

Nazarbayev University
School of Engineering and Digital Sciences

EME 451 Capstone I

Performance Enhancement of a Centrifugal Pump by Impeller Retrofitting

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Abstract

Centrifugal pumps are widely used in different industries, therefore there are numerous researches studying the methods to enhance the performance of the pumps. This paper studies the effect of two design parameters of impeller, namely variable blade inlet angle and winglets, to the efficiency of the pump. Variable blade inlet angle might decrease the impact of the shock losses at off-design conditions, while adding the winglets could reduce the recirculation losses caused by the flow transferred from pressure side to suction side due to the pressure difference. CAD models for the base case and two proposed cases were designed for the future experiments. Preliminary experiment for the impeller with winglets has demonstrated the increase in efficiency. Lastly, by varying inlet angle and size of the winglets for two parameters, the optimized configuration would be determined experimentally.

1. Introduction

1.1. Centrifugal pump

As the world develops, humankind population expands, resources exhaust and overall energy consumption rises around the whole world, optimization and efficiency maximization of various equipment is necessary. Centrifugal pumps are a very common part of equipment in a large number of industries. Centrifugal pumps account for 75% of all the industrial pumps due to their simple design. Fifteen percent of World electricity is consumed by these pumps. Due to this fact many researchers globally have conducted experimental, theoretical and numerical studies to increase centrifugal pumps efficiency (Khoeini et al., 2018).

Despite numerous researches conducted on this topic, there are some problems unknown and unstudied. The most significant works are focused on geometry of pumps, especially impeller geometry, since it is the dynamic part of the pump, that converts rotational energy into kinetic and provides it to fluid. Changes in impeller geometry lead to change in velocity triangles of the fluid passing through it and may eventually lead to an increase in performance of the pump (Chehhat and Si-Ameur, 2015).

The main definition of the centrifugal pumps is “Centrifugal pumps are turbomachines used for transporting liquids by raising a specified volume flow to a specified pressure level” (Gulich, 2010).

Centrifugal pump provides pressure at the outlet by converting mechanical energy from the rotor, generally motor, to the fluid which enters the impeller, that is rotated by motor. Fluid is sucked by impeller center and enters through the inlet and is being thrown out radially along impeller blades, as shown on figure 1. Centrifugal force generated by rotation thus increases fluid velocity which in terms is converted to pressure at the outlet (Grundfos, 2015).

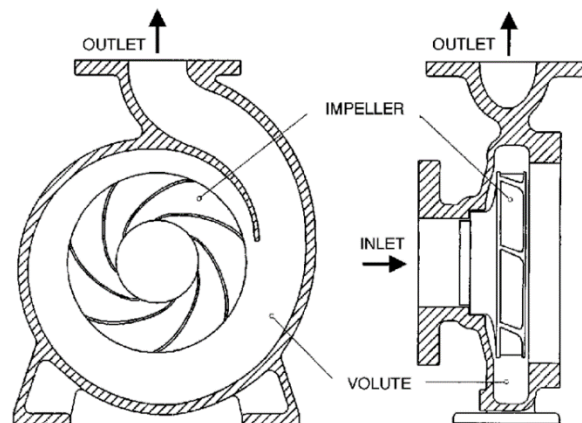


Figure 1. Centrifugal pump and its components.

Figure 2 shows parts of the impeller. The impeller is comprised of the hub, which is the bottom metal plate, the blades which are situated on the hub, and the front and rear shroud. Some cases omit front shroud, in this case the impeller is semi-open (Gulich, 2010). Blades have pressure

side that is located towards the motion and suction side on the opposite surface. Leading edge (LE) that is closer to the center of the impeller called impeller eye, and trailing edge (TE), which is situated on the far edge of the blade.

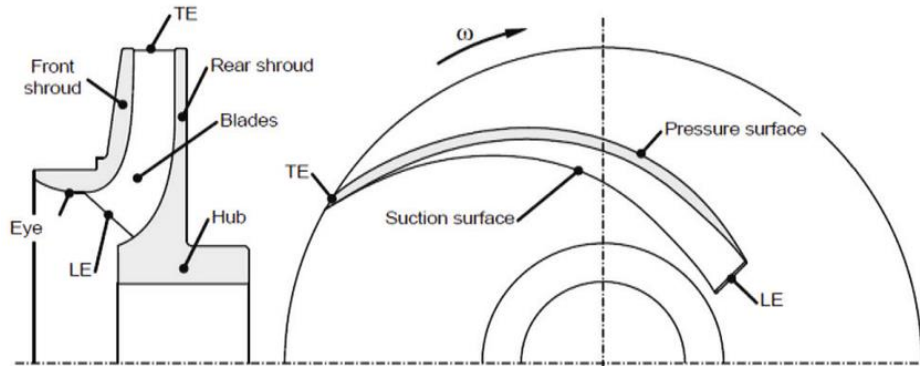


Figure 2. Impeller components.

1.2. Pump losses

In figure 3 Euler head represents the ideal case, while the pump curve demonstrates the actual performance, affected by losses. Generally, pump losses consist of mechanical and hydraulic losses. Mechanical losses occur due to the friction between pump components such as shaft, bearings, gears and so on. Hydraulic losses, as illustrated in figure 3, consist of recirculation losses, leakage, flow friction and incidence losses. Friction loss occurs between the flow and impeller surfaces such as hub and blades, and pump casing (Grundfos, 2015). Recirculation losses happen at the flows lower than design flow. They are caused by pressure difference between impeller tip and eye, which induces small amount of flow to recirculate (IIT Kanpur, 2009). Another type of losses is mixing losses. At the areas of cross-section expansion and contraction the flow separation forms which affects to the consistency of the flow. Additionally, some liquid leaks from small gaps between fixed and rotating parts of the pump. Incidence losses are formed due to the misalignment of flow angle and blade angle. Difference in angles causes some part of the flow to recirculate, and consequently decelerate the flow in channels (Grundfos, 2015).

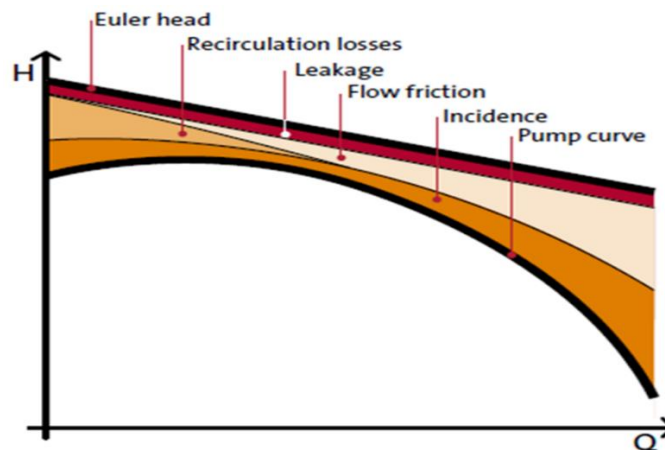


Figure 3. Hydraulic losses of centrifugal pumps.

2. Literature review

2.1. Variable blade inlet angle

Main design parameters for an impeller blades are the angles between tangents of impeller radius and tangents of blade inlet and outlet curvatures, namely β_1 and β_2 angles respectively (IIT Kanpur, 2009). These angles are defined by performance characteristics needed to be obtained from a centrifugal pump, such as head and flow rate output at best possible efficiency (Nelik, 1999). Figure 4 shows theory for impeller design. From this figure it can be seen that the angle made by the blade at inlet, with the tangent to the inlet radius is β_1 .

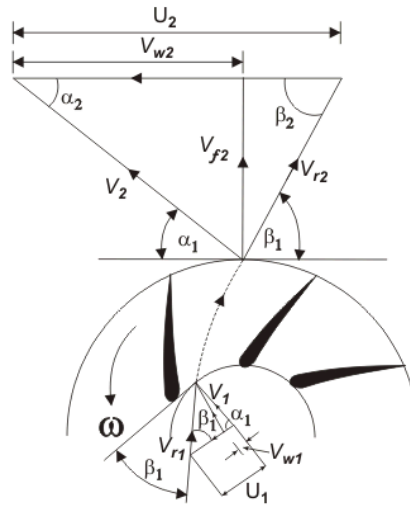


Figure 4. Centrifugal pump impeller velocity triangle.

This angle corresponds to the velocity of incoming fluid stream and is designed to suit certain predetermined flow at Best Efficiency Point (BEP) (IIT Kanpur, 2009). However often pumps operate at off-design conditions, due to differentiating flow, minding the safety factor during acquisition of the pump etc. (Karassik & McGuire, 1998). Consequently, due to off-design operation BEP designed β_1 angle is no longer relevant and introduction of shock losses happens (IIT Kanpur, 2009).

According to IIT Kanpur (2009) academic courses on centrifugal pumps - incidence losses, shown previously in figure 3, are comprised of both shock losses and impeller entry loss due to a change in the direction of fluid flow from axial to radial direction in the vaneless space before entering the impeller blades. During the off-design conditions, the direction of relative velocity of fluid at inlet does not match with the inlet blade angle and therefore fluid cannot enter the blade passage smoothly by gliding along the blade surface. The loss in energy that takes place because of this is known as shock loss.

Shock losses is shown independently in figure 5, where it can be seen that deviation from BEP leads to introduction of shock losses.

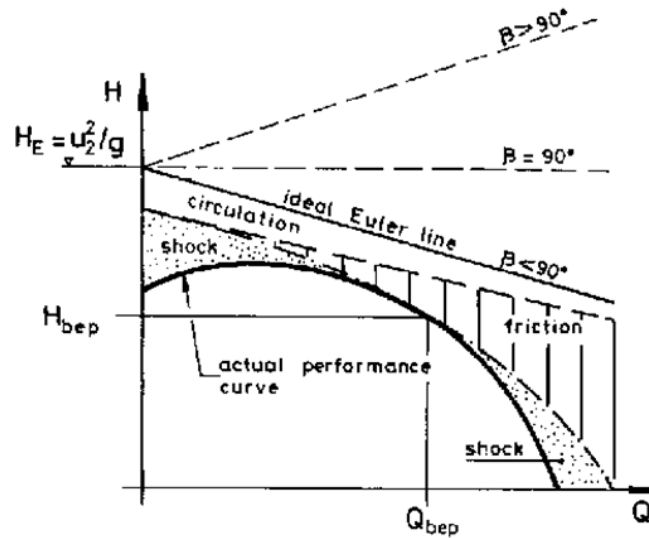


Figure 5. Shock losses on a centrifugal pump performance curve.

To reduce shock losses during off-design centrifugal pump operation - impeller design with variable blade inlet angle (β_1) will be introduced. Introduction of inclination in the blade's leading edge will provide range of β_1 angles per single blade, which will reduce pump's shock losses by providing suitable blade inlet angle for different flow configurations.

Previous studies on the effect of different β_1 angles on the performance of the pump include study conducted by Sanda and Daniela (2012). In this study centrifugal pump impeller blades were given range of inlet and outlet blade angles and a various number of blades were numerically tested in Ansys. As a conclusion the most efficient design have provided efficiency increment in 1-2%.

Another work conducted by Chen et al. (2017) investigates the effect of addition "twisted vice blades" to an existing impeller design. The study aims to parametrize the newly acquired blade, and design parameters that undergo parametrization are blade wrap angle and inlet and outlet blade angles. Three of each inlet and outlet angles are calculated, however numerical values for them are not presented. These angles are given as a parameter to the twisted vice blades additions. As a conclusion, the authors state the increase of efficiency of the modified blades compared to a traditional impeller design.

As it can be seen, the provided studies are not very similar to this one, but they are the closest to what is being researched in this capstone project.

2.2. Winglets

Winglet is a device that reduces the drag by weakening the effect of tip vortices which occur due to the pressure difference at the trailing edge of the blades. Tip vortices negatively affect to performance by increasing the drag and fatigue loads, and inducing vibrations (Lain et al., 2018). Therefore, winglets nowadays are commonly applied in most of the commercial airplanes. (Zhang et al., 2019). Moreover, there are numerous studies about the effect of winglets on various turbomachinery. According to numerical analysis of Elfarra et al. (2013), horizontal axis wind turbine (HAWT) rotor blades with optimized winglets has increase in power of about 9%. Another computational study conducted by Lain et al. (2018) for cross-flow vertical axis water turbine demonstrated that blades with optimized winglets potentially has up to 20% improvement in power

coefficient. Regarding vertical axis wind turbine (VAWT), blades with winglets has improvement in efficiency for about 6% (Zhang et al., 2019).

The phenomenon similar to creation of tip vortices at the trailing edge of the blade also occurs in centrifugal pumps. Gerlach (2018) states that centrifugal pump with semi-open impeller form a flow from the pressure side of the blade to the suction side, which occurs due to the pressure difference between the blade sides. According to the experimental study for the impeller with curved blades of vortex pump, impeller with winglets had efficiency increase for approximately 6 percent (Gerlach, 2018). Moreover, additional tests were conducted to the impeller with straight blades, from which it might be concluded that the most optimal winglet oriented in suction side, and has a length of 1/4 of channel's area covered. The operating principle of a vortex pump is similar to the working principle of a centrifugal pump (Gerlach, 2018), therefore it might be assumed that adding winglets to the impeller blades of centrifugal pumps will possibly prevent most of the fluid flowing from pressure side to suction side and thus maintain more uniform flow by reducing the circulation occurring in the channels.

3. Methodology

Since the Project is experimentally validated, the following methodology for hypotheses testing is proposed:

1. Design and manufacture basic 7-bladed impeller;
2. Design and manufacture 7-bladed impellers with various blade leading edge inclinations and with various winglet length;
3. Test both models at different speeds of motor and flow rates on the Armfield FM50 Centrifugal pump facility;
4. Create matrix of the parameters;
5. Compare results to the benchmark at every design parameter.

The methodology contains design and manufacturing (1,2), experimental (3) and analytical (4,5) parts. Work package of the Capstone I imply completion of the design and manufacturing part, therefore experimental and analytical parts will be performed during Capstone II course. According to official guidelines on laboratory testing facility - experiments are performed at 3 stages of rotational speed 900, 1200 and 1500 rpm and with flow rate incremental steps of 0.1 L/s. Therefore, matrix of parameters will consist of design parameters (range of blade inlet angles / size of the winglet), efficiency, head and flow rate. The most important parameter is an efficiency, which will be examined during result comparison, however other parameters need to at least maintain values of the base case for the design to be comparative at all.

4. Laboratory experiments

4.1. Experimental facility

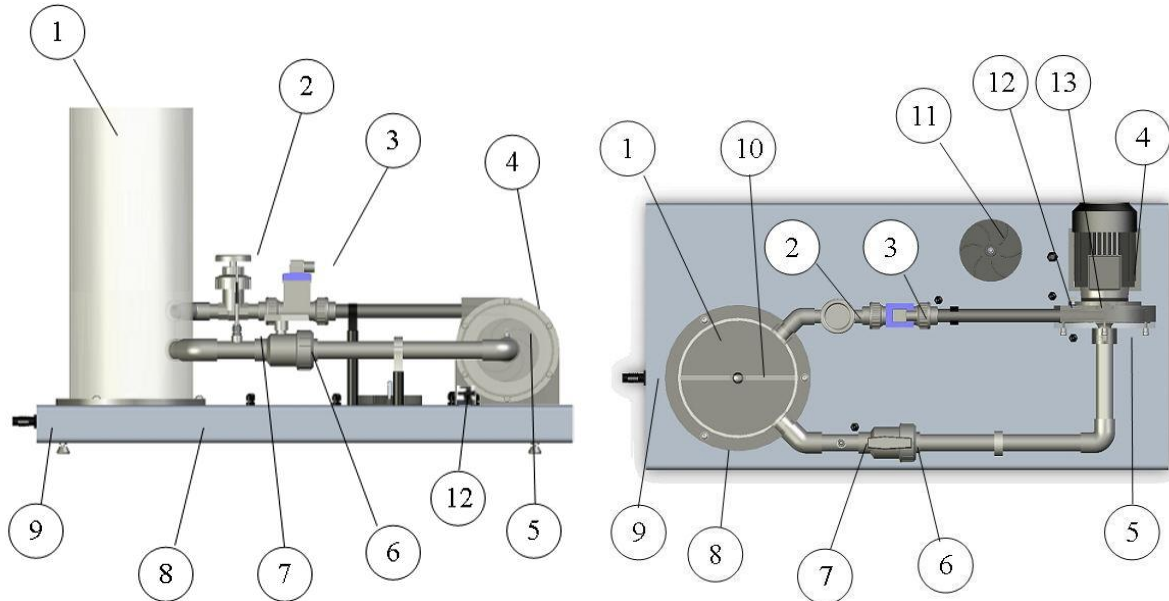


Figure 6. Experimental facility FM50 Centrifugal pump and its components.

Table 1. Components of Armfield FM50 Centrifugal pump.

N	Component	N	Component
1	Reservoir	8	Baseplate
2	Outlet valve	9	Drain valve 1
3	Flow sensor	10	Drain
4	Pump	11	Storage position
5	Pressure sensor at inlet	12	Drain valve 2
6	Inlet valve	13	Pressure sensor at outlet
7	Temperature sensor		

Experiments with different impellers were conducted with application of FM50 Centrifugal pump. The reservoir illustrated in figure 6 stores the water for the experiment. Inlet valve controls the water supply to the pump, and outlet valve controls the flow rate. There are sensors measuring temperature, pressure and flow rate. Drain valves are used to extract water from the system. Pump is a motor driven, which speed is regulated by using the software. The cover plate of the pump might be removed to replace the impeller (Armfield, 2011).

4.2. CAD modeling and prototyping

4.2.1. 7-bladed impeller (base case)

For the base case the impeller of the FM50 Centrifugal pump was recreated, dimensions are presented in table 2.

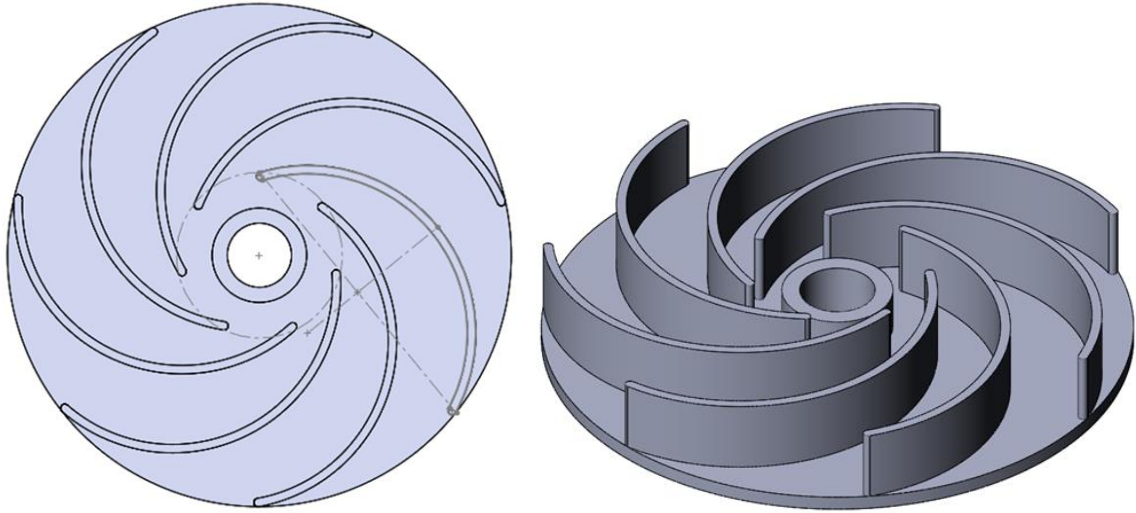


Figure 7. Base case impeller with 7 blades top view (left) and isometric view (right).

Table 2. Dimensions of the impeller.

Name	Dimension [mm]
Impeller outer diameter	120
Inlet outer diameter	22.5
Inlet inner diameter	15
Blade chord length	70.31
Blade thickness	2
Distance between chord and outer wall of blade	25.47
Hub height	3
Blade height	16

4.2.2. Variable blade inlet angle

The aim is to create an impeller with the range of Blade Inlet Angles (β_1 angles) per blade, compared to constant β_1 angle per blades in the base case impeller. To do so inclination of the blade leading edge was introduced. Compared to the base case impeller, with vertical blades, leading edge of the Variable Blade Inlet Angle impeller is inclined by 25 degrees from vertical state. Inclination was performed along the radius of curvature of the blade. This can be seen on figure 8. Leading edge is now at 65-degree angle to the hub, compared to 90 degrees for the base case impeller, however trailing edge has remained vertical to the hub. This means that inclination gradually decreases from leading to trailing edge from 25 to 0 degrees respectively. It can be observed from figure 8 that total vertical height of the blade has remained unchanged - 16mm, which means that the total area of the blade has increased by 5.17%. This will introduce additional friction to the hydraulic losses; however it is expected that total increase in performance will be positive.

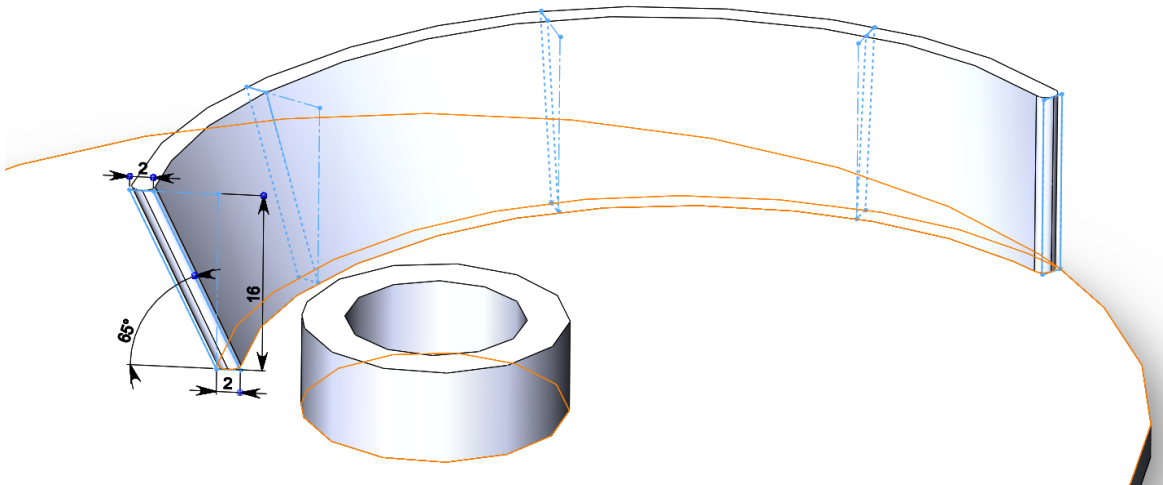


Figure 8. CAD Model of the blade with 25-degree leading edge inclination.

The inclination of the leading edge is introduced to obtain the range of β_1 angles in one blade. By introducing 25° inclination - 8.26° β_1 angle for the top plane has been obtained, compared to 16.7° β_1 angle of the basic impeller, which was preserved at the bottom plane, right and left on the figure 9 respectively. Since β_1 angle is the angle between tangents of the hub and a blade, and considering tangents is at constant 90° angle to the radii, on figure 9 β_1 angle is measured between radii of the hub and the blade. Finally, basic impeller with blade inlet angle $\beta_1 = 16.7^\circ$ has transformed to an impeller with blade inlet angles varying from 8.26° to 16.7°.

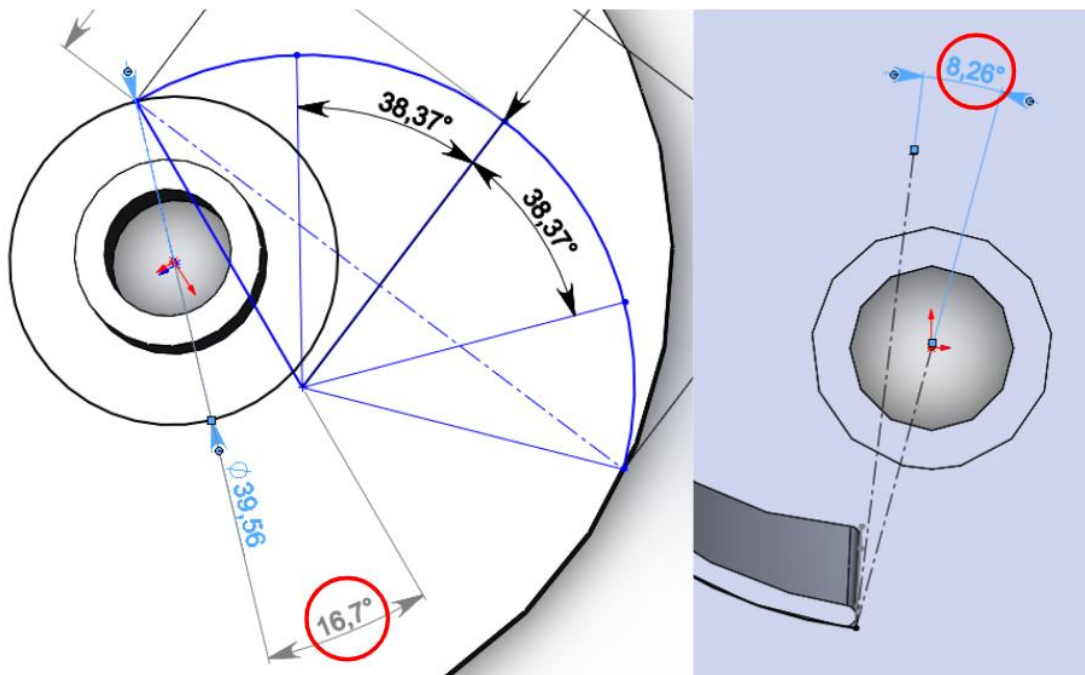


Figure 9. Range of Blade Inlet Angles β_1 obtained by leading edge inclination of 25°. Bottom plane (left), top plane (right).

Final CAD model of the Variable Blade Inlet Angle Impeller with 7 blades is presented on the figure 10, and the 3D printed prototype based on this CAD model is shown on figure 11. The material for the prototype printing was chosen to be Polylactic Acid (PLA) due to its strength characteristics needed to withstand laboratory tests. Infill (percentage of inner space filling by material) was set to 90% to obtain rigid inner structure, and nozzle was set to 0.8 mm (the largest available printing nozzle, provides minimum time of printing) since there are no details smaller than this size present.



Figure 10. CAD models of 7-bladed impeller with Variable Blade Inlet Angle, top view (left) and isometric view (right).



Figure 11. 3D printed prototype of the Variable Blade Inlet Angle Impellers, top view (left) and isometric view (right).

4.2.3. Winglets

To design the winglet, first, the sketches of two adjacent blade curves were drawn. Three points located at the leading edge, middle of the curve, and the trailing edge were connected with the corresponding points of the second blade curve, as illustrated in figure 12. For the first prototype, the 1/4 of the length of connecting lines were selected. Thickness of the winglet is 2 mm, because 1 mm thick winglets were fragile, and they were damaged in the process of removing support structures, which were necessary for proper printing.

Moreover, the base case 7-bladed impeller has 15 mm height as the impeller with the winglets, because with 16 mm height friction between the winglets and volute case of the pump significantly affect to the performance of the impeller.

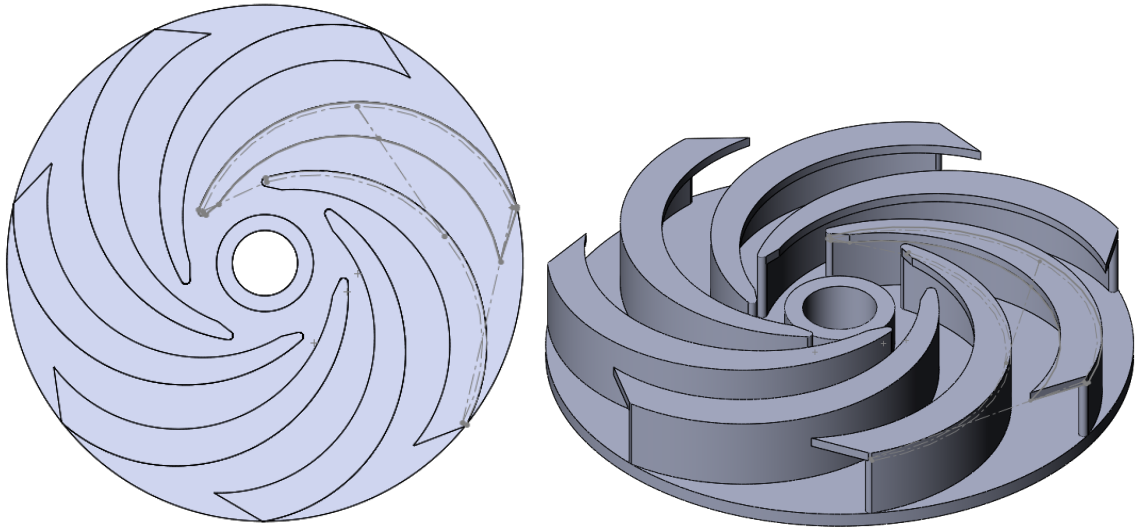


Figure 12. CAD modeling of 7-bladed impeller with winglets, top view (left) and isometric view (right).



Figure 13. 3D printed model of impeller with winglets.

4.3. Preliminary experiment for impeller with winglets

In order to assess the hypothesis, the preliminary experiment for the impeller with winglets was conducted. The speed of the motor was set to 1200 rpm. Measurements were taken three times for all possible flow rate range with increment of 0.1 l/s. Figures 14-15 and table 3 represent the average value of 3 experiments for each flow rate. According to the obtained results, it might be concluded that impeller with winglets has approximately the same total head, but it has higher efficiency for about 5%, which might cause less power consumption.

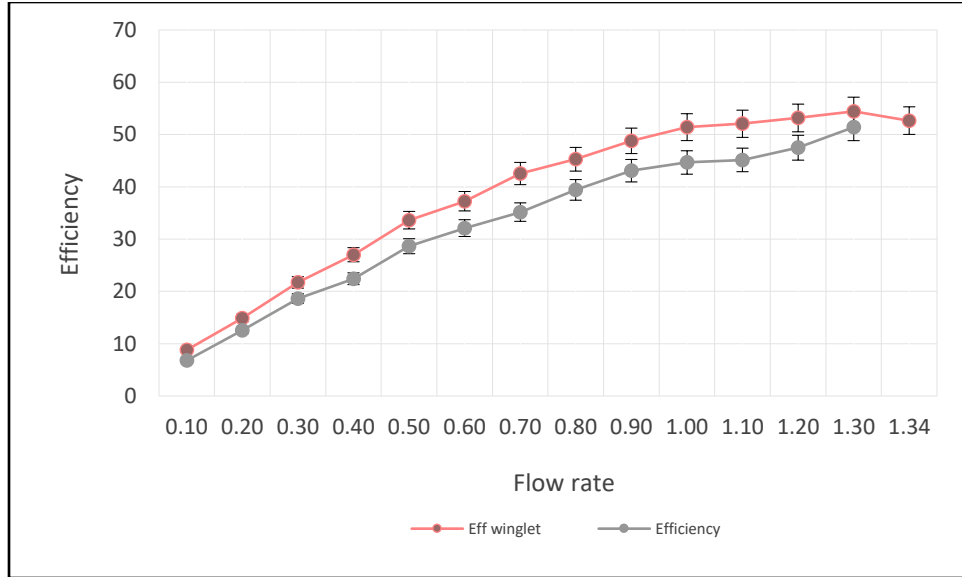


Figure 14. Pump efficiency for 7-bladed impeller (base case) and 7-bladed impeller with winglets.

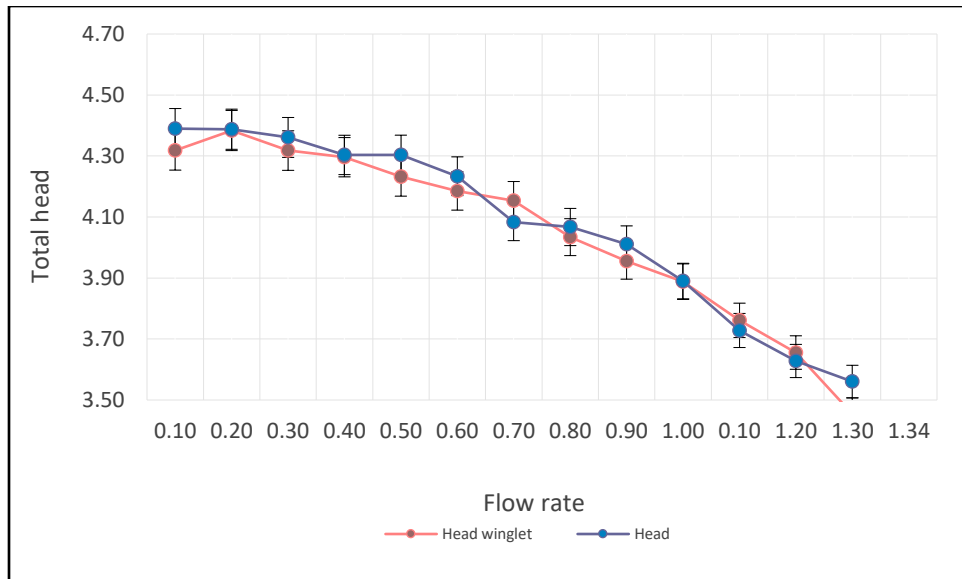


Figure 15. Total head of pump with 7-bladed impeller (base case) and 7-bladed impeller with winglets.

Table 3. Total head and efficiency of the pump with 7-bladed impeller (base case) and 7-bladed impeller with winglets.

Flow rate [l/s]	Total head (base case) [m]	Total head (winglet) [m]	Efficiency (base case) [%]	Efficiency (winglet) [%]
0.10	4.39	4.32	6.80	8.80
0.20	4.39	4.38	12.58	14.91
0.30	4.36	4.32	18.63	21.73

0.40	4.30	4.30	22.42	27.02
0.50	4.30	4.23	28.64	33.62
0.60	4.23	4.19	32.11	37.25
0.70	4.08	4.15	35.17	42.55
0.80	4.07	4.03	39.42	45.28
0.90	4.01	3.96	43.09	48.80
1.00	3.89	3.89	44.66	51.42
0.10	3.73	3.76	45.15	52.07
1.20	3.63	3.66	47.49	53.17
1.30	3.56	3.45	51.40	54.44
1.34		3.38		52.67

5. Conclusion

Centrifugal pumps have significant impact on multiple industries and on the world's energy consumption, therefore increase in their efficiency is a significant objective. Hydraulic losses in centrifugal pumps are the most impactful, containing multiple sources of losses inside. Centrifugal pump impeller design retrofitting may lead to increase of pump overall efficiency and therefore become economic and environmentally feasible solution. Two design parameters that can potentially increase centrifugal pump efficiency were presented in this report. First, variable blade inlet angle that is aimed to reduce shock losses during off-design operation and, secondly, winglets to prevent flow recirculation from the pressure side to the suction of the blade and therefore reduce recirculation losses. Theoretical hypothesis was presented and supported by theory and literature review and will in future be experimentally validated by methodology, described in this report. Parametrized computer aided design models were presented and thoroughly described. Manufacturing of the first prototypes have been completed and preliminary results of the experiment have shown increase in pump efficiency without drop in Head - flow rate performance. Experiments of prototypes with different parameters will be performed in future and presented in Capstone II report with the comparison of the parameters using filled up matrix of parameters.

6. References

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7. Appendix

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