Kathmandu University Journal of Science, Engineering and Technology, Vol. 15, No. 2, August 2021

Kathmandu University
Journal of Science, Engineering and Technology

Comparative numerical and experimental study of golden angle and conventional agitator impellers

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Abstract

Conventional agitator impellers are found to be implemented in mixing tanks of various industries. The performance of these impellers is measured by the quality of the mixture and the cost of mixing in terms of the required power and time. This paper studies the possibility of replacing the conventional impellers with golden angle impellers for a better performance. The golden angle creates a natural spiral shaped impeller, which is an energy-efficient alternative for mixing tanks due to its natural tendency of minimizing the energy. A golden angle impeller has been designed in this study from CAD modelling and computed through CFD. The average velocity, torque, and power number are determined using numerical simulations from Solidworks 2020. The FloXpress solver is used to compute CFD and results from the golden angle impeller are compared with the same diameter of conventional agitator impeller. The results of CFD showed increase in the power output and the average velocity of the flow in the golden angle impeller to be 12.4% and 66.36% more than that of the marine impeller respectively. Moreover, the results from the simulation are validated through experiments by testing conductivity after mixing fine particles of blue vitriol in water, using 3D printed models of the impellers. The experimental study showed an average increase of the conductivity of the mixture and power consumption to be 5.39% and 17.6% more for the case of golden angle impeller respectively which was due to higher turbulence in golden angle impeller than marine impeller. After comparing the performance of the two impellers, it is found that the mixing process can be optimized significantly by using the golden angle impeller. By the given study it is concluded that the golden angle impeller is more preferrable where mixing process plays a significant role like during the production of pharmaceuticals, cosmetics, waste water management, dairy where manufacturing takes a very long time or when the rotational speed is quite low. The paper is aimed to determine the factors that yield the better performance, energy conservative andefficiency of the crafted golden angle impeller model with respect to widely commercialized impellers (marine impeller), addressing the prospects of minimizing the energy required.

Keywords: Golden angle impeller; Agitator impeller; CFD; Experiment; Conductivity; FloXpress solver

1. Introduction

Agitator impellers are found in various process industries such as food, chemical, mineral processing, bio-processing, wastewater management and pharmaceutical industries to mix both Newtonian and non-Newtonian fluids, to emulsify immiscible liquids, to disperse solids or gases into liquids and to mix solids. According to the White Mountain process [1], each operation of mixing has a specific degree of agitation necessary to obtain the desired result. Furthermore, the mixed tanks are used in diverse processes, for instance blending, scattering, emulsifying, suspending and improving heat and mass exchange.

An agitator is a machine used in a tank for mixing various process media together. According to Flexachem [2], media to dissolve include all liquid types, gases & solids (such as salts, powders, granules etc). Impeller is a rotor used to increase the pressure and flow of a fluid [3]. Past research works have shown that the conventional agitator impellers have been creating many limitations like the poor ratio of mixing solid- liquid phase or liquid-liquid phase of immiscible liquids. In the case of pharmaceutical industries, to make medicines or any other medical drugs, when the required mixture is not obtained, the efficiency of the overall system is reduced. According to a study by Jaszczur et al [5], the shape of blades of the impellers had the most significant impact on power reduction and the efficiency of the mixing process. The golden angle impeller was found to have higher turbulence intensity, which ultimately had better performance compared to other agitators. The typical stirred vessels with conventional agitators are often criticized because they generate non-uniform shear distribution, which is recognized as harmful, especially for the pharmaceutical and the cosmetics industry.

Golden angle impeller is a type of impeller which has a geometry of golden angle spiral whose growth factor is ϕ **(**1.618**)** [4] in each pi radian, the golden ratio where each number is the sum of the previous two. That is, a golden spiral gets wider (or further from its origin) by a factor of ϕ for every half turn. The main goal of this paper is to find the most efficient method of mixing, which consumes as low amount of power and energy as possible by comparing the performance of these two impellers. The torque, average velocity and power number are determined using numerical simulations. The results from the simulations are validated through experiments, using 3D printed models of the impellers to investigate the effects of fluid flow and mixing process. The powers consumed by the impellers and the rate of dissolution of crystals (blue vitriol) are measured.

2. Materials and method

The designs of impellers used for the analysis and experiment were prepared in Solid-works 2020 software. The CAD model of the impellers were 3D printed using the PLA (polylactic acid) material. The dimensions of golden angle impeller and the marine impeller is enlisted in Table 1 and the detailed projections with re-

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Table 1: Dimensions of golden angle and marine impeller.

Parameters	Symbols	Golden Impeller (mm)	Marine Impeller (mm)
Height	h	119.57	42.08
Thickness	t	1.5	1.5
Diameter	d	92.79	92.79

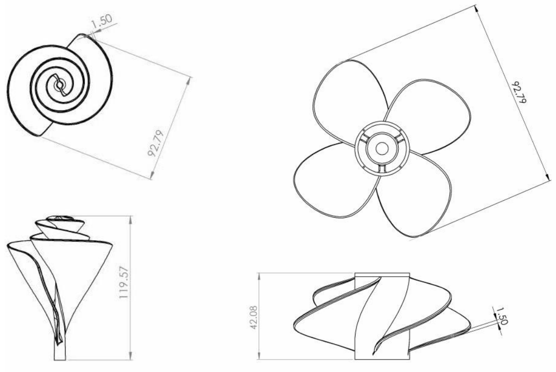

Figure 1: Orthographic projections of golden angle impeller (left) and marine impeller (right).

spective dimensions are shown in Fig. 1. Here, the maximum diameter (d) and thickness (t) of golden angle and marine impellers were assigned equal for an ideal comparison between the two impellers. The study was done keeping thickness and maximum diameter constant, that is 1.5 mm and 92.79 mm respectively where height of golden impeller is 119.57 mm and marine impeller is 42.08 mm.

In Fig. 2(a), diameter of the golden angle impeller was increasing in such a way that a golden spiral gets wider by a factor of ϕ (1.618) for every half turn. The generalized shape for the spiral of the impeller was formula driven. The equation for the golden angle spiral was plotted in the space using cylindrical coordinate system in parametric form, using Equations 1 to 4, where the angle the angle θ varies from 0 to 4π.

$$x = r(\theta)\, cos\theta = a\, e^{0.124}\theta.sin\theta \quad (1)$$

$$y = r(\theta)\, sin\theta = a\, e^{0.124}\theta.cos\theta \quad (2)$$

$$z = r(\theta) = a\, e^{0.124}\theta \quad (3)$$

$$f(x, y, z) = xi + yj + zk = r(\theta)\, cos\theta i + r(\theta)\, sin\theta j + r(\theta) \quad (4)$$

2.1. Experimental setup

The experimental setup implemented in this study is shown in Fig. 2. The experiments were carried out at room temperature and atmospheric pressure. Plain tap water at 11°C, having 6.8 pH and 350 μS/cm conductivity was used as the working fluid (coalescent system). As a major solute for agitating in water, copper sulphate pentahydrate (blue vitriol), having saturation point 168.38 grams/liter at 10°C of water was taken. The reasons behind using $CuSO_4 \cdot 5H_2O$ during the experimental analysis were its availability as well as conductivity. A conductivity meter was attached to the tank that aided in determining conductivity of the mixture throughout the experiment.

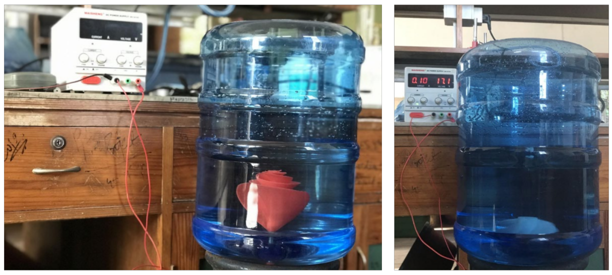

Figure 2: Experimental setup of the agitating vessel with (a) golden angle (left) and (b) marine impellers (right).

The jar had 13.12 cm of radius and 37 cm of height. The impellers were assigned at the bottom of the tank which were further connected with the motor supplying constant voltage of 17 V and the current was let to vary throughout the process. Motor was overclocked by 5 V so that the desired RPM of 180 could be obtained. 10 liters of water was added into the jar which reached the water level of 18.5 cm.

Primarily, a steady conductivity point of 0.1 gram of blue vitriol was calculated at 200 ml of water which is equivalent to mixing 5 grams of blue vitriol at 10 litres of water which gave us an idea about the maximum value of conductivity that could be outstretched.

Initially, for a golden angle impeller, 5 grams of blue vitriol was mixed with water. After a certain time, the conductivity was found to be constant. Subsequently, the same process was repeated for a marine impeller. The value of conductivity was noted down in each 5 seconds. Golden angle impeller was rotated counterclockwise while marine impeller was rotated clockwise to obtain maximum efficiency according to their blade angle. For better precision, the experiment was conducted two times for each impeller.

2.2. Numerical modeling

The solver uses a finite-volume method to combine the fluxes and strain approximations on the faces of control volumes that lead to "pressure-based" and "density-based" approaches. After that, in a SIMPLE-type differencing scheme [6], these mixed approximations are replaced. The solver then obtains either the original SIMPLE-type semi-implicit splitting scheme, the explicit "density-based" scheme or a combination of these methods to handle the mixing weight between the fluxes and pressure approximation [7]. The mesh of the computational domain was generated automatically by the solver.

The simulation was carried in a computational domain with closed boundary conditions. The domain had a cylinder diameter of 30 cm with the height of 40 cm and a shaft at the center with diameter of 6 mm and height of 5 cm. The rotating region with 100 RPM angular velocity was imposed over the impellers. Free surface and multiphase profile were not set during the computation. Walls during the computation were set for no-slip conditions while the cavitation was turned off. Detailed studies were performed through transient explorers in the Solidworks floXpress. Both the impellers were rotated in a closed container with an angular velocity of 100 RPM given the condition of no cavitation and single phase fluid. The axis of rotation was at the center of the cylinder and the cut plots were visualized at the cross-sectional view of the front plane.

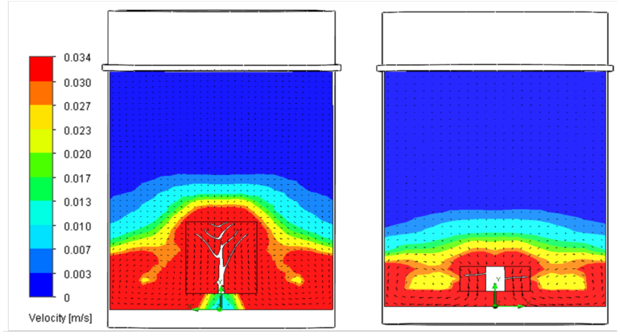

Figure 3: CFD of golden angle impeller (left) marine impeller (right).

Table 2: Computed golden angle impeller data from simulation.

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
Average Velocity	m/s	0.0183	0.0175	0.0161	0.0183
Torque (Y)	N m	0.0013	0.0013	0.0012	0.0014

Table 3: Computed marine impeller data from simulation.

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
Average Velocity	m/s	0.011	0.0104	0.0103	0.0115
Torque (Y)	Nm	0.0011	0.0012	0.0012	0.0011

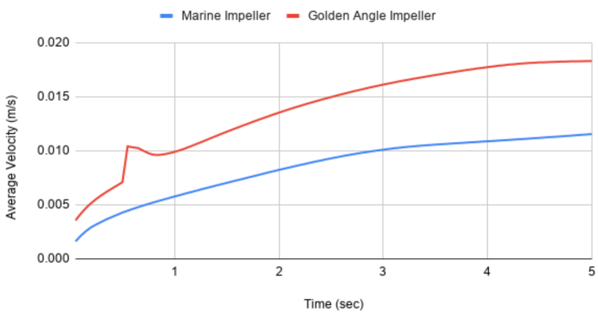

Figure 4: Average velocity comparison between golden angle and marine impeller.

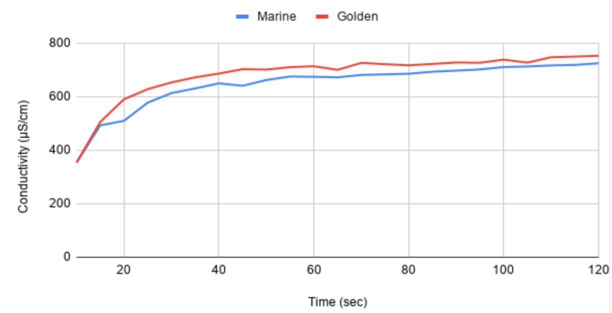

Figure 5: Conductivity comparison for golden angle and marine impeller with respect to time.

3. Results and discussion

3.1. CFD analysis

Fig. 3 shows velocity contours and vectors in the mid plane for the two impellers at the time of 5 s. Fig. 3 (a) has more regions with high velocity, which sums to yield high average velocity than marine impeller of Fig. 3 (b). High velocity around the location of the impeller infers high turbulence intensity needed for mixing of the fluids and any particles that are inside the tank. The vector field and the velocity distribution in Fig. 3 (a) also ascertains homogeneity and quality of the mixture, compared to that of Fig. 3 (b).

Table 2 and 3 show the computed data at 5 s. Average velocity and torque were computed in the computational domain that encompasses the entire fluid at the time step of 0.05 s each for both marine and golden angle impeller. The velocity of the fluid for each of the impellers developed over time can be seen in Fig. 4. It can be observed from both the curves that the velocity of the fluid enclosed in the tank increases gradually. The velocity vs time plot showed that the flow velocity in the case of golden angle impeller was inconsistent at 0.5 s, which could be due to the starting acceleration of the flow field. Rest of the curve was steeply increasing and trying to attain constant average velocity as the time increases. Comparing the two curves, it can be observed that the overall velocity curve is shifted downwards for the case of agitator impeller compared to golden angle impeller. Apart from the velocity, the torque against the axis of rotation for the two impellers shown in Table 2 and 3 shows slight increase in the torque for golden angle impeller, which in the case of CFD performed for a fixed rotational speed, implies increase in the power output and efficiency.

Some further calculations were performed to check the improvement in efficiency of golden angle impeller over marine impeller by using the value obtained from CFD simulation. Table 4 shows a comparison chart between the two impellers in terms of various parameters. Torque (τ), power (P) and rotation per second (n) are related by the equation:

$$P = \tau\, 2\pi\, n \tag{5}$$

Similarly, power number (N_p), density of fluid (ρ), rotational speed (n) in RPS, and diameter (D) of the impeller was related by the equation:

$$N_p = \frac{P}{\rho\, n^3 D^5} \tag{6}$$

Power and velocity of the golden angle impeller while mixing the solution was found to be 12.4 % and 66.36 % more than that of the marine impeller respectively.

Table 4: Comparison of the parameters of two different impellers.

Impellers	Torque (N m)	Power (W)	Power Number	RPS	Diameter (m)	Density (kg/m^3)	Viscosity (Pa·s)	Velocity (m/s)
Golden Angle	0.0013	0.0136	0.426	1.667	0.0928	1000	8.90E-04	0.0183
Marine	0.0011	0.0121	0.381	1.667	0.0928	1000	8.90E-04	0.011

Table 5: Power consumption of Marine and golden angle impeller.

Type of Impellers	Voltage/V	Current/A	Power/Watt
Marine Impeller	17	0.17	2.89
Golden angle Impeller	17	0.14	2.38

3.2. Experimental analysis

The graph between conductivity vs time was plotted as the rate of dissolution of 5 g of copper sulfate. Conductivity was supposed to be 740 μS/cm after the completion of dissolution of crystal. The data which is shown by the graph in Fig. 5 was tabulated after the impellers were rotated and the equal amount of copper sulfate was added to 10 liters of water.

The average difference between the curves of conductivity of the two impellers was 34.61 μS/cm, which is 5.39% more for the case of golden angle impeller. Table 5 showed that the power consumption of golden angle impeller was less than marine impeller by 17.6%. This shows that the golden angle impeller significantly outperformed the conventional marine impeller in terms of both mixing and the amount of energy consumption.

4. Conclusion

Golden angle impeller was found to be more efficient than conventional agitated impellers (reference to marine impeller). The results of CFD showed increase in the power output and the average velocity of the flow in the golden angle impeller to be 12.4% and 66.36% more than that of the marine impeller respectively. Similarly, the experimental study showed the average increase of the conductivity of the mixture to be 5.39% and power consumption to be 17.6 % more for the case of golden angle impeller. The mixing process was found to be better due to higher turbulence in golden angle impeller than in marine impeller.

With the characteristics of consuming low power with higher quality of the mixture, golden angle impeller is more advantageous, especially when it comes to the mixing process during the production of pharmaceuticals, or cosmetics, waste water management where the product manufacturing takes a very long time or when the rotational speed cannot be very high. By adopting the use of a golden angle impeller, energy can be conserved as the shape of the impeller has a golden angle spiral with the tendency to adapt in nature by consuming low power and energy as possible giving more efficiency while mixing. However, more in-depth comparative study could be carried out numerically, experimentally, as well as financially, to have more concrete foundation for the use of this technology.

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