Influence of Impeller Diameter on the Performance of Centrifugal pumps.

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Abstract: The impeller is the most important part of the centrifugal pump because it determines the flow or efficiency of the pump. The design of the impeller and its diameter are very essential when considering pump efficiency. The capacity of the pump is determined from the impeller vanes and channels. The three types of impellers include open impeller, enclosed impeller and semi-open impeller are each designed for a specific application. Impellers are made of cast iron or carbon steel and special alloys depending on their application. The research involves the study of the application of impellers in the centrifugal pumps used by Rand Water Company in Johannesburg. The paper considers how variations in the impeller diameter affect the performance of the centrifugal pump. Simulations were conducted at different diameters of the impeller. The impeller was modelled using AutoCAD and simulated using ANSYS software to determine the performance of the centrifugal pump on different diameters. Calculations were done to compare the results of simulation of the different diameters of 2000mm, 2200mm, and 2400mm. The results show that changing the diameter of a pump impeller affects the flow, head and input brake horsepower of the pump in different proportions. The centrifugal pump gives a high flow rate as the diameter of the impeller increases.

1. Introduction
An impeller is a rotor used to increase or decrease the pressure and flow of a fluid. The impeller is assembled in a centrifugal pump and it is the most important part of the pump [1]. Typical impeller of a centrifugal pump is show in figure 1. A centrifugal pump is a type of general machinery which is widely and fully utilized in the industrial and agricultural fields such as irrigation and water supply [2]. It is also used in many plants to transfer fluids from one point to the other. It normally includes four different parts: suction pipe, impeller, volute, and exit pipe. The impeller is the core part and it converts the mechanical energy into pressure energy which directly determines the transport capacity and the hydraulic performances of a centrifugal pump [3 - 5]. Optimized design of the impeller is essential and significant for the efficient operation of a centrifugal pump [6]. The fluid enters the impeller through the eye then it is pushed by the vanes/blades as the fluid passes the channel. The impeller has a bore to attach the drive shaft. The impeller is a pump component that has more influence on the pump and one can create a new pump by just modifying the impeller. It can change the flow, the differential head, and the speed. Thus the bigger the impeller the greater the flow [5]. Figure 1 shows the model of the complete impeller.
The impeller of a centrifugal pump regulates the performance of the pump [4, 5]. The design of the impeller and diameter are very important when considering pump efficiency. The capacity of the pump is determined from the impeller vanes. Impellers are made of different types of steel cast iron or carbon steel and special alloys depending on their application. The three types of impellers include forward swept impeller, radial exit impeller, and backswept impeller. Forward swept impeller is used for lower head and flow rate, the backswept impeller is used for higher flow rate and head, and radial exit impeller is used for medium head and flow rate. The pump impeller receives the liquid to be pumped and imparts velocity and pressure to it by drawing power from a motor. The speed and diameter of the impeller determines the head or pressure that the pump can generate. The rotational speed and height of the impeller blades determines the flow that the pump can accommodate [4, 5].

2. Design of 3D Solid Model of the impeller
The design of the impeller diameter is critical because it affect the performance of the centrifugal pump. The design stage of the impeller diameter in critical when coming to the performance of the centrifugal pump. The specification of the pump should be accurate in order to achieve the correct result for the flow and head required. The different impeller diameters of 2400mm, 2200mm and 2000mm were model for the purpose of determining the performance of the centrifugal pump with difference diameters of the impeller. The impeller was model using the solidworks software.

2.1. Conceptual Design
2.2. Detailed Design

Figure 3. Design of 2400mm Impeller Diameter

Figure 4. Design of 2200 mm Impeller Diameter

Figure 5. Design of 2200 mm Impeller Diameter

3. Calculations
These calculations are for a single-stage centrifugal pump with a Radial 6-Vanes impeller. All the calculations done were obtained with varying the diameter for an impeller and same goes with the simulation. There were assumptions made in order that the calculations can be done to test the effect of the impeller diameter on the centrifugal pump performance. The diameter was assumed based on the specification of the centrifugal pump as shown in table 1. The impeller diameters of 2000mm, 2200mm and 2400mm was used to do the calculations.
Table 1 Details of the pump

| Description                        | SI Units |
|------------------------------------|----------|
| Duty Flow Rate                     | (ML/d)   |
| Duty Generated Head (Set)(Revised) | (m)      |
| Guaranteed Demand (set)            | (kW)     |
| Guaranteed Efficiency              | (%)      |
| Duty Generated Head (Stage 1)      | (m)      |
| Duty Speed (Stage 1)               | (r.p.m)  |
| Rated Voltage (Stage 1 and 2)      | (kV)     |
| Rated Power                        | (kW)     |
| Rated Amps                         | (A)      |
| Rated Speed 1st Stage              | (r.p.m)  |
| Duty Generated Head (Stage 2)      | (m)      |
| Duty Speed (Stage 2)               | (r.p.m)  |
| Rated Power                        | (kW)     |
| Rated Amps                         | (A)      |
| Rated Speed (Stage 2)              | (r.p.m)  |
| Suction Dia.                       | (mm)     |
| Delivery 1st Stage Dia.            | (mm)     |
| Delivery 2nd Stage Dia             | (mm)     |
| Total Operating Hours              |          |
| Density                            | (kg/m³)  |
| Gravity                            | (m/sec²) |
| Pump-set Utilization               | (%)      |

3.1. Data for the Calculation

Suction diameter $D_s = 1400$ mm = 1.4 m
Discharge diameter $D_D = 1000$ mm = 1 m
Rotational speed $N = 1490$ rpm
Water flow rate at suction side $Q_s = 2,315$ m³/s

3.2. Speed of Water Entry into Suction side of the Pump

$$Q = A \times V$$
but $Q = 2,315$ m³/s
and the $Area = \frac{\pi d^2}{4} = \frac{\pi (1.4)^2}{4} = 1.539 m²$
Therefore $V = \frac{2.315}{1.539} = 1.504 \text{ m/s}$

The following characteristics describe the performance of a centrifugal pump:
- Flow rate
- Head
- Power

Therefore, for our selected pump the following are important known variables we will use when we apply affinity laws for our calculations:
$Q$ (Flow rate) = 200 l/day = 2,315 m³/s
$H$ (Head) = 198 m
**3.3. Affinity Laws for Centrifugal pump**

Affinity laws state that pump impellers are considered to be similar if they satisfy geometric and similarity condition. Affinity law helps to predict the performance of a centrifugal pump for speed and if the impeller is reduced in diameter within the limit of impeller design [5]. The affinity law can be shown in two ways, by keeping the rotational speed and diameter of impeller constant. Mario Savar (2009) proposed the impeller trimming method to improve the efficiency of the centrifugal pump. Impeller trimming adjusts the centrifugal pump head and flows to the actual needs. Trimming of impeller improves the performance of the centrifugal pump. The diameter of the impeller reduces from the original design can results in a low pressure, flow and power consumption. Therefore, the trimming of the impeller should not be more than 75% of a pump original diameter. Different performance can be achieved and reducing impeller size allows the pump to reach specific. Affinity laws only apply to radial pumps and axial pumps.

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

### 3.3.1. Affinity Laws for centrifugal pumps:

\[
\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \quad \frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \quad \frac{P_1}{P_2} = \left(\frac{D_1}{D_2}\right)^3
\]  

(3)

\[
\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \quad \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3
\]  

(4)

The Impeller diameters will be varied with \(D_{\text{original}}\) as the original and two other values \(D_1\) and \(D_2\) as variations from \(D_{\text{original}}\)

\(D_1 = 2200\) mm

\(D_2 = 2000\) mm

### 3.3.2. Applying Affinity law between \(D_{\text{original}}\) and \(D_1\):

\[
\frac{Q_{\text{original}}}{Q_1} = \frac{D_{\text{original}}}{D_1} \quad \frac{2.315}{2400} = \frac{2.122}{2200}
\]

\(Q_1 = 2.122\) m\(^3\)/s (New flow rate)

\[
\frac{P_{\text{original}}}{P_1} = \left(\frac{D_{\text{original}}}{D_1}\right)^3 \quad \frac{4200}{P_1} = \left(\frac{2400}{2200}\right)^3
\]

\(P_1 = 3235,069\) kW (New power)

\[
\frac{H_{\text{original}}}{H_1} = \left(\frac{D_{\text{original}}}{D_1}\right)^2 \quad \frac{198}{H_1} = \left(\frac{2400}{2200}\right)^2
\]

(7)
$H_1 = 166,375 \text{ m (New Head)}$

3.3.3. Applying Affinity law between $D_{\text{original}}$ and $D_2$:

$$\frac{Q_{\text{original}}}{Q_2} = \frac{D_{\text{original}}}{D_2}$$

$$\frac{2,315}{Q_2} = \frac{2400}{2000}$$

$Q_2 = 1,929 \text{ m}^3/\text{s (New flow rate)}$

$$\frac{P_{\text{original}}}{P_2} = \left(\frac{D_{\text{original}}}{D_2}\right)^3$$

$$\frac{4200}{P_2} = \left(\frac{2400}{2000}\right)^3$$

$P_2 = 2430,56 \text{ kW (New power)}$

$$\frac{H_{\text{original}}}{H_2} = \left(\frac{D_{\text{original}}}{D_2}\right)^2$$

$$\frac{198}{H_2} = \left(\frac{2400}{2000}\right)^2$$

$H_2 = 137,5 \text{ m (New Head)}$

The summary of the calculation results is shown in Table 2. The results indicate the performance of the centrifugal pump at the variation of the diameter of the impeller.

| Impeller Diameter (mm) | Flow Rate (m$^3$/s) | Head (m) | Power (kW) |
|------------------------|---------------------|----------|------------|
| Original Diameter      | 2400                | 2,315    | 198        | 4200       |
| New Impeller Diameter  | 2200                | 2,122    | 166,375    | 3235,069   |
| New Impeller Diameter  | 2000                | 1,929    | 137,5      | 2430,56    |

4. Simulation

The simulation was done using the ANSYS software to check the effect of impeller diameter on the performance of a centrifugal pump. The simulation was done to find the Von Mises Stress, 1st Principle Stress, 3rd Principle Stress, for the diameter of 2400mm, 2200mm, and 2000mm. Figure 6, 7 and 8 shows the simulation results for 2400mm diameter. The same procedure was done to obtain the simulation results of 2200 mm and 2000mm, results obtained are summarised in table 3.
Figure 6. Von Mises Stress for 2400 mm

Figure 7. 1st Principle Stress for 2400 mm

Figure 8. 3rd Principal Stress for 2000 mm
Table 3: Summary of the Simulation Results of the Impeller Variation

| Stresses Experienced | Maximum Magnitude 2400mm | Maximum Magnitude 2200mm | Maximum Magnitude 2000mm |
|----------------------|--------------------------|--------------------------|--------------------------|
| Von Mises stress     | 10.08 MPa                | 8.53 MPa                 | 8.71 MPa                 |
| 1st Principal Stress | 12.43 MPa                | 10.34MPa                 | 8.58 MPa                 |
| 3rd Principal Stress | 1.47 MPa                 | 1.045MPa                 | 4 MPa                    |

5. Discussion of the Results
The performance of the centrifugal pump was calculated based on varying the impeller diameter from 2400mm, 2200mm and 2000mm. The simulation was also performed in varies diameters of the impeller to test the stress of the material of the impeller. From the simulation, the results of Von Mises Stress obtained is clearly shown in figure 9. From the calculations, the characteristic graphs for the impeller diameter were obtained for the Flow rate – Impeller Diameter in figure 10, Head – Impeller Diameter in figure 11 and Impeller Diameter – Power in figure 12.

Figure 9. Von Mises Stress Vs Impeller Diameter

Figure 10. Flow Rate Vs Impeller Diameter
The graphs in figures (9) to (12) were plotted according to the results in table 2 in order to evaluate the performance of the operating centrifugal pump with different diameter of the impeller. As indicated by the graph in figure 10 and 11, the flow rate and the head increases as the impeller diameter increases. This indicates that by increasing the impeller diameter, the performance of the pump will increase. Figure 12 shows that by increasing the impeller diameter, the power required to operate the centrifugal pump will increase, due to the weight of the impeller. The more the impeller diameter increases, more material required to build the impeller, thus more power will be required to operate the pump. For this reason the selection of the material is critical in the design and improvement of the centrifugal pump performance.

6. Conclusion
Based on the simulation results, it is observed that the stress encountered by the impeller increases with an increase in the diameter of the impeller. Both strain and displacement also become higher as we increase the diameter of the impeller. More stress is experienced at the tip of the impeller plates and in this regard, the displacement due to the applied pressure also becomes high at the tip of the plates. The mathematical analysis was done using Affinity laws. An initial original design, which included original parameters (rated power, speed, impeller diameter and the head) was used.
The objective was to see the influence of varying impeller diameter on the performance of the centrifugal pump and to do the finite element analysis of different diameters. The original impeller diameter was 2400 mm and this was then varied to 2200 mm and 2000 mm. The results obtained showed that an impeller reduction will result in a decrease in flow rate, head, and power consumption. Therefore, in order to achieve greater flow rate and head, we need a bigger impeller, but power consumption as a result of a bigger impeller is a problem as it is way too high. This greater power consumption could be reduced by decreasing the weight of the impeller. This can be achieved by selecting lighter material for our impeller, the material could be selected whilst taking the fluid we are moving into consideration and how long it will take the impeller before it corrodes, for the various diameters of the impeller as indicated on figures 6, 7 and 8. Both strain and displacement also become higher as the diameter of the impeller is increased. More stress is experienced at the tip of the impeller plates and in this regard, the displacement due to the applied pressure also becomes high at the tip of the plates.

7. References
[1] Yassi Y, Hashemloo S. Improvement of the efficiency of the Agnew micro-hydro turbine at part loads due to installing guide vanes mechanism. Energy Convers Manag 2010;51:1970–5.
[2] Saxena P, Kumar A. Hydropower development in India. In: Proceedings of the international conference on hydraulic efficiency measurement. Roorkee, India; 2010, p. 1–6.
[3] Yassi Y. The effects of improvement of the main shaft on the operating conditions of the Agnew turbine. Energy Convers Manag 2009;50:2486–94.
[4] Matlakala E.M., Kallon D.V.V., Simelane S.P., Mashinini P.M. Impact of Designh Parameters on the Performance of Centrifugal Pumps. Procedia Manufacturing. Volume 35. 2019. Pp 197 – 306.
[5] Matlakala E.M. A Computational Model for the Efficiency of Centrifugal Pumps. Dissertation submitted to the University of Johannesburg. August 2019.
[4] Prasad V, Shukla SN, Joshi SG. Performance characteristics of pump as turbine. Indian Pumps 20