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Experimental Study on the Effect of Blade Exit Angle on Centrifugal Pump Efficiency

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Abstract

Rotodynamic type pumps, particularly centrifugal pumps, enable lifting of liquid from a lower to higher level by developing dynamic pressure. The effect of the blade exit angle on centrifugal pump efficiency is a crucial aspect of pump design and operation as it has significant effects on flow dynamics, energy transfer, and pressure performance. So, careful design and optimization of this parameter is important for substantial improvements in pump efficiency and operational effectiveness. The study focuses on adjusting the blade exit angles and analyzing their effects on the pump's hydraulic performance. Using pumps with varying blade exit angles, a number of tests were carried out under close observation of important performance metrics like discharge rate, flow velocity, and overall efficiency. Impellers were designed using SolidWorks 2020, and fabricated using additive manufacturing by Polylactic acid (PLA) to measure the performance of a centrifugal pump with different blade exit angles ranging from 40° to 90°. The experiments were carried out with a motor running at around 2990 rpm. The results showed that the efficiency of the centrifugal pump was significantly affected by the blade exit angle, with a maximum efficiency obtained at a blade exit angle of 40º. As the blade exit angle decreases, the efficiency of the centrifugal pump increases. When the fluid flowed through the impeller, it gained kinetic energy and was directed towards the pump volute where the kinetic energy was converted into pressure energy. By decreasing the impeller blade exit angle, the fluid was directed more effectively towards the volute and there was less recirculation, resulting in an increased pump efficiency. However, decreasing the blade exit angle too much could also have negative effects on pump performance. It is also concluded that the metallic impeller has a better discharge rate and flow velocity than non-metallic impellers but is very close in terms of efficiency with the impeller of a similar angle. However, the cost of the impeller made using additive manufacturing by Polylactic acid (PLA) is far lower than metallic impellers of the same parameters. The experimental study sheds light on how changing the blade exit angle of the impeller affects the efficiency of a centrifugal pump. Impellers with various exit angles were fabricated using additive manufacturing, their efficiencies were determined, and different parameters were analyzed to successfully conduct this experimental work.

Keywords
Centrifugal pump, Blade exit angle, Pump efficiency, Additive manufacturing.

1. Introduction

Centrifugal pumps are essential in numerous industrial and engineering applications, serving integral roles in fluid transport across a wide range of sectors, including nationwide water supply, wastewater treatment, and chemical processing. The efficiency of these pumps is influenced by numerous design parameters including the impeller blade geometry, blade exit angle, system design and many more. The impeller is the single most important part of a centrifugal pump as it is this part that converts mechanical energy into hydraulic energy. Therefore, impeller-related parameters are important for the overall performance of the pump. The blade exit angle is one of those parameters which, if not designed correctly, will negatively influence the head and the hydraulic efficiency of the pump. The blade exit angle directly affects the velocity and the direction of the fluid leaving the impeller, impacting both the flow rate and head (Babayigit et al. 2015). Moreover, this blade exit angle impacts not only the hydraulic performance of the pump but also its energy consumption and operational stability. Understanding the relationship between blade exit angle and pump efficiency is crucial for optimizing pump design and enhancing overall system performance.

Additive manufacturing, otherwise known as 3D printing, has revolutionized the manufacturing process by enabling design flexibility, customization, and rapid prototyping (Mehrpouya et al. 2021). Additive manufacturing has reduced the need for extensive inventories, simplifying the supply chain. On top of that, additive manufacturing has little to no waste as it fabricates specimen layer by layer, using only the material needed for the final product, compared to subtractive manufacturing process which cuts away metal from a larger block. It is also more cost-effective for low-volume production and allows material variety in the manufacturing process. This study delves into the effect of the blade exit angle on the centrifugal pump with the centrifugal pump being fabricated using additive manufacturing. Polylactic acid (PLA) was used for fabricating three impellers with different blade angles and then the effect of these different blade angles along with the consequences of using different material impeller on the pump efficiency was studied. This experimental study systematically investigated the effects of varying blade exit angles on the efficiency of a centrifugal pump. It also compares the cost-effectiveness of using additive manufacturing to fabricate impellers to traditional methods.

1.1 Objective

This study aims to show how a centrifugal pump's efficiency is affected by changing the blade exit angle. It also intends to show, how other parameters, such as discharge rate and flow velocity changes with the change of blade exit angle. The experimental methodology requires fabrication of impellers of different angles of the same specifications as the impeller that is provided by the pump manufacturer. As the benefits of rapid prototyping and affordability, additive manufacturing is preferred over traditional subtractive manufacturing to fabricate the impellers. The result is expected to show, optimal blade exit angle among the fabricated impellers for manometric efficiency, discharge rate and flow velocity. It will also differentiate between the radial gunmetal impeller that manufacturers provided with radial impeller made with 3D printer.

2.Literature Review

Various researches have been conducted to improve the efficiency by revealing the flow mechanism inside the centrifugal pump aiming to design high performance turbomachinery. A wide range of studies have also been conducted on various aspects of pumps, including efficiency, head, and longevity. Thin et al. (2008) analyzed a single-stage end suction centrifugal pump, calculating theoretical head, slip, shock losses, and friction losses by varying the volume flow rate to obtain a characteristic curve.Zaman et al. (2017) worked on optimizing the cost efficiency of a centrifugal pump by minimizing power consumption. Various design parameters were analyzed to enhance performance, and an algorithm was developed to streamline pump selection based on iterative calculations.Bacharoudis et al. (2008) conducted research on the parametric study of a centrifugal pump impeller by varying the outlet blade angle, focusing the numerical analysis on how alterations in the blade exit angle impact various parameters of the pump. H. Zhang et al. (2020) examined the impact of various blade profiles on the performance of a plastic centrifugal pump, utilizing single arc, double arc, logarithmic spiral, and B-spline curve methods for design. The findings indicated that the impeller designed with the logarithmic spiral method demonstrated superior performance compared to the other profiles.

Numerous numerical studies have been conducted on pumps to explore the complex interactions between various parameters and their impact on overall performance. Hasu et al. (2017) examined the effects of varying vane angles on single-stage centrifugal impeller pumps. Using 3D modeling, static and modal analyses were conducted to evaluate stresses, deformations, and frequencies under rotational velocities for materials such as stainless steel, aluminum alloy

A356, S-glass composites, and carbon fiber reinforced plastic. The findings provide insights into how the deformation and stress changes with the varying blade angles. Grapsas et al. (2008) developed a numerical methodology for optimizing hydrodynamic design in centrifugal pumps while focusing on improving impeller hydraulic efficiency through blade shape enhancements. Shojaeefard et al. (2012) numerically simulated 3D flow of a centrifugal pump pumping viscous fluids The obtained numerical results are compared with the experimental ones showing acceptable agreement between the two.

Several studies have also been conducted to examine the impact of impeller geometry and material on pump performance. Luo et al. (2008) investigated the effect of impeller inlet geometry on the performance of a boiler feed pump with a specific speed and impeller blade exit diameter. They found that extending the blade leading edge and increasing the inlet blade angle improved hydraulic and cavitation performance. Uniform flow at the impeller inlet was also found to enhance cavitation performance. Han et al. (2018) combined numerical simulation with experiment to optimize the impeller design of a centrifugal pump by varying the blade wrap and exit angles. Performance tests showed that the optimized impeller improved the pump's head and efficiency compared to the original design. Heo et al. (2016) researched about design optimization of a backward-curved blade centrifugal pump with a specific speed of to enhance hydraulic performance using surrogate modeling and 3D Reynolds-averaged Navier-Stokes analysis.

3.Methodology

3.1 Material Selection

While designing the impellers, two major factors were considered. One of them is the mechanical properties of the impeller material and another is cost-effectiveness. A centrifugal pump's performance is impacted by the materials of the impeller. Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS) and Nylon – these three materials are vastly used for the additive manufacturing process. Nylon and ABS both absorb moisture and ABS becomes brittle at low temperatures. PLA, however, exhibits negligible degradation in mechanical properties while being immersed in room temperature water (Banjo et al. 2022). As the impeller has to rotate at a high speed, the material with higher strength and stiffness is preferable. PLA has higher strength and stiffness than ABS and Nylon (Sudin et al. 2023). It is also a biodegradable thermoplastic, whereas ABS and Nylon are non-biodegradable materials. So, considering all these aspects, PLA is the best choice for 3D printing the impeller among these three materials.

3.2 Design and Fabrication

Three impellers with blade exit angles of 90°, 70° and 40° were modeled using SOLIDWORKS 2020 with respect to the dimensions of the impeller that came with the centrifugal pump. Then, these models were converted into .stl format and was inputted into Pursa slicer software to determine how much material and fabrication time would be required for the 3D printing process. After that, the models are uploaded to the 3D printing machine with PLA material roll inserted for fabrication completion. The CAD models are shown in figure 1 and fabricated impellers are shown in figure 2. 3D printing was done in FAB lab facility of Khulna University of Engineering and Technology (KUET). The fabrication process for all three impellers took around 4 hours and 47 minutes and the material required was 32g of PLA.

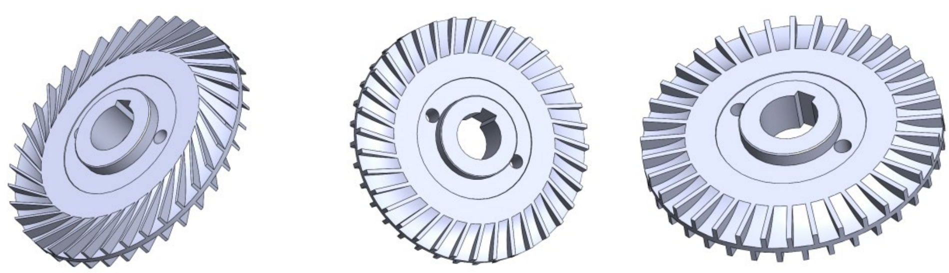


Figure 1. CAD Model of Impellers with 40º, 70º and 90º Blade Exit Angle

Figure 2. 3D Printed Impellers with 40°, 70° and 90° Blade Exit Angle

3.3 Experimental Setup and Experimental Procedure

The experimental setup included a centrifugal pump equipped with the fabricated 90° blade angle impellers. The pump's suction line was connected to a calibrated water container with a maximum 20 liter capacity and a one-sided suction valve. The pump was linked with a 3-phased induction motor with a Variable Frequency Drive (VFD). Water traveled through the suction line to the impeller in the pump. A delivery line was installed with the pump for water disposal. A tachometer was used for determining the rotational speed of the impeller inside the pump. The suction head was 0.5 meters and the discharge head was 0.2 meters, resulting in a 0.7 meter static head. A schematic diagram of the experiment setup is shown in figure 3. The real test setup is shown in figure 4.

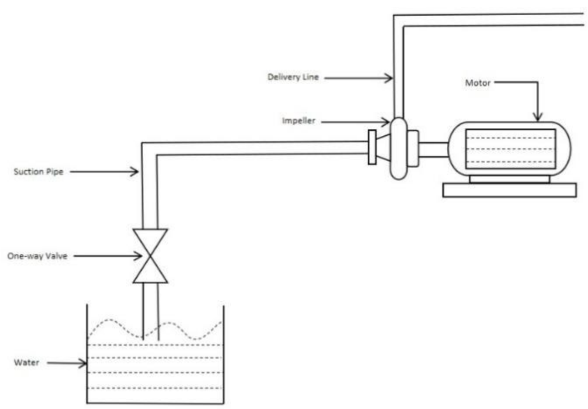


Figure 3. Schematic Diagram of Experimental Setup

Figure 4. Experimental Setup

At first, the rotational speed of the motor was recorded using a tachometer. Then, before starting the water flow, a tube gasket was placed between the volute casing and the adjacent metal surface to prevent water leakage from the volute chamber. After that, the centrifugal pump was first equipped with a radial impeller and then primed using water to eliminate air pockets in the volute chamber. The electric motor was started with the delivery line closed to minimize starting torque.

As the impeller rotated, it created a forced vortex, generating a centrifugal head in the liquid. After some time, the delivery line was opened, allowing the liquid to flow outward radially. The liquid exited the impeller blades' outer circumference at very high velocity, which was then converted into pressure energy upon reaching the delivery line. The time taken to discharge 10 liters of water was measured with a stopwatch. Using this data and related equations, the discharge rate, pump efficiency for the specific impeller, and manometric head were calculated. The 70° and 40° impellers were then mounted sequentially, and similar measurements were taken for each.

4. Results and Discussion

Data collected from the experiment is used for calculating manometric efficiency (η_{mano}) through necessary equations (Modi and Seth, 2017). The equations and data are listed below-

The rotational speed of the impeller, N = 2992 rpm
The outer diameter of the impeller, D = 60 mm = 0.06 m
The distance between adjacent blades, B = 5 mm = 0.005 m

The tangential velocity of the impeller, $u = \dfrac{\pi DN}{60} = \dfrac{\pi \times 0.06 \times 2992}{60} = 9.4$ m/s (1)

Discharge rate, $Q = \dfrac{10000}{T_m}$ (2)

Flow velocity, $V_f = \dfrac{Q}{\pi DB}$ (3)

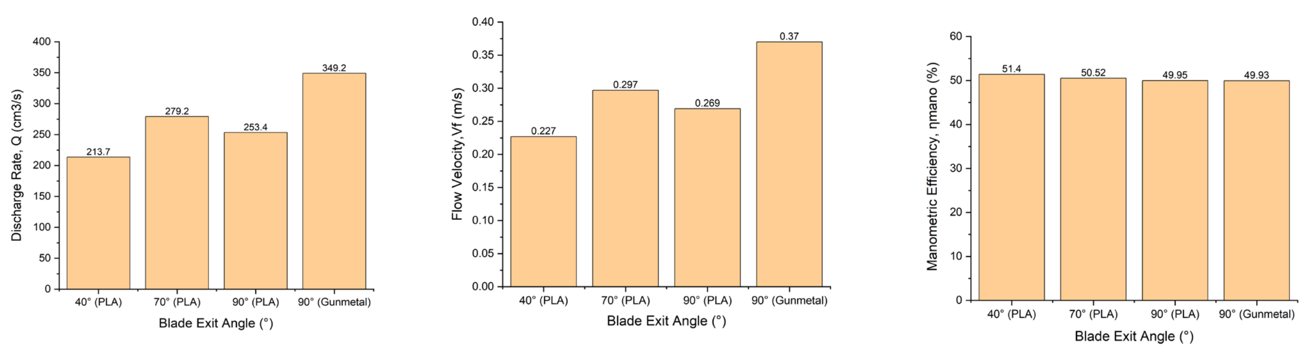
Manometric efficiency, $\eta_{mano} = \dfrac{u^2 - V_f^2 \operatorname{cosec}^2\phi}{2u\,(u - V_f \cot\phi)}$ (4)

Quantity of liquid discharged = 10 liter = 0.01 m^3 = 10,000 cm^3

Table 1. Flow Velocity, Discharge Rate and Manometric Efficiency for Various Impeller Blade Angles

Blade Exit Angle	Mean Time T_m (s)	Discharge Rate Q (cm^3/s)	Flow Velocity V_f (m/s)	Manometric Efficiency η_{mano}
90° (PLA)	39.467	253.4	0.269	49.95%
70° (PLA)	35.813	279.2	0.297	50.52%
40° (PLA)	46.790	213.7	0.227	51.40%
90° (Gunmetal)	28.643	349.2	0.370	49.93%

Table 1 shows the discharge rate, flow velocity and manometric efficiency for using 90º, 70º, 40º impellers respectively. To facilitate a more effective comparison, graphs have been constructed using the acquired values.



(a) (b) (c)

Figure 5. (a) Blade exit angle vs Discharge rate graph
(b) Blade exit angle vs Flow velocity graph
(c) Blade exit angle vs Manometric efficiency graph

Based on the calculations and graph presented above, it is evident that the gunmetal impeller with 90° blade angle had the highest discharge and flow rate among all the impellers. But the PLA impeller with the same 90° blade angle surpassed the gunmetal impeller in manometric efficiency by 0.02%. To figure out the underlying reasons, the authors delved deep into the internal factors influencing these parameters.For the 40° blade exit angle, water flowing through the vanes had to navigate a long, narrow channel to reach the periphery of the impeller. Additionally, the lower blade angle resulted in longer impeller blades, which caused the water to take more time to discharge compared to the other two impeller designs. Intriguingly, the 70° blade exit angle demonstrated better centrifugal action than the 90° blade exit angle, despite the slightly longer blades. In terms of efficiency, apart from the original gunmetal impeller, the 40° blade-exit angle impeller exhibited the highest efficiency, followed by the 70° and 90° blade exit angle impellers respectively. This aligns with the observed relationship between the blade-exit angle and the efficiency of centrifugal pumps; as the blade-exit angle decreases, efficiency tends to increase. As the fluid moves through the impeller, it gains kinetic energy, which is then directed toward the pump volute where this kinetic energy is converted into pressure energy. If, however, the impeller blade exit angle is excessively large, the fluid may not be properly directed toward the volute, leading to recirculation back toward the impeller inlet. This recirculation diminishes the net fluid flow through the pump, thereby reducing its efficiency.

Thus, a higher blade angle diminishes the efficiency of pumps. By lowering the impeller blade exit angle, fluid is directed more effectively toward the volute, resulting in less recirculation and enhanced pump efficiency. That being said, overly decreasing the blade exit angle can also negatively impact performance. The impeller with a 40° blade exit angle achieved approximately 0.88% greater efficiency than the 70° impeller and 1.45% more than the radial impeller.When it came to the 90° gunmetal impeller, it exhibited superior discharge and flow velocity compared to the 3D-printed impellers, achieving a discharge rate that was 95.8 cm^3/s higher than that of the 90° PLA impeller, with nearly similar efficiency levels between the two. The gunmetal impeller benefited from a better surface finish, resulting in significantly lower frictional losses compared to the 3D-printed designs. Centrifugal pumps typically utilize metallic impellers, which are more durable and possess better finishes than non-metallic 3D-printed impellers. The machining precision of traditional methods far exceeds that of 3D printing, which often produces impeller blades with rough surfaces, leading to higher frictional losses and lower discharge rates relative to their metallic counterparts.

5. Conclusion

The experimental study investigated how variations in the blade exit angle of an impeller affect the efficiency of a centrifugal pump. Impellers with different exit angles were fabricated, and their efficiencies were measured alongside the analysis of key parameters. The primary findings are as follows:

Among the three impellers tested, the one with the smallest blade exit angle achieved the highest efficiency at 51.40%, followed by 50.52% for the 70° impeller and 49.95% for the 90° impeller. This suggests that decreasing the blade exit angle enhances efficiency up to an optimal point for centrifugal pumps. The 70° impeller had the highest discharge rate at 279.2 cm^3/s, followed by the 90° and 40° impellers, which produced discharge rates of 253.4 cm^3/s and 213.7 cm^3/s, respectively. Therefore, the 40° impeller demonstrated the lowest discharge rate. The study also compared metallic and non-metallic impellers, concluding that while the metallic impeller exhibited superior discharge rate and flow velocity, its efficiency was only marginally better than that of a non-metallic impeller with a similar blade angle. While the 40° impeller delivered the highest efficiency for a half-horsepower centrifugal pump, its fabrication was more complex and costly, and it exhibited the lowest discharge rate. Conversely, the 70° impeller, although slightly less efficient, achieved the highest discharge rate, with a higher fabrication cost than the radial impeller. Considering all factors, the 70° blade exit angle impeller is the most suitable option for a ½ hp centrifugal pump, with efficiency comparable to that of the gunmetal impeller.

The results further suggest that while traditional gunmetal impellers still provide the highest efficiency and durability, impellers made from PLA using additive manufacturing are a more cost-effective solution for small production lines where similar efficiency is required, but high manometric head or extended longevity are not as critical. The experiment demonstrates that PLA impellers manufactured through additive processes offer efficiency on par with gunmetal impellers, with the added benefit of lower cost. Further research is recommended to address the challenge of lower head performance to improve the applicability of PLA impellers.

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