# Optimization of the Pumping Capacity of Centrifugal Pumps Based on System Analysis

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**Abstract.** The pumping capacity is the maximum flow rate through a pump at its design capacity. In the process of pumping water and other fluids, pumping capacity is required to accurately size pumping systems, determine friction head losses, construct a system curve and select a pump and motor. Failure to choose the right pump size for pumping system, improper installation and pump operation results into higher consumption of energy. The insufficient pumping capacity affects the plant's operations such as maintenance cost, downtime, loss of production and increase in operating cost. In this study variation of the impeller diameter is used to calculate the new pump curve to improve the pumping capacity. The pumping system is analysed to determine the pumping capacity of the pump. Computational fluid dynamic (CFD) simulations are carried out to determine the performance of the pump and analyses the pumping system to achieve the pumping capacity. Results show that enhanced pumping capacity is achieved at a given impeller design with a specific shift in the pump curve. It is recommended that the pumping capacity can be optimized through trimming of impeller. Trimming of the impeller improves pump efficiency and increases the performance of the pump. In addition, the pumping capacity can also be optimized through the system analysis by adjusting the diameter of the pipes and throttling of the valves. Optimization of the pumping capacity helps with running the pumping system efficiently.

**Keywords:** Pumping Capacity, System Analysis, Computational Fluid Dynamics, Cost, Impeller, Pump Efficiency.

# 1. Introduction

Sizing of pumping systems are difficult since the pumps must fit the pumping systems, as a result, it affects the installation, maintenance, and operations of centrifugal pumps and pumping systems. Centrifugal pumps contain two main parts: an impeller (rotor) that rotates at speeds of the motor and imparts centrifugal forces to the production fluid and diffuser (stator) the fixed part that guides the flow to the discharge [1, 2]. Optimization of pumping capacity is carried out through system analysis which involves process analysis, engineering design, maintenance, cost analysis, risk and viability analysis. The impeller of a centrifugal pump regulates performance of pump and determines pumping capacity of the centrifugal pump [3]. Figure 1 shows layout of centrifugal pump with two major components, impeller and volute.

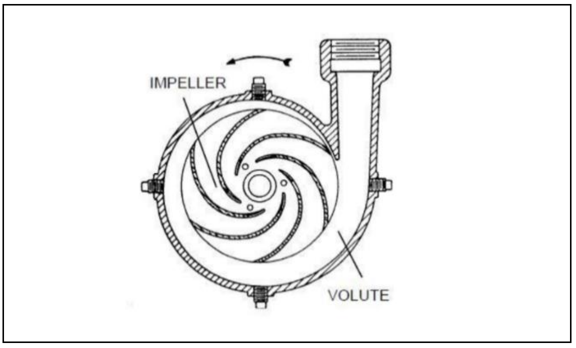


**Figure 1.** Centrifugal Pump [2]

The design of the impeller diameter has a major effect on the pump efficiency, an entirely new pump can be designed by just modifying the impeller. The pumping capacity is the maximum flow rate through a pump at its design capacity [4, 5]. The speed and diameter of the impeller determine the head or pressure head that the pump can generate [3]. A typical failure mode of centrifugal pumps is caused by the difficulty of installation, operation and maintenance of the pump. The challenge of implementing proper maintenance plans for the pumping system affects the efficiency of the pump. The centrifugal pump efficiency can drop below 5% of required operation duty point, consuming more energy and cost a company more than usual [6]. In the present study we have identified that companies find it challenging to design, install, operate and maintain centrifugal pump of which it affects the efficiency of centrifugal pump. The aim of the paper is to carry out an investigation with the aim to improve the efficiency and reliability of centrifugal pumps through better design of impeller, installation, operation and maintenance practices. This paper present affinity laws to help with predicting the performance of a centrifugal pump and to determine whether a change in the impeller design is a limiting factor. The parameters of the pumping system are considered to establish the operating points of centrifugal pumps.

# 2. Methodology

## 2.1. Conceptualization

A multiple method was used to identify potential causes of centrifugal pump failure and dropping of efficiency of the pump. A review of grey and white literature was undertaken to identify the challenges of installation, operation and maintenance of centrifugal pump. System analysis of centrifugal pumps is done through engineering design where specification for the pump is provided based on the pumping system. Affinity laws are presented to help with predicting the performance of the centrifugal pump. A representative variation of pump impeller diameters was used to prove affinity laws on the performance of centrifugal pump. Cost analysis is also taken into consideration to analyze the risk and viability if centrifugal pumps are not restored to their original efficiency [6, 7]. Simulation is a technique used to manage and improve performance of centrifugal pump. It also helps with time saving and cost for companies. Simulation process can help industries to effectively manage and maintain centrifugal pumps.

### 2.2. Design and Simulation of Centrifugal Pump

In the process of pumping water and other fluids, pumping capacity is required to accurately size pumping systems, determine friction head loss, construct a system curve and select a pump and motor to achieve the pumping capacity [4, 5]. The most critical area that contribute to performance of centrifugal pump is wet area of the pump which include impeller. An efficiency of centrifugal pump can be improved by trimming of impeller diameter even although reducing of impeller diameter from the original design can results in low pressure, flow and power consumption. Therefore, the trimming of the impeller should not be more than 75% of a pump original diameter [1, 3]. Different performance can be achieved and reducing impeller size allows the pump to reach specific. The affinity law can be shown in two ways, by keeping the rotational speed and diameter of impeller constant. Impeller trimming adjusts the centrifugal pump head and flows to the actual needs. Simulation is conducted varying impeller diameters to improve efficiency of centrifugal pump. Design of centrifugal pump with simulation save time and cost of companies because designs are tested on software to identify errors and failures before actual design is made.

## 3. Results and Discussions

### 3.1. Pumping System Design

To meet the requirement of pumping systems, Total Dynamic Head (TDH) is used. [8, 9]. The Total Dynamic Head (TDH) is the combined total head of the elements, pipe friction losses ($H_f$), static head ($H_s$), and velocity head ($H_v$). The sum of these three elements of the total head is represented in equation (1):

$$Total\ Head = H_s + H_f + H_v \qquad (1)$$

A pumping system was designed based on system specifications and assumptions that the flow rate varies from 0.05 to 0.4 m3 $m^3/s$. The material of the pipe is commercial steel pipe; therefore, pipe roughness is, $\varepsilon$ = 0.045mm, see Table 1 [8, 10]. The final results are summarised in Table 2.

**Table 1**. Absolute Roughness of Steel Pipe Material

| Pipe Material | Absolute Roughness, ε | |
|---|---|---|
| | **Feet** | **Microns** |
| Drawn brass or copper | 0.000005 | 1.5 |
| Commercial steel | 0.000150 | 45 |
| Wrought iron | 0.000150 | 45 |
| Cast Iron | 0.000850 | 260 |

The parameters used to calculate the pumping system are as follow:
Pipe Diameter, D = 0.3 m,
Length of the pipe of the system = 45,
The static head (Hs) = 30m.
Equations (2) to (8) are used to calculate the pumping system:

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

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

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

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

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

$$H_f = \frac{f\,L\,v^2}{2gD} \tag{7}$$

$$H_v = \frac{v^2}{2g} \tag{8}$$

The calculations of total head were carried out at different flowrates varying from 0.05 $m^3/s$ to 0.4 $m^3/s$ with the pipe diameter of 0.3 m and length of 45m. The final results are summarised in Table 2. It can be seen that an increase in the flowrate increases the total head of pumping system 1.

**Table 2.** Pumping System Calculation Results of System 1 With A Pipe Length of 45m and Diameter Of 0.3m

| Flow | Velocity | Reynold Number | Friction Factor | Head Sys |
|---|---|---|---|---|
| m3/s | m/s | | | m |
| 0.3 | 4.24 | 712408.77 | 0.0145 | 32.92 |
| 0.25 | 3.54 | 593673.98 | 0.0148 | 32.05 |
| 0.2 | 2.83 | 474939.18 | 0.0151 | 31.33 |
| 0.15 | 2.12 | 356204.39 | 0.0156 | 30.77 |
| 0.1 | 1.41 | 237469.59 | 0.0164 | 30.35 |
| 0.05 | 0.71 | 118734.8 | 0.0182 | 30.1 |

The same procedure was followed to calculate pumping system 2 at 0.35 diameter of the pipe and length of 45m. The results for pumping system 1 and system 2 were plotted on the same graph in Figure 2 to illustrate how the system curve will change when increasing the pipe diameter from 0.3 to 0.35 m. Figure 2 shows that the pumping capacity can be achieved by adjusting the diameter of the pumping system at a constant length of the system. Increasing the diameter of the pipe in a pumping system, the head reduces thus increasing the flowrate. Due to this finding, the centrifugal pump is tested at varying impeller diameters.

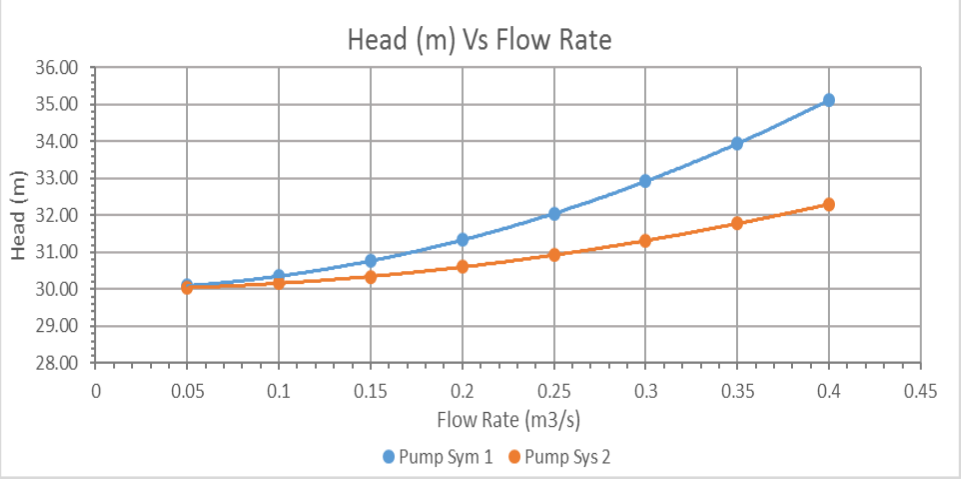


**Figure 2.** Pump system curve 1 and 2

## 3.2. Centrifugal Pump Design at Varying Impeller Diameter

The optimization of the pumping capacity of the centrifugal pump is done by trimming the impeller to adjust the head (m) and flowrate ($m^3/s$) [6]. Assumptions were made to determine the effect of the impeller diameter on the pumping capacity of the centrifugal pump. Impeller diameters of 350mm, 344mm and 338mm were used to do the calculations. The pump specification to suit the existing pumping system design with the impeller diameter of 350mm at the flowrate varying 0.05 $m^3/s$ to 0.4 $m^3/s$ are shown in Table 3.

### 3.2.1 Affinity Laws for centrifugal pumps

Affinity laws only apply to radial and axial pumps [3, 11]. The formulas applied for affinity laws in constant impeller diameter and constant rotational speed are represented in equations (9) and (10):

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

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

**Table 3.** Pump Specifications

| Flow | Total Heat | Water Power |
|---|---|---|
| $m^3/s$ | M | kW |
| 0.4 | 31.36 | 123.07 |
| 0.35 | 31.8 | 109.19 |
| 0.3 | 32.18 | 94.71 |
| 0.25 | 32.5 | 79.71 |
| 0.2 | 32.76 | 64.28 |
| 0.15 | 32.97 | 48.51 |
| 0.1 | 33.11 | 32.49 |
| 0.05 | 33.2 | 16.29 |

The impeller diameters are varied from $D_0$ as the original and two other values $D_1$ and $D_2$ as variations from $D_0$. The specifications of the pump (Table 1) is at the original impeller diameter of 350 mm. The head and flowrate of the centrifugal pump was calculated varying discharge flowrate, see the calculation summary of the result in Table 4.

https://doi.org/10.1051/matecconf/202134700024

**Table 4.** Affinity Law Calculation Results

| Total Pump Head (m) | | | Flow (Ml/d) | | |
|---|---|---|---|---|---|
| 350 mm | 344 mm | 338 mm | 350 mm | 344 mm | 388 mm |
| 32.18 | 31.09 | 30.01 | 0.3 | 0.295 | 0.289 |
| 32.5 | 31.39 | 30.06 | 0.25 | 0.246 | 0.241 |
| 32.76 | 31.65 | 30.56 | 0.2 | 0.197 | 0.193 |
| 32.97 | 31.85 | 30.77 | 0.15 | 0.147 | 0.145 |
| 33.11 | 31.989 | 30.882 | 0.1 | 0.098 | 0.096 |
| 33.2 | 32.073 | 30.965 | 0.05 | 0.049 | 0.048 |

Affinity laws were applied to determine the pumping capacity of centrifugal pumps. The results were summarised in a table format in Table 4. The head and flowrates were compared at the variation of the impeller diameters of 350 mm, 344 mm and 338 mm. The results obtained from the calculations in Table 4 and Figure 3 shows that the trimming of the impeller reduces the flowrate and the head of the pump. The plotted graph, Figure 3, shows that the trimming of the impeller diameter reduces the head and the flow rate of the centrifugal pump. It was observed that it is important to trim the impeller diameter with the limit of 75% of the original diameter to keep the centrifugal pump operation at the duty point. The duty point of the pump was calculated at two different pumping systems to determine the pumping capacity of the centrifugal pump. The duty point is being shown with a red dot for system 1 and yellow dot for system 2. The two pumping systems in Figure 3 give the operation duty point of the centrifugal pump as shown in Table 5.

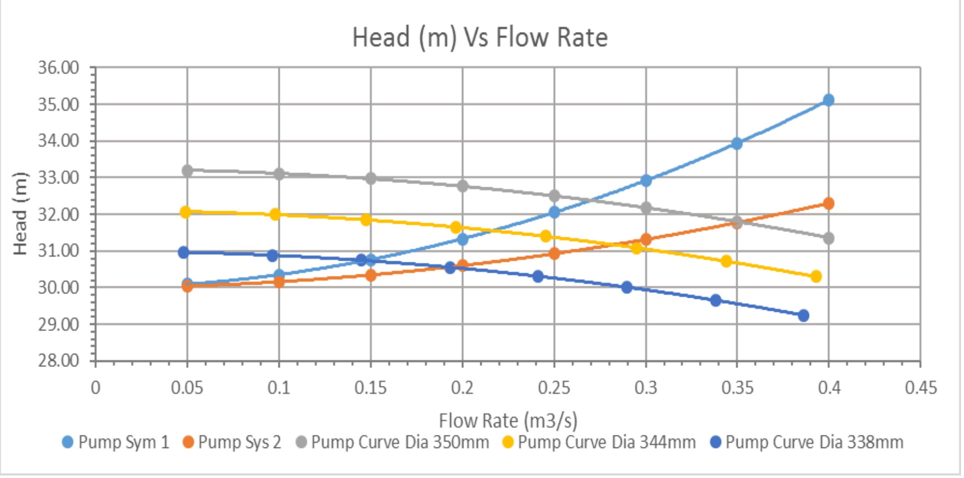


**Fig. 3**. Head Vs flow rate pump and pumping system curve.

**Table 5:** Duty Points of the Centrifugal Pump Operating at Pumping System 1 and 2

| Impeller Diameter | System 1 Length 45mm | | System 2 Length 40 mm | |
|---|---|---|---|---|
| | Flow Rate | Head | Flow Rate | Head |
| 350 | 0.27 | 32.4 | 0.35 | 31.8 |
| 344 | 0.215 | 31.6 | 0.295 | 31.2 |
| 388 | 0.15 | 30.8 | 0.195 | 30.6 |

It can be seen in Table 5 that at the system 1 the flowrate is lower compared to flow rate at system 2 and the head at system 1 is higher as compared to head at system 2. It means to increase the flowrate of the centrifugal pump, reduce the length of the pipe of the pumping system and to increase the head of the pump, increase the length of the pipe of the system. The pumping capacity of the centrifugal pump can be achieved by either increasing the length of the pumping system or trimming of the impeller diameter.

### 3.3.Simulation of the Impeller Diameter

The diameter of the impeller has an impact on the performance of the pump [12]. The impeller trimming adjusts the centrifugal pump head and flows to the actual needs. The trimming of the impeller should not be more than 75% of a pump original diameter. The simulation of the centrifugal pump was performed with the impeller diameter varying at 350mm, 344mm and 338mm.  The study parameters of the centrifugal pump are assumed to be: rotational Speed = 1800 rpm, Pressure outlet = 15000 Pa, and Velocity = 0.6 m/s. The results were obtained after the analysis has been carried out. The results were taken from counterflow through the pump in the midplane view, see Figures 4 – 6.

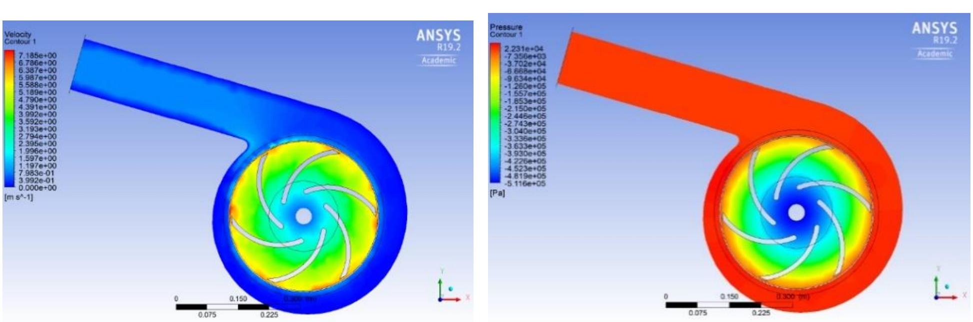


**Fig. 4.** Velocity and Pressure counter flow through the pump in the mid plane view for 350 mm Impeller Diameter

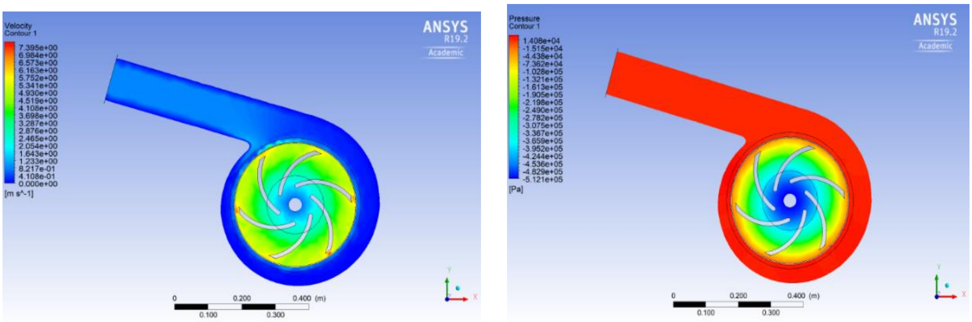


**Fig. 5.** Velocity and Pressure counter flow through the pump in the mid plane view for 344 mm Impeller Diameter

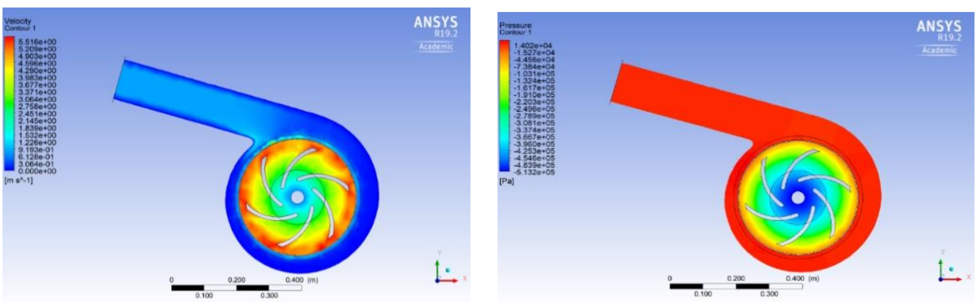


**Fig. 6.** Velocity and Pressure counter flow through the pump in the mid plane view for 338 mm Impeller Diameter

**Table 6:** CFD Results of Variation of Impeller Diameter

| Impeller Dia (mm) | Maximum Pressure (kPa) | Maximum Velocity (m/s) | Flow Rate (m3/s) | Head (m) | Water Power (W) | Eff (%) |
|---|---|---|---|---|---|---|
| 350 | 20.59 | 8.79 | 0.20 | 2.09 | 4156.8 | 91.59 |
| 344 | 14.08 | 7.39 | 0.17 | 1.44 | 2389.6 | 52.66 |
| 338 | 14.02 | 5.52 | 0.13 | 1.43 | 1777.3 | 39.17 |

The variation of impeller diameter influences the performance of the centrifugal pump as is indicated in Table 6. The pressure and velocity of the centrifugal pump were found to be increasing with increase of the impeller diameter, see Figure 7. It can be observed that the pressure rises more than the velocity. More pressure is achieved at the bigger impeller diameter of 350mm because of decrease in space inside the pump casing. It appears that the assumption made for the impeller diameter of the model causes the pump to operate efficiently.

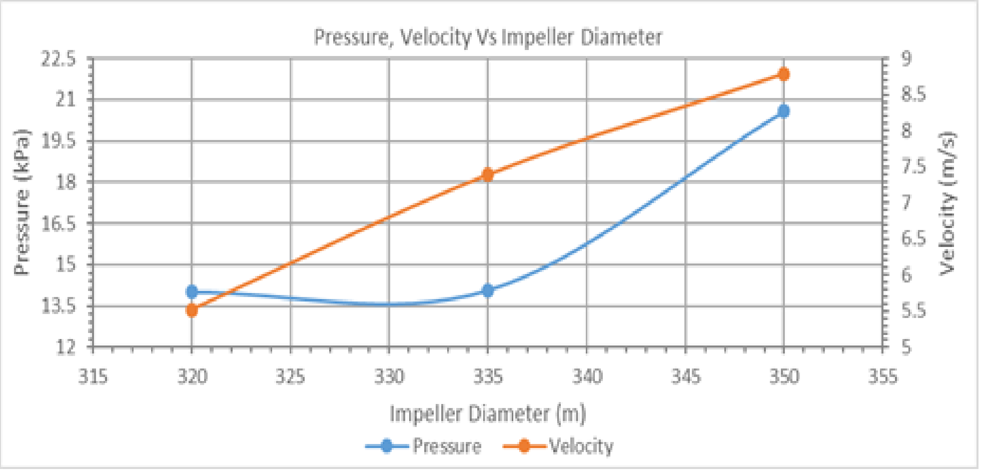


**Figure 7.** Pressure, Velocity Vs Variation of Impeller Diameter Simulation.

The efficiency of the centrifugal pump in Figure 8, increases with increase of impeller diameter. According to the selection made for the parameters of the model, the pump is found to be more efficient with reducing of the impeller diameter. The Best Efficiency Point (BEP) of the pump is at the maximum flowrate and efficiency of 0.203m3/s and 91.59% respectively. Affinity laws of pumps states that the pump can only be trimmed up to 75% of its original diameter, which means according to these results there is no further trimming that can be done because it will affect the performance of the pump.

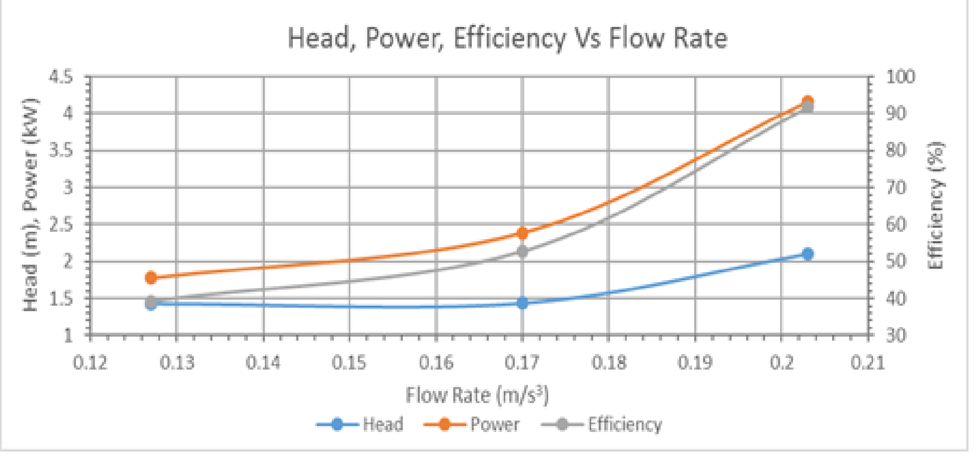


**Figure 8.** Head, Power, Efficiency Vs Flow Rate for Variation of Impeller Simulation

The simulation results show that the efficiency of the centrifugal pump in Figure 8 increases with increase of impeller diameter. According to the selection made for the parameters of the model, the pump is found to be more efficient with reduction in impeller diameter. The Best Efficiency Point (BEP) of the pump is at the maximum flowrate and efficiency of 0.203m3/s and 91.59% respectively, see Figure 8.

## 4. Conclusion

The paper presents two ways to improve efficiency of centrifugal pumps, which are systems analysis, trimming of impeller design using affinity laws and simulation. As previously discussed, reduction of the impeller diameter gives a new operation point of the centrifugal pump, therefore, it is imperative to consult with the manufacturers before trimming the impeller because the reduction of impeller affects the flowrate and head. From literature review it was found that the impeller can be reduced up to 75% not above so that the centrifugal pump can continuously operate efficiently. Also reducing the impeller changes the length and overlap of vanes, the width at the impeller exit and often the discharge angle as well. The total pumping system head increases when the flowrate increases and the total head of the pump decreases with the increase of the pump flowrate. To increase the pumping capacity, ensure that the flowrate is kept lower as possible to achieve a higher pressure and head at the centrifugal pump discharge. According to the calculations results illustrated in Figure 3, increasing the length of the pumping system at the constant diameter of the impeller, will reduce the flowrate while increasing pressure and head of the pump. Trimming of impeller diameter improves performance of centrifugal pump. The energy charge of the centrifugal pump is estimated to be R/kWh = R0.82. Monthly saving if the centrifugal pump is restored to original efficiency is R16523.83 therefore the saving cost if the pump is restored is R1,080,820.99.

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