

THRUST OPTIMIZATION OF WATERJET IMPELLER FOR SPEED BOAT USING CFD ANALYSIS

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ABSTRACT

The development of high-speed craft (HSC) can be partly attributed to the application of water jet propulsion systems. Without them, water transportation at high and low tides and long distances would be much more difficult. In addition, the cost of such operations would be much higher. The thrust created in a waterjet propulsion system is the key to the watercraft movement. Among many, one of the propulsion system's fundamental parameters is the propeller's blade number. This study investigated the optimized impeller design that produces the highest thrust and best pump efficiency using CFD analysis. The 3D models of impellers with three, four, and six blades have been designed. Fluid flow in a transient condition has been set as the primary boundary condition. Based on the numerical analysis, it has been found that increasing the impeller blade number increases the thrust, head, and overall system efficiency. The transient study shows that an impeller with six blades produces the highest thrust force value. Furthermore, the efficiency of the impeller was 95%, which is the highest among all the other designs.

Keywords: *thrust optimization, impeller, waterjet, computer fluid dynamics (CFD)*

1.0 INTRODUCTION

The ability to go faster and further is as old as human civilization itself. However, there has been a tremendous advancement in how people travel from one location to another. Initially, it was just over land, but later, it was also possible to travel by sea. Furthermore, for the past century or so, it has also been possible to travel by air. The advancements in automotive and aerospace technology are universally recognized. However, the significant advancement in high-speed craft (HSC) or ship transportation likely goes. For example, fast ferry catamarans running at 50 knots (equivalent to around 90 km/h) were in commercial service worldwide only by the end of the twentieth century (Legaz & Soares, 2021). However, this sort of vessel had only been on the market for less than two decades.

The considerable development in HSC can be partly attributed to the application of waterjet propulsion systems. Without them, the fluid transportation between different water levels for significant distances would be much more complex. The thrust forces created in a waterjet propulsion system are responsible for determining its movement and pressure output (Luo et al., 2020). One of the contributing components to such an attribute is the impeller.

The impeller, a series of vanes that drive the fluid flowing through them, is the main component of this equipment. It is the rotating element responsible for converting mechanical energy into fluid energy. The impeller is often referred to as the "heart" of a centrifugal pump because it is where the total energy changes (Rosa & Emerick, 2018). The fluid flowing through it is accelerated by its centrifugal action, which increases the pressure energy.

The physical characteristics of the impeller, such as the number of blades, vane angle, and diameter, significantly impact the overall performance of the waterjet propulsion system. The change of these parameters alters the amount of available hydraulic energy in the impeller's exit and, consequently, the amount of available work the flow can perform.

The theory of energy transformation into a pump can be simplified based on the angular momentum equation in one dimension. In ideal conditions, with no viscosity fluid, the impeller should have an infinite number of blades to properly guide the flow and provide the same pressure for each radius into the impeller. Therefore, the number of blades influences the impeller performance (Abo Elyamin, Bassily, Khalil, & Gomaa, 2019). In practice, the flow is best guided when there are many blades, but the loss due to viscous friction is higher. Figure 1 shows the theoretical comparison between an impeller with a few blades and an infinite number of blades (Rosa & Emerick, 2018).

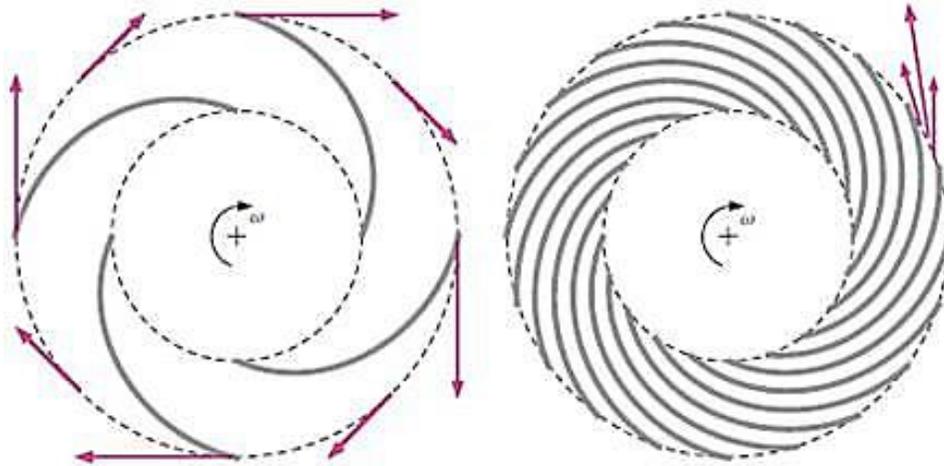


Figure 1. Theoretical comparison of angular momentum in impellers with lesser and infinite numbers of blades

Fluid driving with higher performance and lower energy losses is a prerequisite of a significant component in the propulsion system development since it contributes to lower maintenance, upgrades, and energy costs. Before it is physically implemented, many improvements have to be made to a project, but the high costs of prototyping often hinder its development. In this sense, Computational Fluid Dynamics (CFD) analysis has emerged as an alternative approach to fluid flow problems. Numerical simulations can accurately predict the performance of a particular piece of equipment in a determined framework before its implementation (Ramadhan Al-Obaidi, 2019). As a result, changing the design of a component is much simpler and less costly if the designers know what can be changed before constructing any prototypes. The use of CFD software to design a waterjet propulsion system is only possible because computational resources are becoming more readily accessible. These grew in tandem with an improvement in numerical process precision, and CFD transitioned from a purely academic research tool to a thriving industrial helper.

This study presents the model and simulation of three types of centrifugal pump impellers with proposed upgrades in the impeller's design. It aims to improve water jet propulsion by optimizing the impeller design via CFD analysis by determining the optimum number of impeller blades (three, four or six blades). The simulation results were used to create the impeller's characteristic curves, which were then compared to each impeller to determine the optimum design.

2.0 LITERATURE REVIEW

2.1 Operation principle of waterjet propulsion system

The idea of using water as a power source was first considered as early as 1661 by Toogood and Hayes that theorized the propulsion system is possibly generated by using water. Waterjet propulsion is a type of unique propulsion system that is different from a propeller. This device has been widely used in many high-speed ships because of its high propulsion efficiency, low noise and vibration, and simple transmission structure (Bulten, 2008). In general, a waterjet propulsion system consists of four main components, which are inlet duct, propulsion pump, nozzle, and steering device. The thrust produced by a waterjet is generated from accelerated water flow between the entrance (inlet duct) and exit (nozzle) as shown in Figure 2. Water from underneath the hull flows into the jet inlet duct and then is accelerated by the propulsion pump. The streamline indicates the water flow entering the inlet duct and passing by a few components before being discharged outside through the nozzle (Luo et al., 2020).

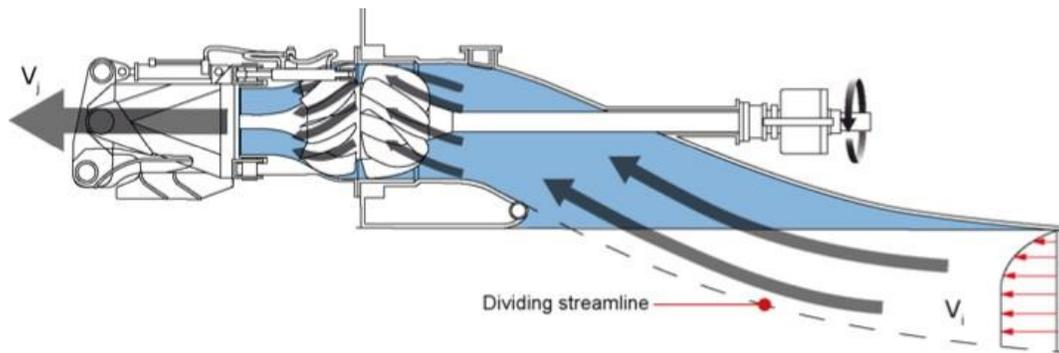


Figure 2. Typical accelerated water flow in a waterjet propulsion system

2.2 Influence of impeller blade number on the propulsion system

The purpose of a propulsion system is to produce thrust to propel a vessel. Therefore, water is accelerated by the impeller, which results in a reaction force on the ship structure in the opposite direction. Bacharoudis, Filios, Mentzos, and Margaris (2008) stated that various parameters affect the pump performance and energy consumption. Various factors that could affect the efficiency of the waterjet propulsion system have been investigated, as well as the suitable types and characteristics of pumps, have been described (Arcand & Comolli, 1968). Ping-chung (1978) emphasized the procedures for determining the main parameters that affect waterjet propulsion by considering the pump characteristics at an early stage of system design. Overall optimization analysis of the waterjet propulsion system with a nozzle based on flow and geometric parameters also has been performed (Jiao et al., 2019).

A centrifugal pump's performance depends mainly on its impeller's performance. Tan (2010) simulated six centrifugal pump models running at the designed and off-design flow rates at different speeds. Ansys Fluent solver with standard k -epsilon (k - ϵ) turbulence model, combined with SIMPLEC algorithm based on Navier-Stokes equation, was chosen to perform the simulation. Steady flow and moving reference frame were used to consider the impeller volute interaction. The head and efficiency of the six models at different flow rates were compared with the experimental ones. As a result, it was concluded that the Ansys Fluent simulation results were feasible and accurate in predicting the performance of centrifugal pumps as the deviation of the predicted head and efficiency were less than 5%.

Among many, the focus was given to one of the influencing parameters of a waterjet propulsion system is the blade number. Liu (2010) investigated the effect of blade number on the flow field and characteristics of a centrifugal pump. The pump model had a design-specific speed with five impeller blades, where the blade number was 4, 6, and 7, while other parameters were constant. Ansys Fluent solver was used to simulate and predict the flow field. They concluded that the blade number significantly affected the area of a low-pressure region behind the blade inlet. By increasing the blade number, the pump head was also increased.

A numerical investigation of a centrifugal pump with various impeller blade numbers was performed by Chakraborty, Pandey, and Roy (2012). In their investigation, a series of rotational speeds at 2900, 3300, and 3700 rpm were applied for a centrifugal pump having 4, 5, 6, 7, 8, 9, 10, 11, and 12 impeller blades. The results indicated that the efficiency of the centrifugal pump varies with the number of blades. The efficiency and head coefficient increased as the speed of rotation increased. Moreover, the head coefficient increased with the blade number, but the maximum efficiency was achieved for 10 blades. Further increment in the blade number had an insignificant effect on the overall pump performance.

Kang, Mao, Zhang, and Gu (2017) investigated the centrifugal pump that operated under cavitation conditions. Both experimental and numerical methods were used. Three impellers with different blade numbers were designed to improve the cavitation performance. The distribution of flow parameters, pump head, and cavitation were systematically investigated. In research performed by Rajendran and Purushothaman (2012), as a result of manipulating the blade numbers between 6 to 8 blades, it was observed that the efficiency of the impeller decreased and the pressure head increased as the rotating speed of the rotor increased. Additionally, it was found that the pressure head increased as the blade outlet angle increased.

In conclusion, the effect of blade numbers of impeller has a significant impact on a propulsion system. However, it is difficult to conclude the optimum number of impeller blades since each impeller design is different and specialized for specific applications. Thus, it is necessary to perform a similar study applied to the impeller designed for speed boats that utilized a waterjet propulsion system.

2.3 PROBLEM STATEMENT

One of the main issues related to the waterjet propulsion system is its efficiency. Poor efficiency is directly related with high fuel consumption, especially for small speed boats used in fishing industries. In the past years, the fishing industry's demand for a high-performance waterjet propulsion system in speed boats increased tremendously. The annual operating expenses of fuel consumption by fishermen are usually accounted for more than 50%. Hence, reducing fuel consumption is expected to decrease the overall operating cost. However, ensuring an efficient waterjet propulsion system for a speed boat is not easy. Much research has been conducted to enhance the propulsion system's efficiency, but optimizing the design of the impeller blade to increase the thrust still requires further development.

In research related to enhancing the propulsion system's efficiency, the impeller's vane and design are sometimes dismissed as something that brings an insignificant impact to the efficiency of the water jet propulsion system. However, the vital component in producing momentum by obtaining thrust in propulsion systems is the impeller itself. Thus, simulational studies are an excellent approach to prove the influence of impeller blades in improving the propulsion system's efficiency, especially the produced thrust. This study deals with a specific application of the waterjet propulsion system for an electric speed boat used in fishing industries that limit the number of impeller blades to be less than eight.

2.4 SIGNIFICANCE OF RESEARCH

Since watercraft is a commodity, it is critical to have a boat with good anti-cavitation capacity, high system performance, excellent maneuverability, and stable activity. The outcome of this study would generally contribute to the advancement of speed boat technology in the marine sectors, such as the fishing industry and water rescue teams. Due to the expected efficiency of a waterjet propulsion system, it has recently been used in various vessel types, including amphibious vehicles. In addition, these systems have several advantages over traditional screw propeller systems, particularly in marine military transportation vessels. These benefits include high power at low speeds to aid maneuverability and withdrawal from the water as well as good operational capability in shallow waters. Combining these factors, it increases the demand for waterjet propulsion systems in a wide range of amphibious transportation and marine applications.

Most notably, the results of this research are expected to be shared with the industry, primarily the speed boat manufacturer that targets the fishing industry. Fishing vessels, especially in Southeast Asia, such as Malaysia and Indonesia, operate on short trips ranging from a few hours to a few weeks. Capital expenditure for such a short operating period is very high. Significantly reducing the fuel consumption of the fishing fleets should serve as an excellent countermeasure to minimize operating costs. One of the primary aims is to provide an energy-efficient

system with a dependable propulsion system. Since this research focuses on finding the best impeller design for speed boats, the outcomes of this research might meet the demand for a high-performance speed boat that is energy-efficient and economically friendly.

3.0 RESEARCH METHODOLOGY

Three impeller designs with various blades have been used to investigate the optimum number of blade propellers that produce the best propulsion system using CFD analysis. The research methodology started by creating the 3D model of the waterjet impellers with a various number of blade using CAD software, Solidworks. The waterjet impellers were designed based on the original model provided by an electric speed bot manufacturer, Hayatech Sdn. Bhd. The designed models then meshed in Ansys Workbench. Verifications of independence from the grid number and time step were used to eliminate the influence of the number of grids on the calculation of the results. Then, the bodies are linked together and CFD analyses were done in Ansys CFX.

3.1 3D modelling

The fundamental design of a waterjet impeller consists of three blades that provide sufficient efficiency. Its simplicity and manufacturability are the main reasons such design is widely used. The 3D model of the impeller with three blades provided by Hayatech Sdn. Bhd. is shown in Figure 3(a). Based on that, modifications have been made to the number of blades while keeping the other parameters constant, as given in Table 1. Figures 3(b) and 3(c) show the designed impeller with four and six blades.

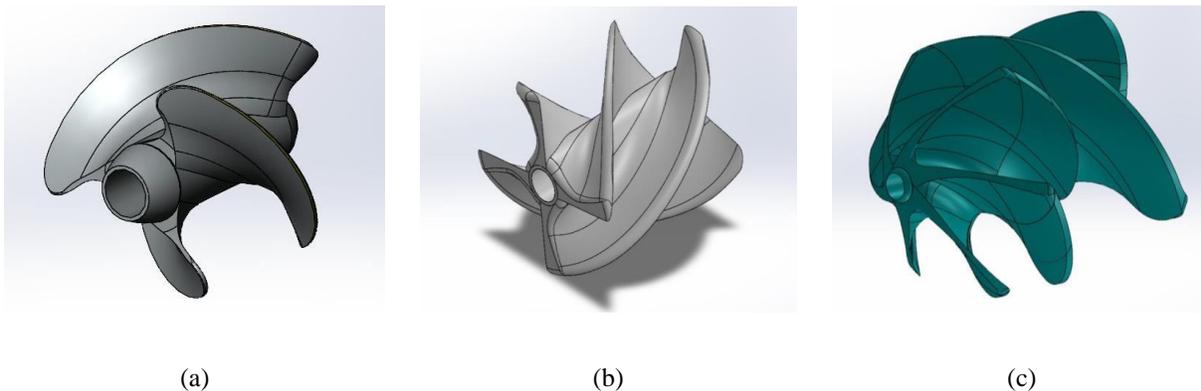


Figure 3. 3D model of impellers with (a) three, (b) four, and (c) six blades

Table 1. Constant parameters for impeller designs

Geometric Parameter	Value
Inlet diameter, $D1$ (mm)	25.5
Outlet diameter, $D2$ (mm)	250.5
Impeller width, $b1$ & $b2$ (mm)	312.5

3.2 Meshing

Fully tetrahedral meshes were adapted to discretize the computational domains, as shown in Figure 4. The number of grids was set to the automatic setting to achieve an optimum value for accurate numerical calculations. Theoretically, the higher mesh quantity should provide higher result accuracy at the expense of high processing power. However, high mesh quantity increases the calculation time and reduces convergence speed, leading to irrelevant

accuracy. Therefore, to eliminate the influence of the number of grids on the calculation of the results, it is necessary to check its independency from the grid number.

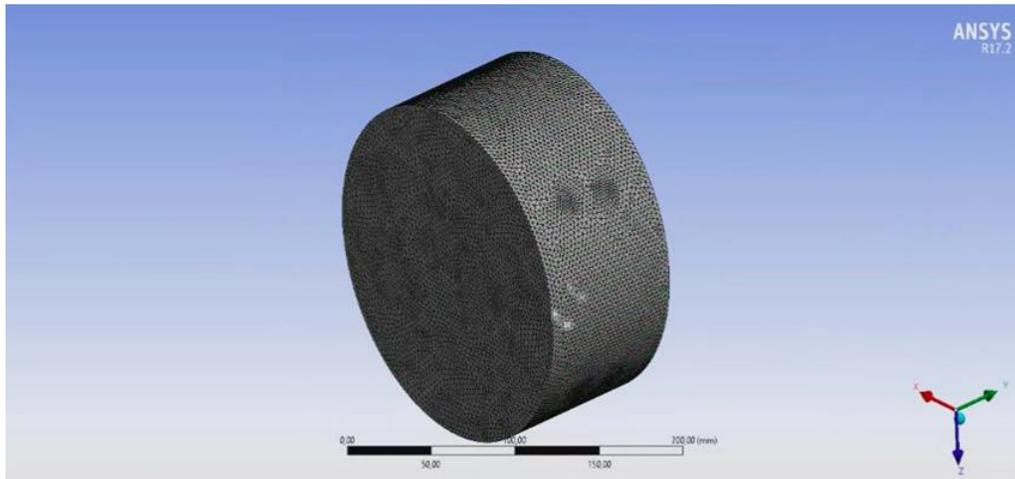


Figure 4. Meshed impeller in a volumetric fluid body enclosed in an imaginary casing

3.3 Simulation conditions and fluid properties

In order to analyze the impeller, the renormalization group (RNG) K-epsilon turbulence model was employed (Yakhot, Orszag, Thangam, Gatski, & Speziale, 1992). Then, the boundary conditions for each part in the 3D model are given in Table 2. The relative velocity of the impeller is defined as the global rotating reference frame. To prevent errors caused by unsteady boundary conditions of the inlet and outlet walls, it has been assumed that water flow was stationary and that the pressure difference between the inlet and outlet was zero at the beginning of the start-up. The impeller is the only rotating part with a rotational speed of 1450 rpm with an initial head of 20 m. Based on such assumptions, the boundary conditions of the inlet and outlet were all set as stable total pressure where the reference pressure was set as 0 atm.

Table 2. Boundary conditions for CFD analysis

Boundary	Set Condition
Blades walls	Rotating and non-slip and wall surface is considered rough
Hub walls	Rotating and non-slip and wall surface is considered smooth
Hub outlet walls	Rotating and non-slip and wall surface is considered smooth
Inlet wall	Fixed walls
Outlet wall	Fixed walls
Shroud wall	Rotating and non-slip and wall surface is considered smooth

Water has been defined as the fluid for the analysis. For its properties, the water flow has been considered as incompressible, resulting in a constant density. All impeller models scale calculations have been carried out with a density ρ of 1000 kg/m³, and dynamic fluid viscosity μ is set to 0.001 kg/ms.

4.0 RESULTS AND DISCUSSION

In this research, CFD analyses were carried out on a series of impellers having three, four, and six blades in order to investigate the relationship between blade number and its efficiency. Thrust was calculated using Ansys CFX, and the impeller efficiency was calculated using the velocity triangle formula. The obtained transient thrust force, velocity streamline, and fluid pressure distribution are shown in Figures 5, 6, and 7, respectively. Based on that, Table 3 summarizes the performance characteristics of each impeller.

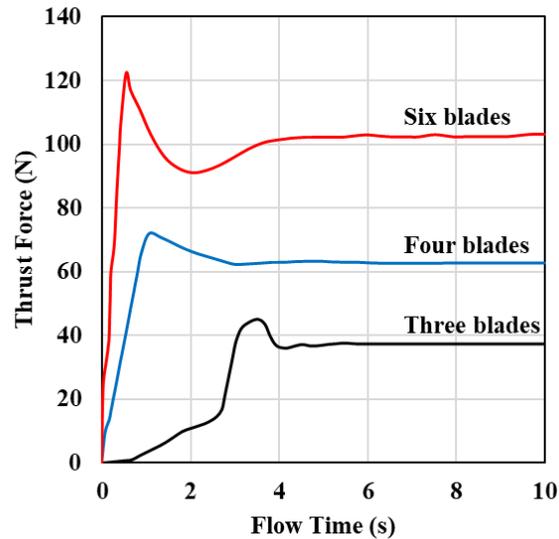


Figure 5. Transient thrust force for each impeller

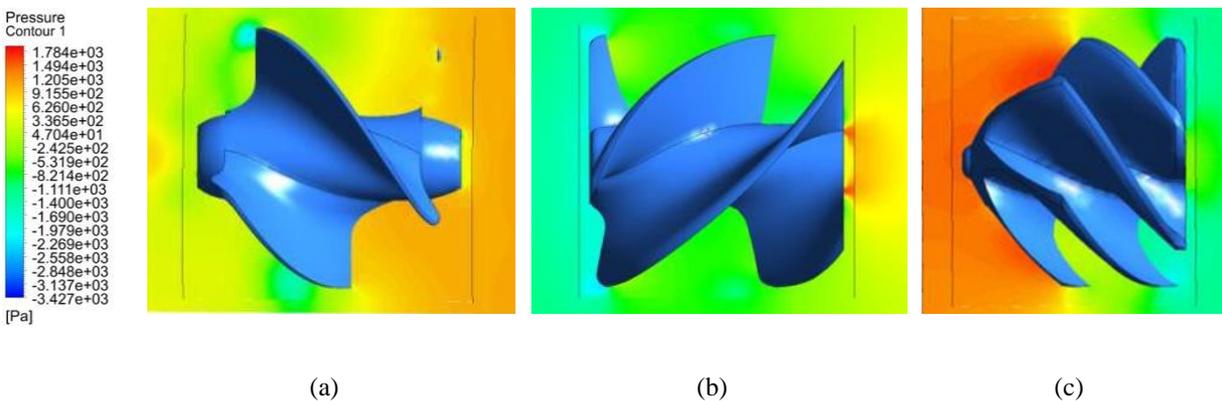
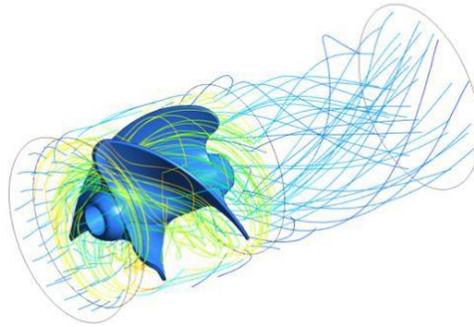
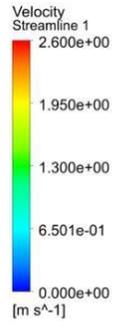
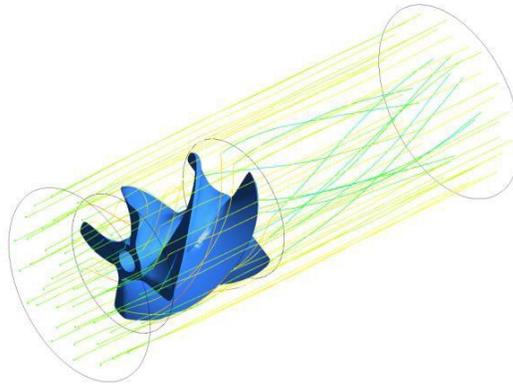
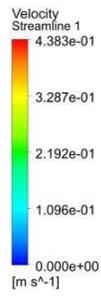


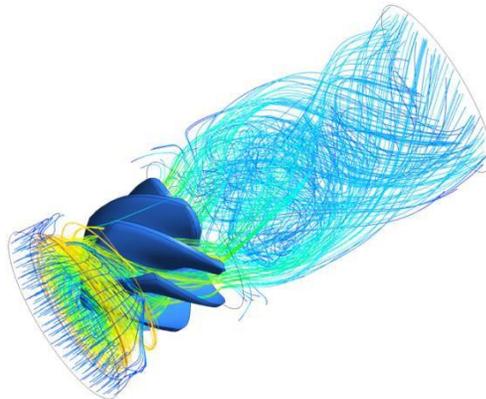
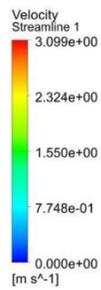
Figure 6. Fluid pressure distribution for impeller with (a) three, (b) four, and (c) six blades



(a)



(b)



(c)

Figure 7. Velocity streamline for impeller with (a) three, (b) four, and (c) six blades

Table 3. Performance characteristics of each impeller

Properties	Blade number		
	Three	Four	Six
Speed (rpm)	1450	1450	1450
Head (m)	16.75	21.18	22.31
Power (kW)	0.0030	0.0041	0.0035
Total efficiency (%)	84.01	92.78	94.37

It can be observed in Figure 5 that for all types of impellers, generally, the thrust force rises to its peak and then gradually stabilizes to a constant value. During the start-up stage, it is observed that the three-blade impeller had a slow start-up compared to the rest before reaching its peak. On the other hand, for four and six-blade impellers, their forces increase rapidly during the start-up stage. After a few seconds, all impellers reach a steady condition where the force are 37, 62, and 103 N, respectively.

From Figure 6, the maximum velocity streamline is 2.6, 4.3, and 3.1 m/s, respectively, for three, four, and six blades' impellers. The generated power by these impellers is related to the produced power. Even though there is a slight deviation in power between three, four, and six blades, the results show no significant effect of blade number on the produced power. Moreover, in Figure 7, it is shown that the fluid pressure distribution produced by the impeller with three blades has a maximum mass flow rate of 7.651 Pa, followed by 6.68 and 1.78 Pa, respectively, for four and six blades' impellers. Six blades impeller design has significantly reduced the fluid pressure compared to the others.

In order to see how the number of blades affects the impeller's efficiency as one of the influencing parameters, the performance curve in Figure 8 has been illustrated based on Table 3. It shows the influence of impeller blades number on the efficiency and the head of the propulsion system at the rotational speed of 1450 rpm. At a glance, as the blade number increases, the efficiency increases. Among all, six blades impeller design has the best performance with 94.37% efficiency, making it a good option for the waterjet propulsion system of a speed boat. It is known that a waterjet propulsion system generates propulsive thrust from the reaction created when water is forced in a rearward direction. Thus, a higher value of efficiency is desirable.

However, the performance curve shows that there is only around 2% efficiency difference between four and six blades compared to 8% efficiency difference between three and four blades. Such efficiency properties mean that increasing the blade number further (more than six) could not necessarily increase the impeller's overall performance. Moreover, as the blade number increases, the manufacturability of the impeller becomes complicated, which may not be feasible in actual fabrication and system assembly.

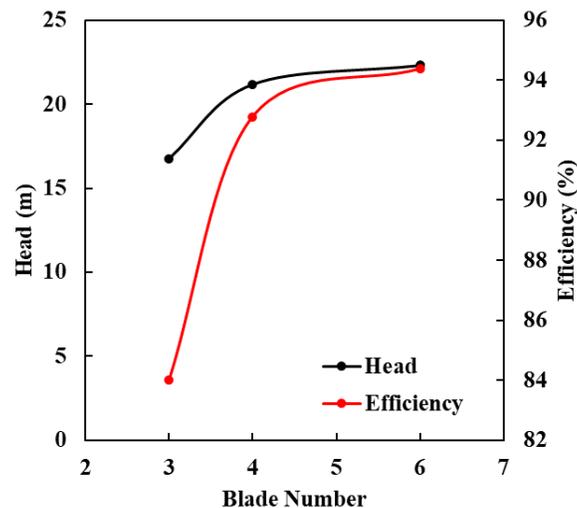


Figure 8. Relationship among blade number, head, and efficiency

Furthermore, the comparison between the characteristic curves among the impellers in Figure 8 has shown that the model with six blades presented approximately 25% higher impeller head for the usual range of volume flow rates compared to the one with three blades. Such performance indicates that the six-blade impeller has better fluid flow guidance, which positively overcomes the viscous friction. The fluid flowing from the inlet is accelerated by the improved impeller and thus, volutes fast towards the outlet of the propulsion system.

5.0 CONCLUSION

This study investigates the relationship between the blade number of impeller and its corresponding performance characteristics where a series of impellers with three, four, and six blades had been simulated and analyzed. It has been found that increasing the number of blades improves the efficiency of a water jet propulsion system. A well-designed impeller may produce systems with 90% or greater efficiencies, where a six-blade impeller could achieve an efficiency of 95%. A six-blade impeller is considered as an optimum design that balances the thrust output and practical feasibility. Such a result is beneficial since a waterjet propulsion system for speed boats needs to produce a high thrust to perform optimally. Further analyses for other critical parameters of impeller, such as blade angle and trim profile, are expected to be conducted in the near future before fabricating an actual propeller for experimental studies.

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