System-Based Optimization of Pumping Capacity of Centrifugal Pumps

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Abstract

In this study, the impeller is optimized in order to make advances in the performance of a centrifugal water pump. A centrifugal pump design incorporates many limitations that affect pump performance. By modifying the parameters within an acceptable range, it improves pump performance and results in saving of costs and energy for companies. The design parameters from vane plane improvement are chosen for the impeller plan, and the influence of the plan parameters on the pump's performance is analyzed using computational fluid dynamics to optimize the impeller. The findings shows that suction diameter, impeller diameter and discharge diameter have a significant impact on the performance of a centrifugal pump.

Keywords
Centrifugal pump, Design, Pump proficiency, CFD, Impeller.

1. Introduction
Pumps are widely used in industry to supply cooling and oil organizations, to transfer fluids for planning, and to offer intentional control in weight-driven systems pumping (Hydraulic Institute and Europump, Matlakala et al., 2019a). In reality, most collecting plants, trade buildings, and regions rely on pumping systems for routine operation. Pumps address about 27 percent of the control used by cutting-edge systems in the amassing region (Matlakala et al., 2019b). Pumps are mostly used in warming, ventilation, and cooling (discuss conditioning) systems in the trade region to allow water to warm trade. Pumps are used in municipalities for water and wastewater movement and treatment, as well as for arrival leaks (Matlakala et al., 2019b). Pumps differ in size from parts of a drive to a couple of thousand quality because they fulfill such specific needs (Berkeley, 2014).

The weight of putting up the pumping system is included in the difficulties of assessing the pumps to suit the pumping system; therefore, it influences the foundation, support, and errands of the outer pumps and pumping systems (Berkeley, 2014, Matlakala and Kallon, 2019a). Unique pumps are made up of two major components: an impeller (rotor) that rotates at the speed of the motor and provides spiral forces to the creation fluid and a diffuser (stator), which is the fixed section that regulates the flow to the discharge. The impeller of a transmitting pump coordinates the presentation of the pump and choose the pumping restrain of the unique pump (Matlakala and Kallon, 2019b). A centrifugal pump is the most popular type of pump used in mechanical areas such as water, sewage, and water medical plants, as well as the industrial business. Due to industry demands, optimization utilizing mechanical ideas has recently been investigated in order to produce more effective pumps with greater heads (Hydraulic Institute and Europump). A centrifugal pump is the most common type of liquid apparatus, converting apparatus energy into liquid weight and dynamic vitality via impellers. The impeller, among all pump components, has the greatest impact on pump performance and is the most important component of the pump since liquid flow within the pump creates vitality via it (Matlakala et al., 2019a). As a result, an accurate investigation is required to optimize elements that impact the pump's performance (Matlakala and Kallon, 2019b; Matlakala, et al., 2020). Figure 1 depicts the diffusive pump's design, which has four major components: impeller, discharge, suction, and volute channel.

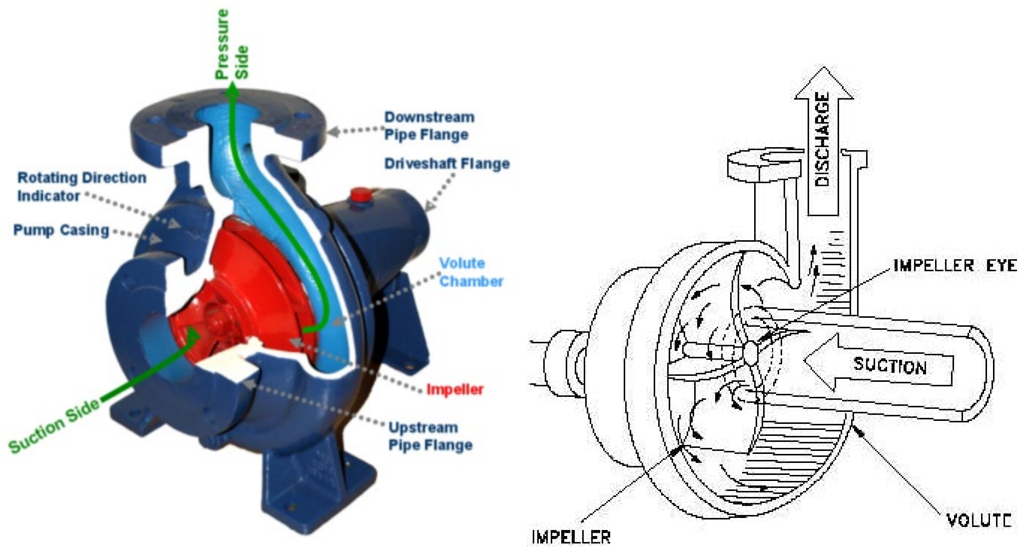

Figure 1. Centrifugal pump (Hydraulic Institute and Europump).

The design of the impeller distance across has a significant influence on pump productivity; the modern pump may be described by properly modifying the impeller. The pumping capacity is the maximum flow rate via a pump at full capacity. Pumping capacity is necessary inside the handling of pumping water and other liquids to accurately measure pumping framework, determine contact head loss, create a framework bend, and pick a pump and engine to achieve the pumping capacity (Berkeley, 2014; Matlakala, et al., 2020). The head or weight head that the pump may generate is determined on the speed and width of the impeller (Berkeley, 2014).

2. Experimental Work

The framework examination of the centrifugal pump is done through the building plan where the determination of the centrifugal pump is given based on the pumping framework. The taken a toll investigation is additionally taken into thought to examinations the chance and practicality if the centrifugal pump is not re-established to its unique effectiveness (Berkeley, 2014; Matlakala and Kallon, 2019a).

2.1. Pumping System Design

To meet the prerequisite of the pumping framework, the overall dynamic head (ODH) is utilized (Matlakala and Kallon, 2019b; Matlakala, et al., 2020). The Whole Energetic Head (WEH) is the combined add up to head of the components, pipe contact misfortunes (Hf), static head (Hs), and speed head (Hv). The whole of these three components of the total head is as shown in equation 1:

$$\text{Total Head} = H_s + H_f + H_v \quad (1)$$

The pumping framework was planned based on framework determination and presumptions that the stream rate shifts from 0.1 to 0.4 m^3/s. The calculations are carried out at 0.1 m^3/s and the same method is utilized to calculate the pumping framework to the stream rate of 0.4 m^3/s. The ultimate comes about are abridged in Table 1. The fabric of the pipe is Commercial Steel pipe; subsequently, pipe unpleasantness is, ε = 0.045mm as shown in Table 1 (Matlakala and Kallon, 2019b; Bachus and Custodio, 2003).

Table 1. Absolute roughness of steel pipe material

Pipe Material	Absolute Roughness, ε	
	Feet	Microns
Drawn brass or copper	0.00 0005	1.5
Commercial steel	0.000150	45
Wrought iron	0.000150	45
Asphalted cast iron	0.000400	120
Galvanized iron	0.000500	150
Cast Iron	0.000850	260
Wood stave	0.0006 - 0.003	200 – 900

The parameters were utilized to calculate the pumping framework are as take after:

Pipe Diameter, D = 0.25 m; Length of the pipe of the system = 50; The static head (Hs) = 30m

The pumping system was calculated using the equations 2 to 8:

$$H_f = \frac{f\,L\,v^2}{2gD} \tag{2}$$

$$\text{Area of the Pipe} = \frac{\pi D^2}{4} \tag{3}$$

$$\text{Velocity} = \frac{\text{Flow Rate}}{\text{Area}} \tag{4}$$

$$\text{Reynold's Number} = \frac{\text{Velocity} \times \text{Diameter}}{\text{Kinematic Viscosity of Water}} \tag{5}$$

Friction factor:

$$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{R_e^{0.9}}\right)\right]^2} \tag{6}$$

$$H_v = \frac{v^2}{2g} \tag{7}$$

$$W = \rho Q g H \tag{8}$$

The computations of the full head were carried out at diverse stream rate shifting from + m^3/s to 0.2 m^3/s with the pipe distance across of 0.25 m and length of 50 m. The ultimate comes about are outlined in Table 2. It is shown that the increment within the stream rate increments the full head of the pumping system.

Table 2. Pumping system 1 calculations results of system with a pipe diameter of 0.25 m and length of 50 m.

Flow m^3/s	Dia. m	Length m	Area m^2	Velocity m/s	Reynold Number	Friction Factor	Head m
0.2	0.25	50	0.05	4.0	561798	0,006133	54.482
0.175	0.25	50	0.05	3.5	491573	0,006034	48.745
0.15	0.25	50	0.05	3.0	421348	0,005923	43.773
0.125	0.25	50	0.05	2.5	351124	0,005795	39.566
0.1	0.25	50	0.05	2.0	280899	0,005644	36.123

0.075	0.25	50	0.05	1.5	210674	0,005458	33.445
0.05	0.25	50	0.05	1.0	140449	0,005211	31.532
0.025	0.25	50	0.05	0.5	702247	0,004826	30.384

The same method was taken after to calculate the pumping framework 2 at 0.30 distance across of the pipe and length of 50m. The comes about for pumping framework 1 and framework 2 were plotted on the same chart in Figure 2 to demonstrate how the framework bend will alter if expanding the pipe breadth from 0.025 to 0.30 m. Figure 2 appears that the pumping capacity can be accomplished by altering the breadth of the pumping framework at a steady length of the framework. Expanding the distance across of the pipe in a pumping framework the head is diminished and increments the stream rate, see Figure 2.

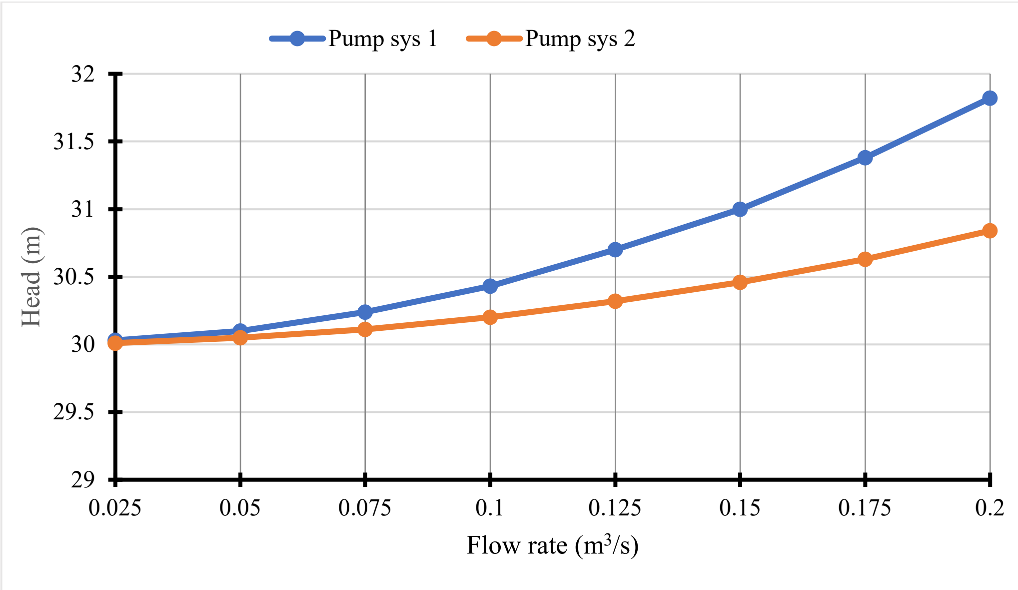

Figure 2. Pump system curve 1 and 2.

2.2. Centrifugal pump design varying the impeller diameter

The optimization of the pumping capacity of the centrifugal pump is done by trimming the impeller to adjust the head (m) and flow rate (m^3/s) (Matlakala and Kallon, 2019b). The assumptions were made to determine the effect which the impeller diameter has on the pumping capacity of the centrifugal pump. The impeller diameters of 223 mm, 217 mm and 211 mm were used to do the calculations. The pump specification to suit the existing pumping system design with the impeller diameter of 223 mm at the flow rate varying 0.025 m^3/s to 0.2 m^3/s are shown in Table 3:

Table 3. Pump specifications

Flow rate (m^3/s)	Total head (m)	Waterpower (KW)
0.2	33,05	64.844
0.175	32,31	55.468
0.15	31,68	46.617
0.125	31,15	38.198
0.1	30,73	30.146
0.075	30,4	22.367
0.05	30,17	14.798
0.025	30,04	7.367

Affinity Laws for centrifugal pumps:

The formulas applied below are for affinity laws in constant impeller diameter and constant rotational speed are as follow:

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \qquad \frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \qquad \frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^3 \tag{9}$$

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \qquad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \qquad \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \tag{10}$$

The impeller diameters are varied from D_0 as the original and two other values D_1 and D_2 to be the different from D_0. Pump specification in Table 3, is at the original impeller diameter of 350 mm. The centrifugal pump head and flow rate was calculated varying the discharge flow rate, see the calculation summary of the result in Table 4.

D_1 = 217 mm
D_2 = 211 mm

Table 4. Affinity law calculation results

Total Pump Head (m)			Flow (Ml/d)		
223 mm	217 mm	211 mm	223 mm	217 mm	211 mm
35,71	33,09	33.05	0.2	0.195	0.190
34,32	32,35	32.31	0.175	0.170	0.165
33,14	31,71	31.68	0.15	0.146	0.142
32,15	31,46	31.15	0.125	0.122	0.118
31,35	30,76	30.73	0.1	0.097	0.095
30,74	30,42	30.4	0.075	0.073	0.071

The affinity law was applied to determine the pumping capacity of the centrifugal pump performance. The results were summarised in a table format in Table 4. The head and flow rate were compared at the variation of the impeller diameters of 223 mm, 217 mm, and 211 mm. The results obtained from the calculations in Table 4 and Figure 3 show that the trimming of the impeller increases the flow rate and the head of the pump.

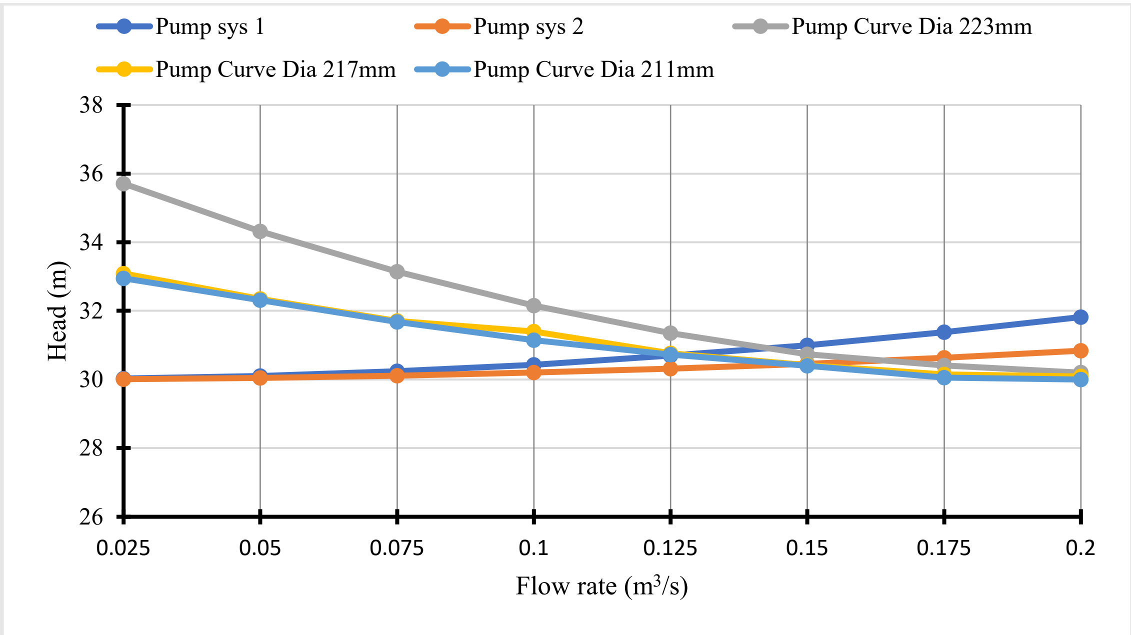

Figure 3. Head vs flow rate and Pumping system curve.

3. Design of 3D model

A centrifugal pump was design for the simulation. The material used for the pump was chosen to be steel as it is cheap and ensures a long pump life. Open impellers were chosen based on being lighter in weight. Open impellers normally operate in higher efficiency. The major criteria of for the selection of materials of a pump was mainly based on the lightness in weight and weather and long service life. The pump must be able to deliver 10 m^3/s of water and a head of 10 m at a low temperature of 25°C. Two models were developed for this model; one was the original centrifugal pump (with complex geometries), and the other was a solid model that contains a flow region and a volume for the rotating zone of the impeller to be simulated and analysed. The model was created using Autodesk inventor, the fluid volume was split into a fixed wall, rotating fluid volume, inlet(suction) and outlet (discharge) ducts. The description of the pump was studied before the impeller was designed as a radial flow pump is hugely affected by the impeller. Table 5 shows the specifications of the pump while Figures 4 and 5 shows different view of the models of the pump.

Table 5. Specification of a pump

Parameters	Dimension
Pump Head	10 m
Flow rate	1-3 m^3/s
Number of blades	6
Inlet diameter	90-130 mm
Outlet diameter	75-100 mm

Impeller specification

Outer diameter (d) = (200-400) mm
Number of vanes (z) = 6
Inlet blade angle (β_1) = 20 degrees
Exit blade angle (β_2) = 24 degrees

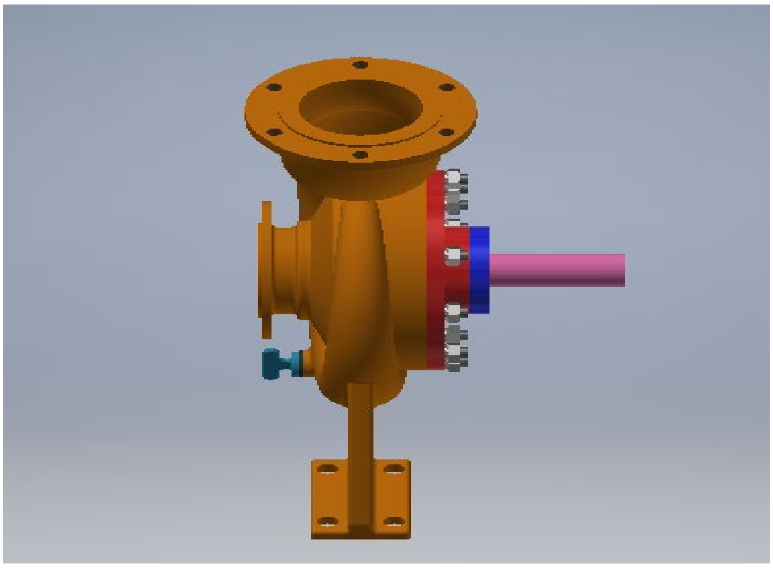

Figure 4. Centrifugal pump 3D model

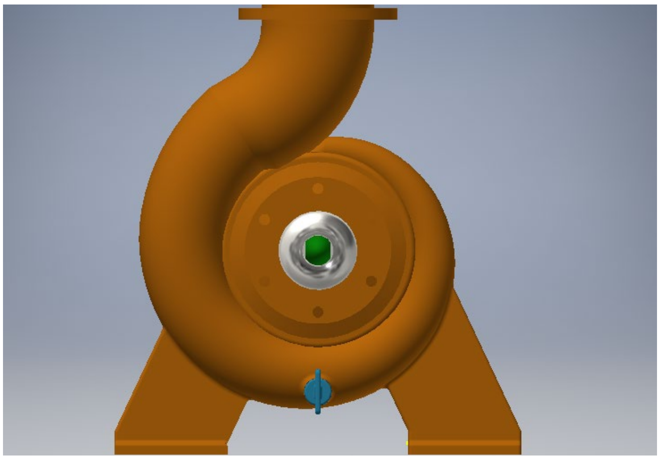

Figure 5. Centrifugal 3D model left view.

4. Simulations

4.1. Simulation of the impeller diameter

The impeller diameter plays a critical role in the performance of your pump. The head and flow rate of this centrifugal pump can be adjusted by trimming of the impeller diameter to suit their actual needs. The trimming of the impeller diameter must not exceed 75% of the pump original impeller diameter. The fluid flow (CFX) simulation was performed on the impeller diameter of 223 mm, 217 mm, and 211 mm. The main parameters used in the simulation were assumed to be:

Velocity = 0.8 m/s
Pressure = 18 000 Pa
Rotational speed = 1600 rpm

The results were obtained after the CFX simulation analysis are shown in Figures 6 – 8. The forward flow was taken. Pressure and velocity were taken into consideration from the results of simulation. The orange colour in Figures 6 – 8 represent higher pressure and velocity while the blue colour represents low pressure and velocity. It can be observed with increase of diameter, the pressure within the casing of the pump increases which will result with increase of efficiency of the pump, see Table 6.

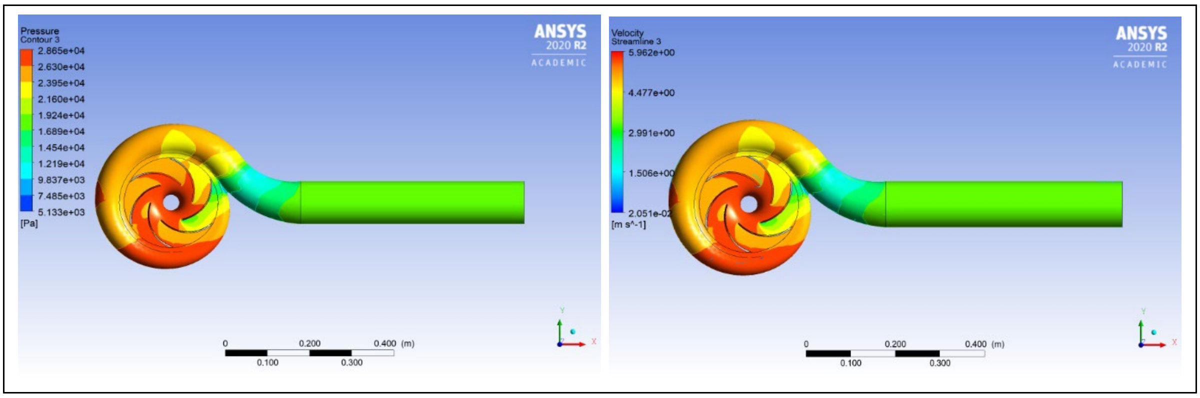

Figure 6. Pressure and velocity contour flow through a pump for 223 mm impeller diameter

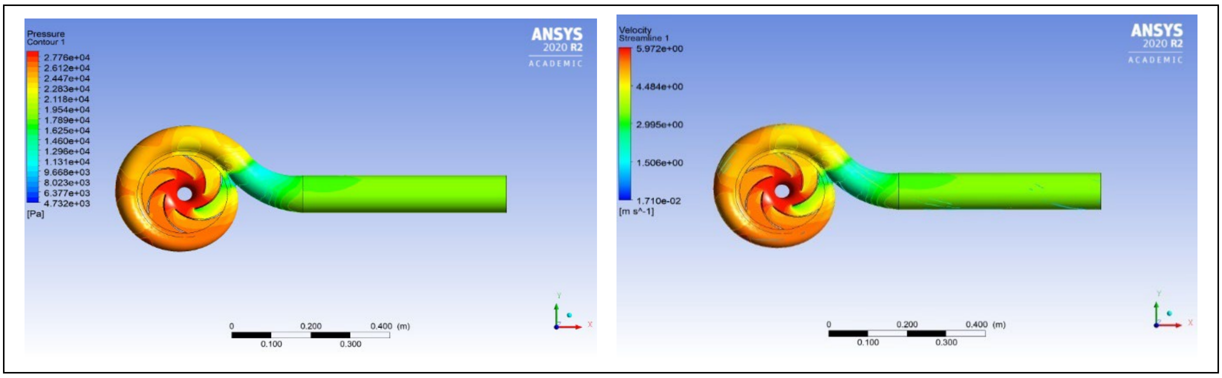

Figure 7. Pressure and velocity contours flow through the pump for 217 mm impeller diameter

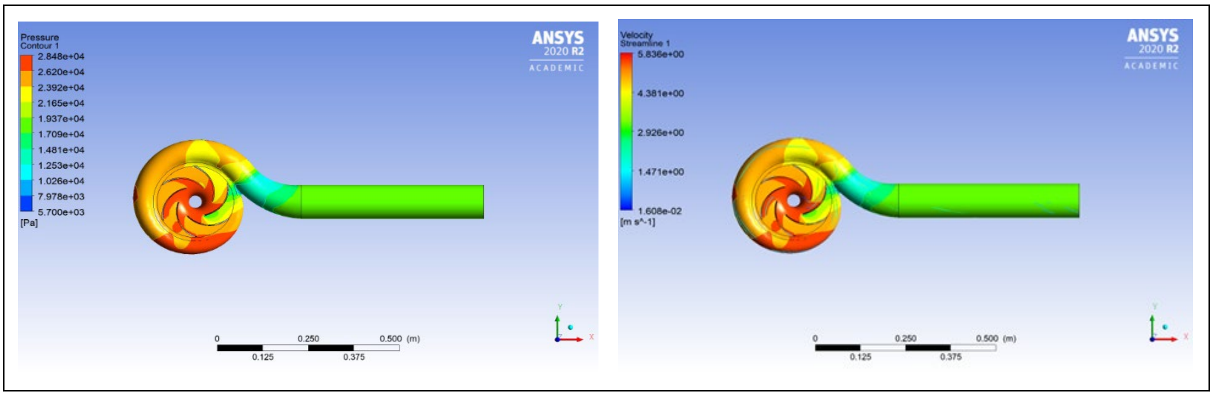

Figure 8. Pressure and velocity contours forward flow through the pump for 211 mm impeller diameter.

Table 6. CFD results of variation of impeller diameter.

Impeller Diameter (mm)	Maximum Pressure (kPa)	Maximum Velocity (m/s)	Flow Rate (m^3/s)	Head (m)	Waterpower (W)	Efficiency (%)
223	28.651	5.962	0.3	3.23	4265.9	91.59
217	20.587	4.654	0.22	2.12	2389.6	52.66
211	19.479	4. 123	0.11	2.01	1777.3	39.17

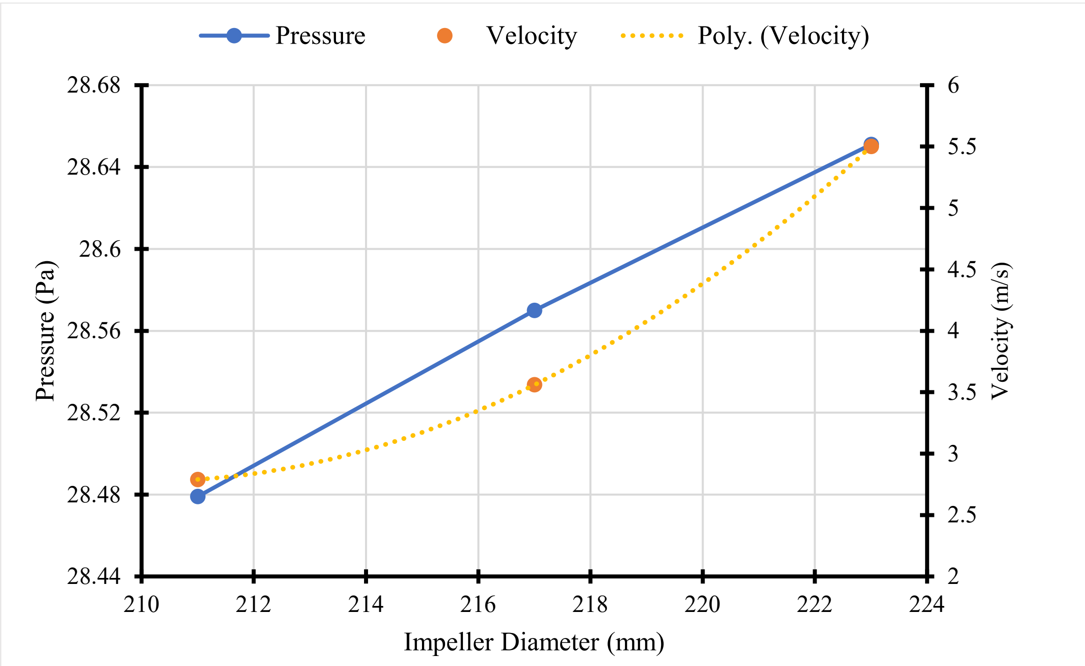

Figure 9. Graph showing a relationship between pressure, velocity, and impeller diameter.

The trimming of the impeller diameter has a direct impact on the performance of the centrifugal pump as shown in Table 6. The pressure and velocity of the pump were showed a gradually increase as shown in Figure 9. It is clearly shown in Table 6 that the pressure increased significantly compared to the velocity of the pump. The bigger the impeller diameter (223 mm) the higher the pressure (28,641 kPa) developed in the pump. This shows that with the impeller diameter of the centrifugal pump is directly proportional to the pressure and velocity and therefore, the assumptions taken in the model development causes the pump to operate efficiently.

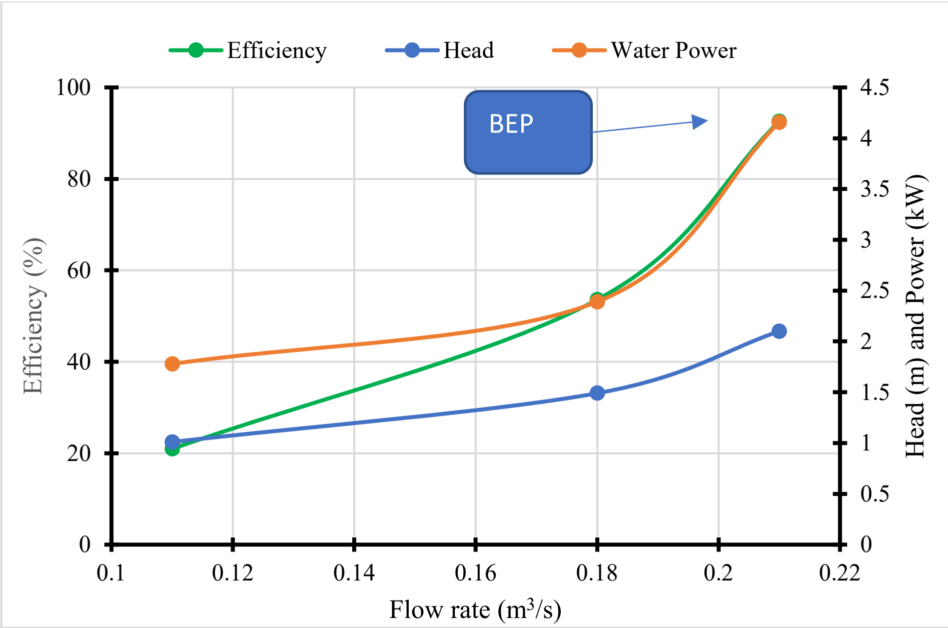

Figure 10. Graph showing the relationship between the head, power, efficiency vs flow rate.

According to Figure 10 the head, power, and efficiency of the centrifugal pump increase with the increment of the impeller diameter. The model parameter selected in the beginning of this simulation made it easy for the pump to function efficiently. The best efficiency point (BEP) of a pump is a very important measure that happened at the maximum flow rate of 0.21 m^3/s and it was found to be 92.59 %.

4.2. Effect on variation of the inlet (suction) diameter of the Pump

Since fluid flows from a high-pressure area to a low-pressure area, operators are having a difficulty in operating a centrifugal pump. The pump inlet conditions are often not paid special attention, and this is a reason why pumps fail. The simulation of the centrifugal pump was performed with alternating the suction diameter at 85 mm, 88mm and 91 mm. The results are shown in Figures 11-13. The orange colour in Figures 11 – 13 represent higher pressure and velocity while the blue colour represents low pressure and velocity. The Best efficiency point of the centrifugal pump takes places at the highest efficiency of 90.84% and a flow rate of 0,172 m^3/s. Table 7 shows the simulated efficiency at various suction diameter of the pump while Figure 14 depicts the pump curve at various suction diameter.

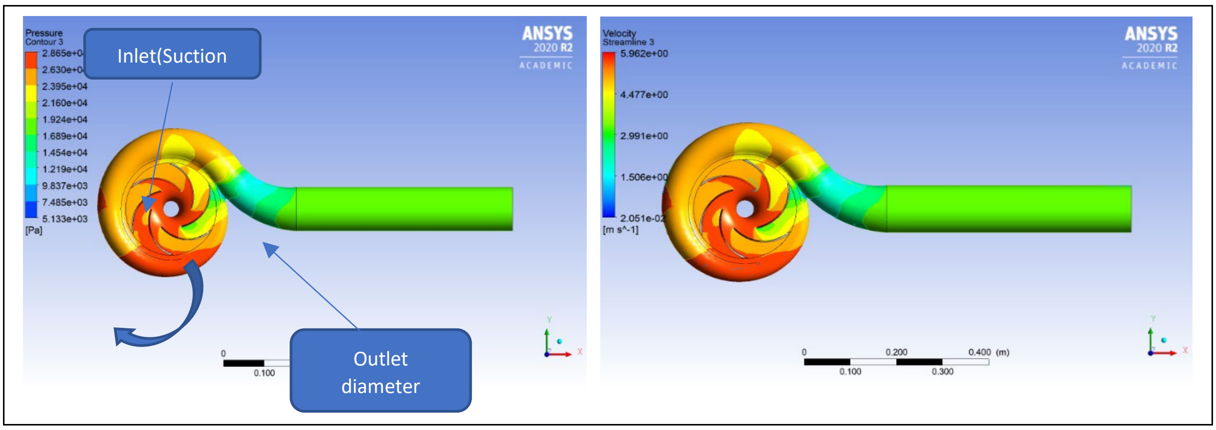

Figure 11. Simulation of Suction Diameter of 110 mm

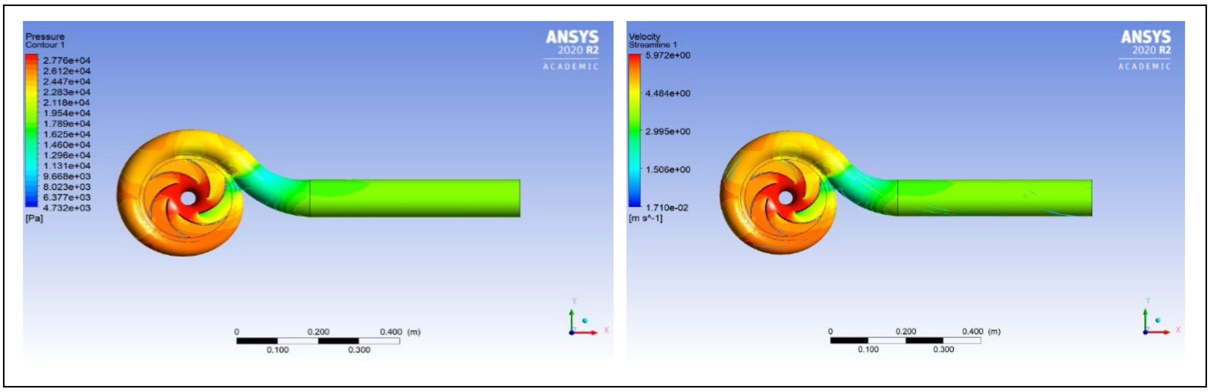

Figure 12. Simulation of Suction Diameter of 100 mm

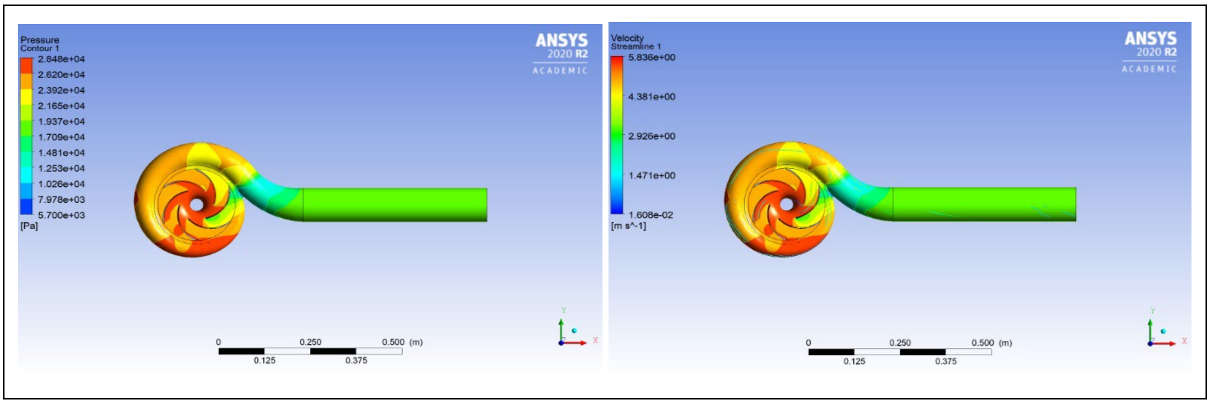

Figure 13. Simulation of suction diameter of 90 mm

Table 7. Results for simulation of the suction diameter

Suction Diameter (mm)	Maximum Pressure (kPa)	Maximum Velocity (m/s)	Flow Rate (m^3/s)	Head (m)	Water Power (kW)	Efficiency (%)
90	24.76	5,343	0.172	2.524	4,12	90,84
100	26.31	5,674	0.21	2.682	5,523	111,45
110	28,587	5,973	0.32	2.964	6,98	159,72

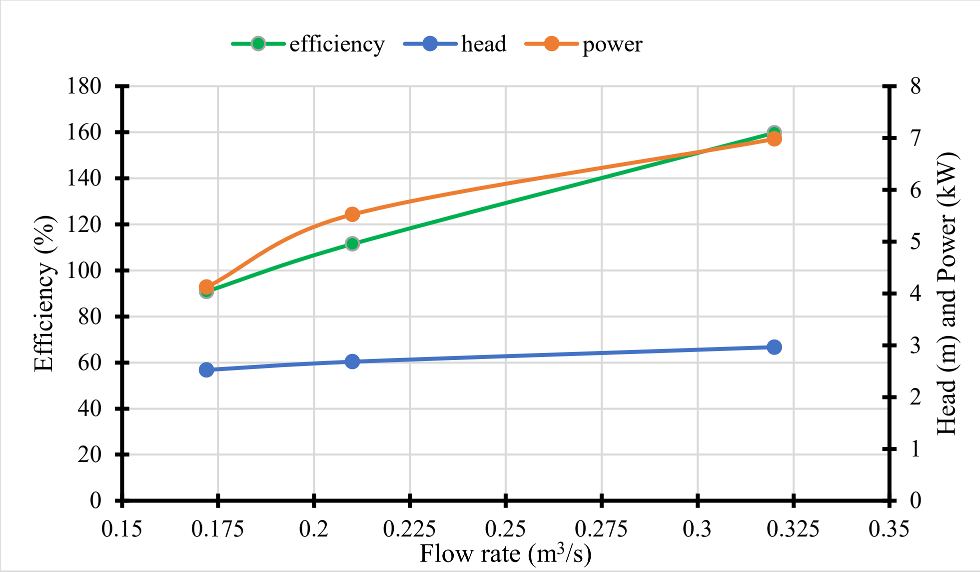

Figure 14. Pump curve for suction diameter

4.3. Effect on variation of the outlet (discharge) diameter of the Pump

The performance of a centrifugal pump is heavily influenced by the discharge (outlet) diameter. The delivery valve is present in a centrifugal pump to help adjust the performance when the pump starts to perform far away from its duty point. The discharge diameter was simulated with changing its diameter at 85 mm, 88mm and 91 mm. It can be seen in Table 3 that the as the discharge diameter is increased so does the efficiency. The Best Efficiency Point is a maximum at flow rate of 0.165 m^3/s and efficiency of 75583% as shown in Figure 18.

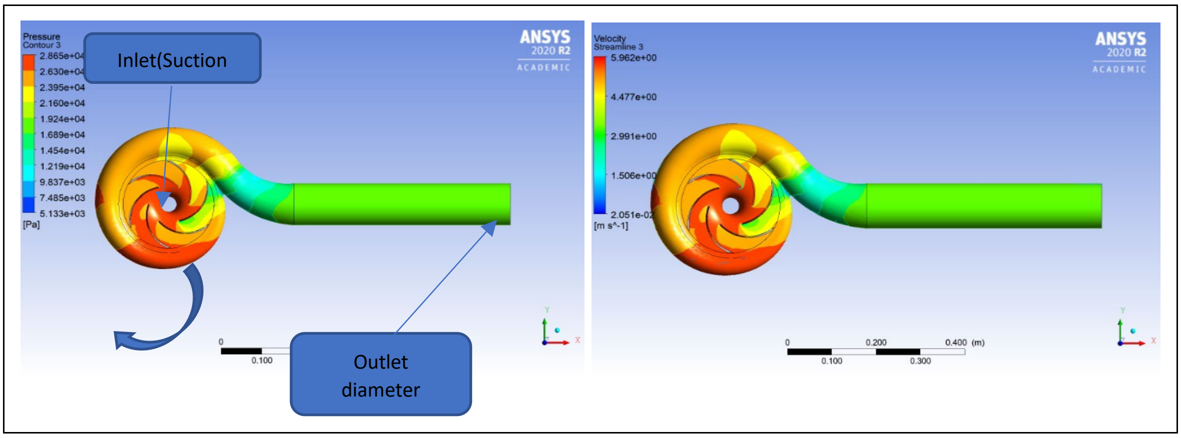

Figure 15. Simulation of discharge diameter of 85 mm

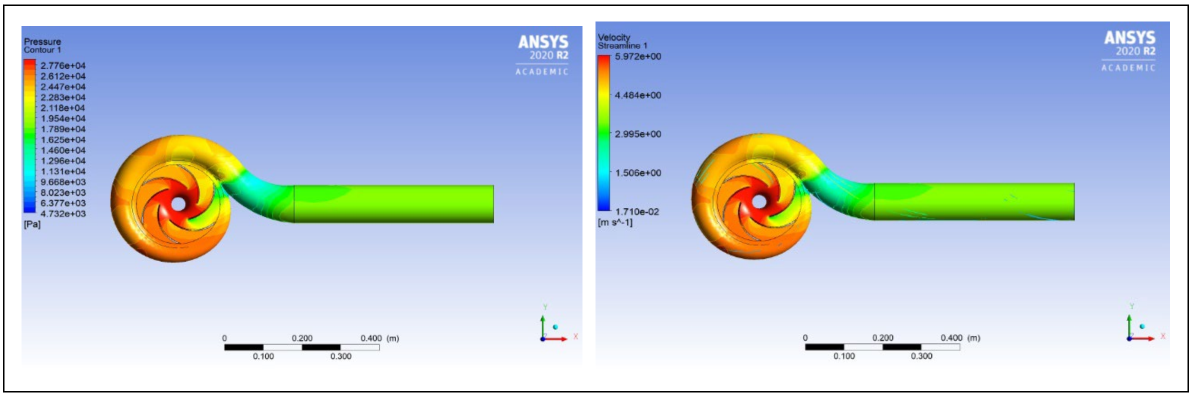

Figure 16. Simulation of discharge diameter of 88 mm

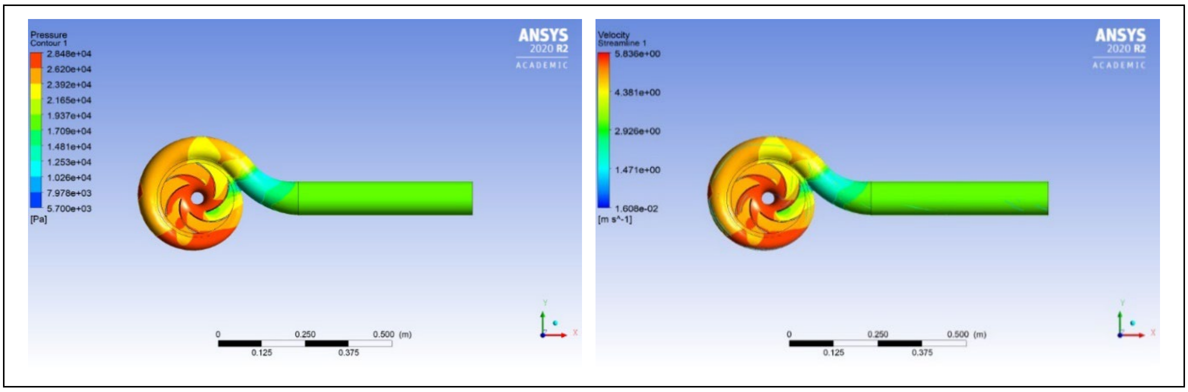

Figure 17. Simulation of discharge diameter of 91 mm

Table 8. Simulation results of the discharge diameter

Discharge Diameter (mm)	Maximum Pressure (kPa)	Maximum Velocity (m/s)	Flow Rate (m^3/s)	Head (m)	Water Power (W)	Efficiency (%)
85	25.76	5,87	0.135	2.524	2088.182	68.268
88	24.31	5,65	0.158	2.356	2372.608	74.556
91	22.99	4,87	0.165	2.242	2417.061	75.538

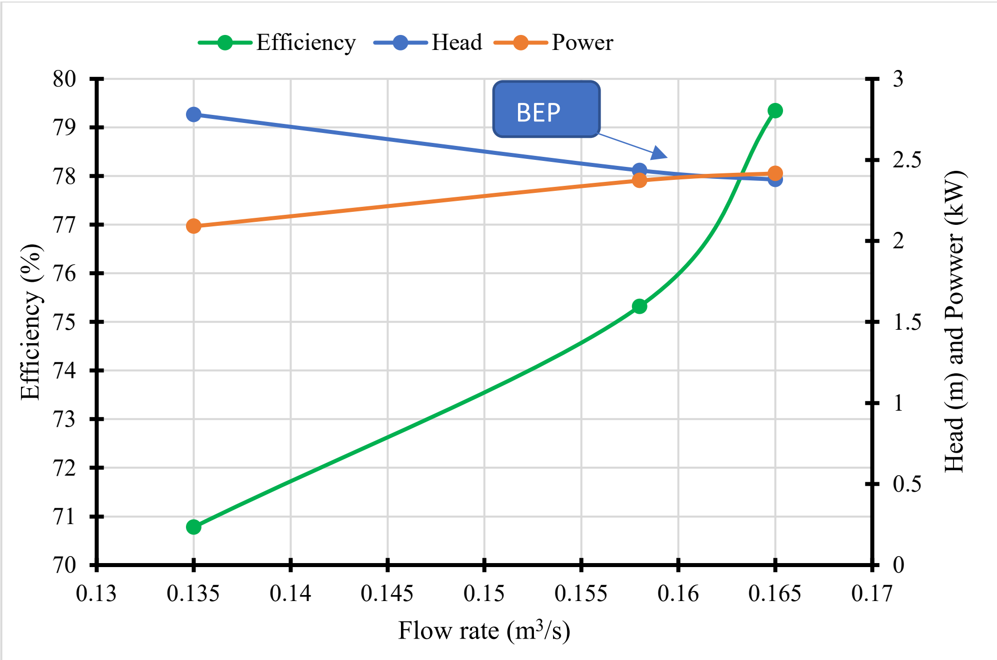

Figure 18. Pump Curve for discharge diameter

5. Discussion of Results

The graph plotted in Figure 3 shows the trimming of the impeller diameter. By trimming the impeller diameter to within 75% of its original diameter, the head and flow rate of a centrifugal pump are decreased. It was discovered that the impeller diameter needed to be reduced by 75% of its original diameter to work at its duty point. The centrifugal pump's pumping capacity was found by computing the duty point at various pumping systems, as shown in Figure 3. The pump duty point for system 1 is represented by a red dot, while the pump duty point for system 2 is represented by a yellow dot. The duty point of a centrifugal point is given by the two pumping systems depicted in Figure 3 as it gives the duty points of a centrifugal pumps as follow.

Table 9. Duty points of the centrifugal pump operating at pumping system 1 and 2

Impeller Diameter	System 1	Length 55mm	System 2	Length 50mm
	Flow Rate	Head	Flow Rate	Head
223	0.27	32.4	0.35	31.8
217	0.215	31.6	0.295	31.2
211	0.15	30.8	0.195	30.6

It can be seen in Table 9 that at system 1 the flow rate is lower when it is compared to the system 2 flow rate. The implies that to increase the flow rate of a centrifugal pump, reduce the length of the pipe of the pumping system and to enhance the head of a pump, increase the length of the system. The optimal pumping capacity of the pump can be achieved by increasing the length or trimming the impeller diameter.

The results obtained during the simulation, showed that the efficiency of the pump increases as the impeller diameter is also increased. the parameter selection of the model made it possible for their centre finger pump to be efficient by reducing the impeller diameter. The Best Efficiency Point (BEP) off the pump is at a maximum flow rate and efficiency at 0.21 m^3/s and 92.59 % respectively is the impeller diameter is trimmed down, see Figure 7. According to the affinity law, the impeller diameter can be trimmed up to 75 % of its original diameter, which implies that trimming cannot be done further in this project since it would affect the pump's performance. The results of the simulation of the suction diameter showed that the efficiency of the pump is directly proportional to the suction diameter, when the suction diameter increases so does the efficiency of the pump. The Best Efficiency Point is at a maximum at the flow rate of 0.172 m^3/s and efficiency of 90.84 % as shown in Figure 11. The results of the simulation of the discharge diameter showed that the efficiency of the pump increases with an increase in the discharge diameter. The head of the pump decreased, and this is the results of the increased flow rate which introduces friction into the system.

6. Conclusions and Recommendations

The pumping system capacity and optimization has been carried out for water as the working fluid. The impeller diameter plays a huge role in centrifugal pump performance and decreasing impeller diameter result in a decrease in the flow rate, head, and power consumption. A decrease in the impeller diameter gives a centrifugal pump a new operating point. If the pump is to be trimmed, the pump manufacturer should be consulted first because the reduction of impeller affects the flow rate and head. Affinity law was mathematically used to analyse. This was to better understand the effect that varying impeller diameter has on the overall performance of a centrifugal pump and to actually enable the analysis of different impeller diameters. The diameter of the impeller, impeller suction diameter and the discharge diameter were changed to optimize the pumping capacity of a water pump. The original impeller diameter was 223 mm, and this was then varied to 217 mm and 211 mm. Final results found showed that reducing the impeller will have a reduced flow rate power consumption and head. To accomplish bigger head and flow rate, a bigger impeller is required, but higher energy usage because of a larger impeller is the biggest challenge. This bigger energy consumption can be decreased by using a lesser weight impeller. It can easily be accomplished by using a lesser weight material for the impeller. When selecting the material of the impeller, the fluid being pumped should be taken into consideration and the life span of the impeller should also be considered.

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Mr Motsi Ephrey Matlakala is a South African holder of a M-Tech in Mechanical Engineering from the University of Johannesburg. Mr Matlakala is currently working as a Mechanical Engineering Graduate at Rand Water Zuikerbourch Pumping Station since June 2017. During his Masters studies, He published eighteen (18) papers and was also selected as a reviewer of paper in four (4) conferences, locally and internationally. Mr. Matlakala is preparing to enrolling PhD in Mechanical Engineering with the University of Johannesburg. Mr. Matlakala is a member of South African Institute of Mechanical Engineering SAIMECH and Professional Engineering Technologist with ECSA. Mr Matlakala's primary research areas are System Analysis and Dynamics, Optimization, Computational Fluid Dynamics, Finate Element Analysis and Water Research.

Dr Daramy Vandi Von Kallon is a Sierra Leonean holder of a PhD degree obtained from the University of Cape Town (UCT) in 2013. He holds a year-long experience as a Postdoctoral researcher at UCT. At the start of 2014 Dr Kallon was formally employed by the Centre for Minerals Research (CMR) at UCT as a Scientific Officer. In May 2014 Dr Kallon transferred to the University of Johannesburg as a full-time Lecturer and later a Senior Lecturer in the Department of Mechanical and Industrial Engineering Technology (DMIET). Dr Kallon has more than twelve (12) years of experience in research and six (6) years of teaching at University level, with industry-based collaborations. He is widely published, has supervised from Masters to Postdoctoral and has graduated seven (7) Masters Candidates. Dr. Kallon's primary research areas are Acoustics Technologies, Mathematical Analysis and Optimization, Vibration Analysis, Water Research and Engineering Education.