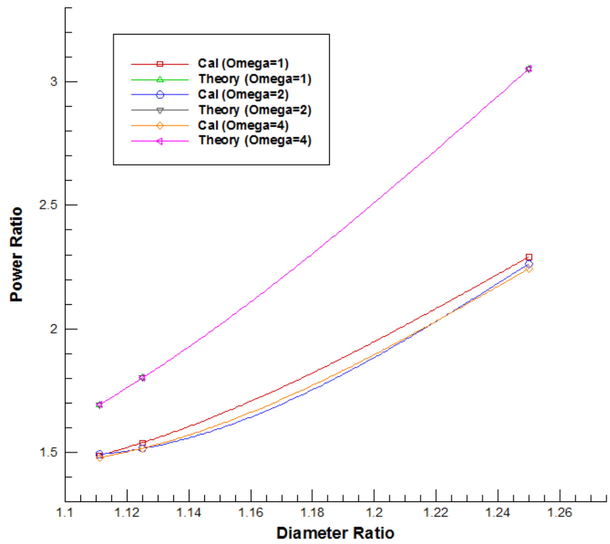

Figure 7. Effect of diameter on power consumption (comparison to theory).

magnitude is more pronounced at higher diameters which means that if you double the rotational speed of two mixers, the one with a larger diameter will experience a more significant effect of velocity enlargement. As a purpose of illustration, the reasoning made above is presented in the Figure 6.
The power consumption of the mixer is calculated for different diameters at different rotational speeds and are summarized in the Tables 3, and 4.
It should be also noted that the effect of increasing the rotational speed is more pronounced at larger diameters for the power as it was true in the case of maximum velocity.
According to [11], the power number of a mixer or agitator is defined as:

$$N_p = \frac{P}{\rho N^3 d^5} \quad (1)$$

Which shows that power consumed by the equipment is proportional to the third power of the rotational speed and the fifth power of the diameter. The amount by which power consumption is increased is almost the same for different rotational speed but the numerical analysis here predicts lower power consumption ratios compared to the amount predicted by theory. It means that the theory predicts the mixer will consume more power and our numerical scheme says it is lower. There are some power losses due to mechanical parts in a real operational mixer which are not considered in numerical schemes, that is why we have lower levels of power consumption in our solution. The discrepancy between numerical and theoretical results is graphically shown in the Figure 7.
In Figure 8, power consumption values for different diameters at three rotational speeds are plotted to state the fact that there is a rotational speed at which the influence of

Table 3. Power consumption of the propeller for different diameters.

Diameter (m)	Power (kW) @ omega = 1 rad/s	Power (kW) @ omega = 2 rad/s	Power (kW) @ omega = 4 rad/s
1.6	0.0672	0.5453	4.39
1.8	0.1035	0.827	6.662
2	0.154	1.234	9.8514

Table 4. Ratios of power consumption of the propeller for different diameter ratios.

Diameter Ratio	Omega = 1 rad/s	Omega = 2 rad/s	Omega = 4 rad/s	Theory [11]
$1.8/1.6 = 1.125$	1.54	1.52	1.52	1.8
$2/1.8 = 1.11$	1.49	1.49	1.48	1.68
$2/1.6 = 1.25$	2.29	2.26	2.24	3.05

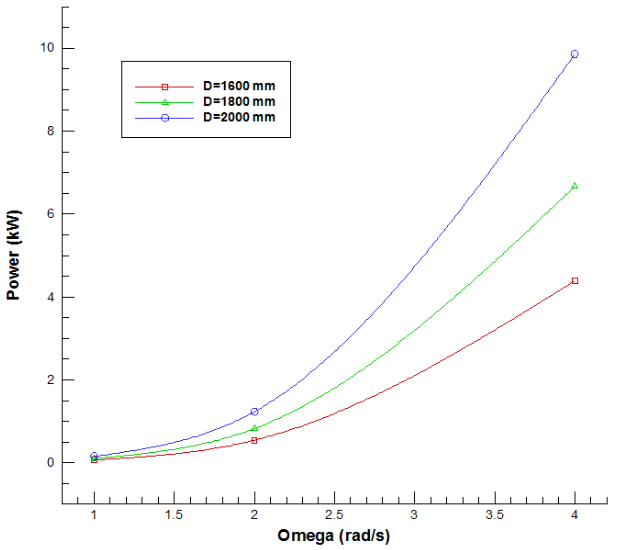

Figure 8. Effect of diameter on power consumption of the propeller.

diameter causes the power to exponentially increase.
There is a threshold for rotational speed of mixers beyond which the power consumed by it will increase in a way that there is no justification for diameter enlargement. For the case of twist angle effect, values of the maximum velocity and the power consumed by the mixer are calculated for a 2-meter diameter agitator and results are summarized in the Tables 5,and 6.
It is worth mentioning that the twist angle has negligible influence over the maximum velocity value but installing the blade at some specific inclination (here TA = 45 degrees) leads to lower levels of power consumption which could be promising in designing efficient vertical agitators. These explanations are illustrated in the Figures 9 (a), (b), and (c). Again, the diminishing effect of twist angle on the power consumption is more pronounced at higher twist angles such as TA = 45 while preserving almost the same value of maximum velocity meaning that the blades are able to make a proper flow of water in the tank by consuming lower levels of electric power without sacrificing the maximum velocity. Therefore, it is recommended to install the blades at a 45-degree angle for more efficiency.

Table 5. Values of maximum velocity for three different twist angles.

Omega	TA = 0	TA = 22.5	TA = 45
1	0.9969	1.041	1.091
2	1.99	2.091	2.186
4	4.115	4.182	4.376

Table 6. Values of power consumption for three different twist angles.

Omega	TA = 0	TA = 22.5	TA = 45
1	0.154	0.14	0.0975
2	1.234	1.12	0.782
4	9.8514	9.01	6.2698

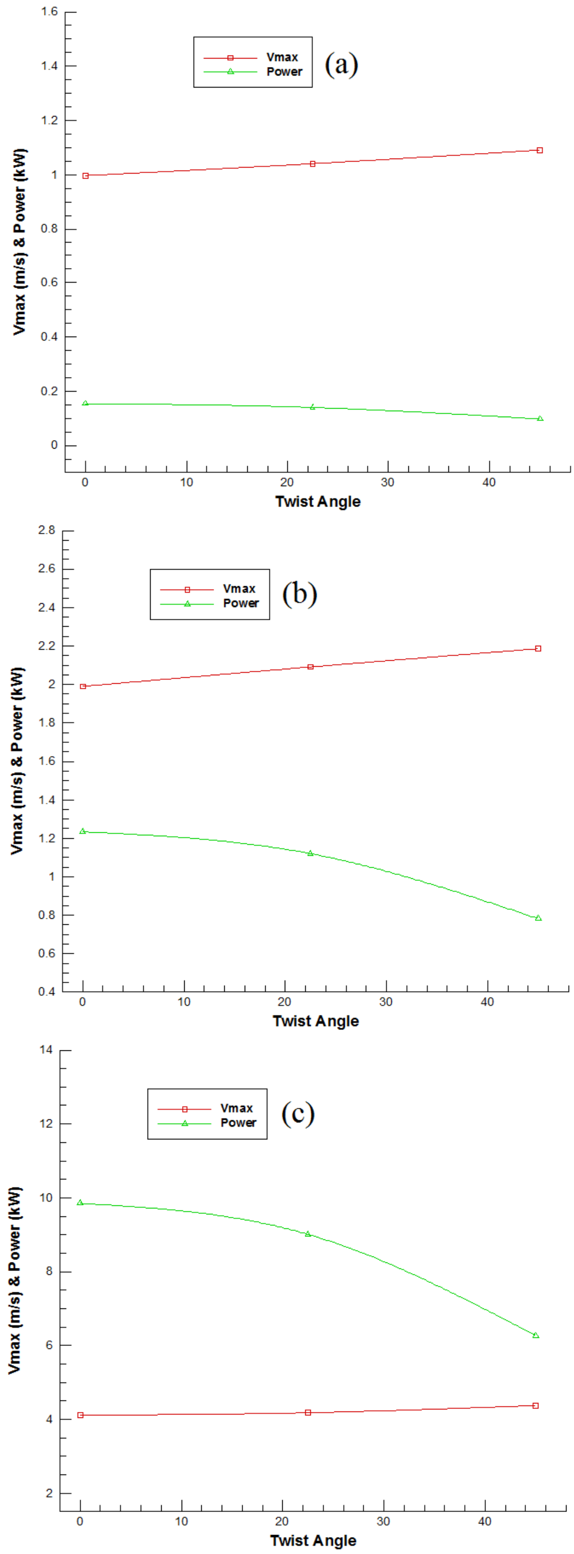

Figure 9. Effects of twist angle on power consumption and maximum velocity of the propeller (a): TA = 0, (b): TA = 22.5, (c): TA = 45).

4. Conclusion

In this study, researchers numerically investigate a vertical axis agitator equipped with four rectangular blades. The focus is on performance metrics, including mixing power and power consumption. The effects of blade diameter, rotational velocity, and twist angle on power consumption and maximum velocity are thoroughly examined. The results are compared to theoretical formulas to identify discrepancies and explain the reasons behind them. Notably, higher diameters exhibit a more pronounced effect of velocity enlargement when rotational speed is doubled. However, there exists a rotational speed threshold beyond which increasing power consumption is not justified by diameter enlargement. Additionally, while twist angle has minimal influence on maximum velocity, installing the blade at an inclined angle reduces power consumption.

Authors contributions
Both authors have participated equally and sufficiently in the intellectual content, conception and design of this research work or the analysis and interpretation of the data as well as the writing of the manuscript.

Availability of data and materials
No data was used for the research described in the article.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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