Design of a Centrifugal Pump for Efficiency Optimization

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Abstract

A centrifugal pump is a rotodynamic pump using a rotating impeller to maximize the fluid pressure. A typical company in South Africa using Centrifugal Pumps to supply water is the Rand Water and its pumping stations. They pump about 4.7 billion liters of drinking water from their booster stations per day through centrifugal pumps. The pump-set has two stages connected in series and is designed to deliver 200 megaliters per day (ML/day) at a generated head of 197 meters of water. In the course of the years, the pump's hydraulic output has dropped to a point where more energy is expended to provide the required head and flowrate. The reduction in centrifugal pump output causes increased energy consumption. The high consumption of energy is a direct result of the centrifugal pump not operating as required by the standards. In this project a new centrifugal pump for Rand Water is designed that to be more efficient in its water pumping performance as compared to existing designs. Three concepts were selected for evaluation in order to choose best two concepts. Appropriate calculations were done to obtain the desired dimensions in order to improve the performance of the pump.

Keywords Centrifugal pumps, pump performance, pump design, optimization and efficiency.

1. Introduction

Rand Water is a bulk water supplier which provides treated water to more than 12 million people in Gauteng, parts of Mpumalanga, the Free State and North West provinces of the Republic of South Africa; an area that stretches over 18 000 km^2. Rand Water's area of supply includes a distribution network of over 3 056 km of large diameter pipelines, feeding 58 strategically located service reservoirs as shown in Figure 1 (Matlakala, 2021). Its customers include metropolitan municipalities, local municipalities, mines and industries and it supplies, on average, 3 653 million liters of water to these customers daily (Rand Water, 2019). The Plant and pumping stations have about 32 Centrifugal Pumps to pump approximately 4.7 billion liters per day of potable water to their Booster stations. Centrifugal pumps (Figure 2) are a part of vibrant axisymmetric work-absorbing turbomachines. Hydrodynamic energy of flow of a fluid arises as a result of the conversion of the revolving kinetic energy when a fluid is being transported (Christian, 2006; Fernandez, et al., 2002). This rotational energy is normally from an electric motor or an engine (Fernandez, et al. 2002).

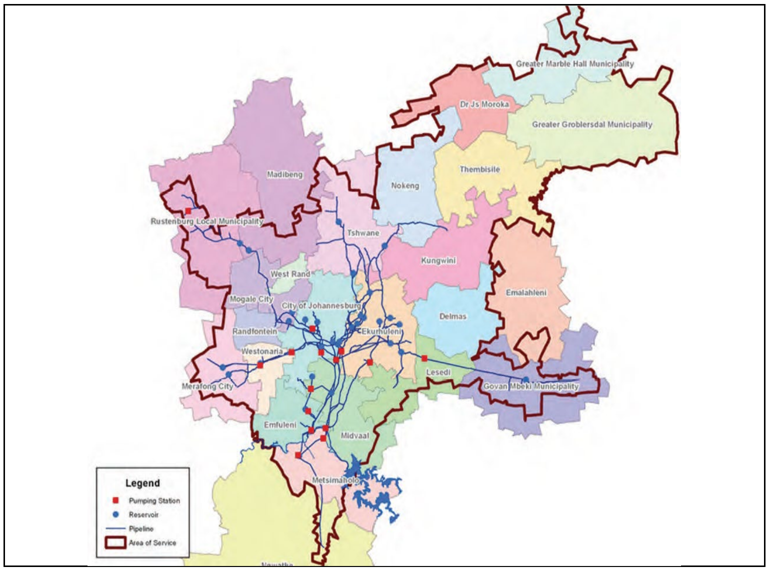

Figure 1: The Rand Water area of supply in Gauteng and the surrounding (Ncube, et al., 2011)

The fluid enters the pump at the suction side and is accelerated by the impeller to flow in the radial and outward direction into the discharge side of the pump as shown in Figure 2 (McGuire, et al. 1998). The centrifugal pumps have different torque characteristics depending on the size, specification and application (Kallon, et al 2019; Matlakala & Kallon, 2019; Matlakala et al, 2019). The amount of energy to the liquid relates to the velocity at the edge of the impeller. Their uses include, but not limited to water, sewage, petroleum and petrochemical stations (Gülich, 2010).

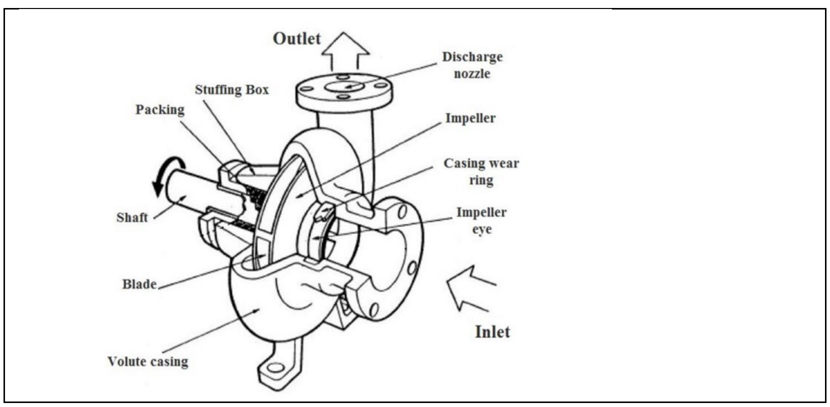

Figure 2: Centrifugal pump construction (McGuire, et al. 1998).

2. Centrifugal Pumps

A pump is a machine used to move liquids through a piping system and raise the pressure of the liquid, it uses several energy transformations to increase the pressure of a liquid (Matlakala, et al. 2019), Figure 3.

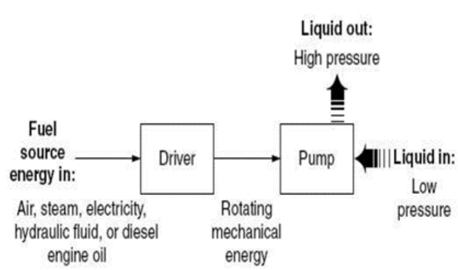

Figure 3: Basic working principle of a pump (Matlakala, et al. 2019)

2.1 Types of Pumps

There are two main pump types, namely rotodynamic and positive displacement. In a rotodynamic pump, a rotating impeller imparts energy to the fluid. Rotodynamic pumps are further divided into radial, mixed and axial-flow pumps. Centrifugal pumps (radial flow pumps) are the most common type of rotodynamic pumps, see Figure 3 (Matlakala, et al. 2019; Allan & Budris, 2014). The amount of liquid that passes through the pump is inversely proportional to the pressure at the pump outlet. In addition, the outlet flowrate of rotodynamic pumps varies nonlinearly with pressure. In a positive-displacement pump, discrete amount of fluid is trapped and forced through the pump and discharged. A gear pump is an example of a positive-displacement pump (Figure 4). This pumping uses a pulsating flow rather than a smooth flow. Its output tends to vary little with respect to the pressure at the pump outlet, because the moving displacement mechanism pushes the slug of the liquid out at constant rate (Moran, 2016).

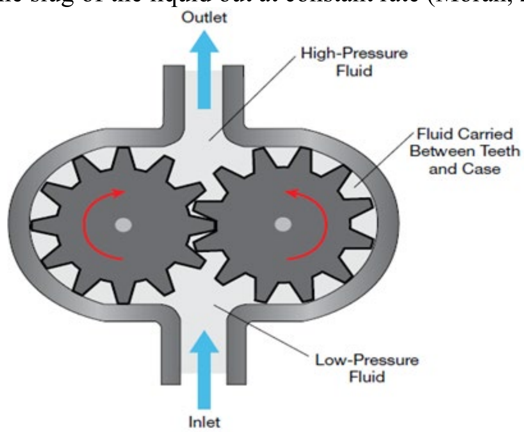

Figure 4: Typical example of gear pump (Fernadez, et al. 2002).

2.2 Components of a Centrifugal Pump

Centrifugal pumps can be regarded as hydraulic pumps. This type of pump has two main components, an impeller attached to the rotating shaft and a stationery casing enclosing the impeller. The impeller has several curved blades arranged in a regular pattern around the shaft. Centrifugal pumps can be classified on the basis of speed (low, medium and high-speed pumps), direction (radial, mixed and axial flow pumps) and head pump (low head, medium and high head pump) (Evans, 2005). Figure 5 shows the major components of a centrifugal pump.

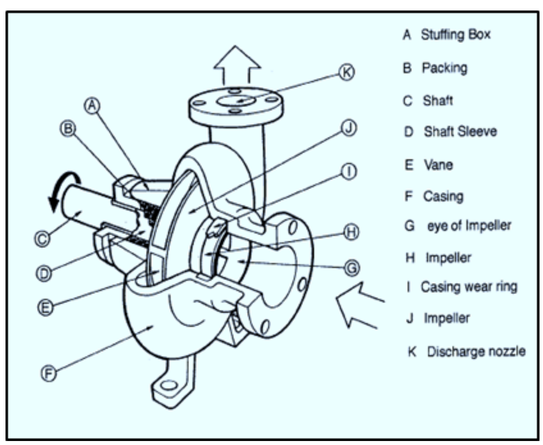

Figure 5: Centrifugal pump components (Evans, 2005).

3. Design Concept Development

3.1. Concept Generation

Matlakala et al (2019), investigated the impact of design parameters on the performance of centrifugal pumps. Various tests were performed on the Rand Water centrifugal pump installed at Zuikerbourch Rand Water Pumping Station.

These tests showed that design parameters such as the diameter of the impeller, blade angles, number of blades, suction diameter and discharge diameter can have considerable influence on the performance of the centrifugal pumps (Kallon, et al. 2019; Matlakala & Kallon, 2019; Matlakala, et al. 2019). On this basis, the design of a suitable suction diameter, discharge diameter, impeller, blade angles, and number of blades was proposed. These parameters were determined with the factors associated with efficiency losses of the Rand Water Centrifugal Pumps over the years taken into consideration. CFD analysis was carried out on the new model for potential optimization of the model (Matlakala, 2021). In this paper a new model of centrifugal pump is developed.

3.2. Specification

The specifications for the designed centrifugal pump were chosen based on what was found by Matlakala et al, (2019). The following are the specifications used for this design:

- Suction diameter (500 - 1400 mm),
- Discharge diameter (300-1000 mm),
- Type of impeller (Semi-closed or closed),
- Diameter of the impeller (1000 – 2200 mm),
- Number of blades (6 - 8),
- Efficiency (75 – 90%),
- Flowrate (2 - 3 m^3/sec).

4. Concept Development

4.1. Model First Variant: Standard Centrifugal Pumps

Standard centrifugal pump provides an economical choice for general purpose dewatering. A number of different sizes are available. These pumps are commonly used in clear water applications (agricultural, industrial, residential) as they have a limited solid handling capability of only 10% by volume. The impellers typically use a six-vane design and the volute is compact, preventing the passage of large solids (Figure 6). The rule of thumb is that the pump will only pass spherical solids that are a quarter in size of the diameter of the suction inlet. One advantage these pumps have over comparably sized trash models is their low initial cost. There are several reasons for this difference. Lower horsepower engines are utilized that are smaller in size and more fuel-efficient. The mechanical seals, since they are not subjected to harsh working conditions, can be made of less costly materials. Additionally, the casings are smaller and have fewer machined parts when combined with the smaller engines to make the pumps much lighter in weight.

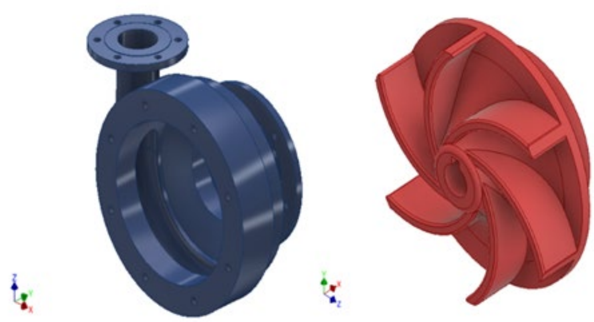

Figure 6: Standard Centrifugal Pumps.

4.2. Model Second Variant: High-Pressure Centrifugal Pumps

High-pressure centrifugal pumps are designed for use in applications requiring high-discharge pressures and low flows. Contractors may use them to wash down equipment on the job site as well as install them on water trailers. Other uses include irrigation and as emergency standby pumps for firefighting applications. The impellers used on these pumps are a closed design (Figure 7) and not open like those used on other types of centrifugal pumps. Similarly, the diffuser (Figure 7) is more compact than a regular volute in order to generate the high discharge pressures. These pumps by design are not capable of handling any types of solids or even sandy water. Silt, sand or debris would almost immediately clog the pump if allowed to enter into the casing. Additionally, the impeller and diffuser may be made of aluminium rather than wear-resistant cast iron since they are not subject to abrasive materials.

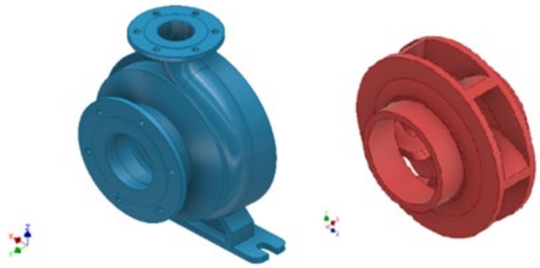

Figure 7: High-pressure Centrifugal Pumps.

4.3. Model Third Variant: Trash Centrifugal Pumps

Trash centrifugal pumps get their name from their ability to handle large amounts of debris and are the preferred choice of contractors and the rental industry. The rule of thumb is that a trash pump will generally handle spherical solids up to half of the diameter of the suction inlet. Solids (sticks, stones and debris) flow through without clogging making them ideal for the water conditions typically found on job sites. Trash pumps handle up to 25% suspended solids by volume. Trash pumps offer another benefit in that they can be quickly and easily disassembled for service or inspection. While standard pumps require special tools that are not always available the inside of a trash pump housing can be accessed with common tools. The impeller used in these pumps are open design (Figure 8) hence they are not normally used where high discharge pressure and pressure head is required.

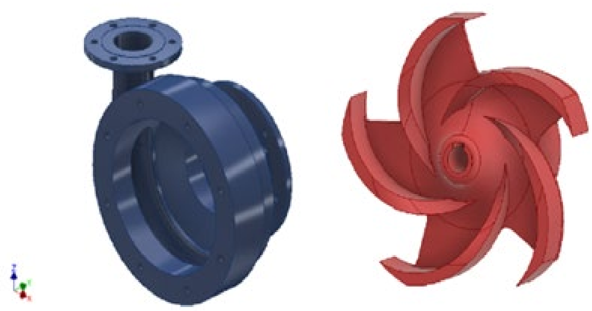

Figure 8: Trash Centrifugal Pumps.

4.4. Top Two Concepts

4.4.1. Model First Variant: Standard Centrifugal Pumps

This concept was chosen because of its operations which are more similar to the ones which are currently being used at Rand Water. One advantage these pumps have over comparably sized trash models is their low initial cost. There are several reasons for this difference. Lower horsepower engines are utilized that are smaller in size and more fuel-efficient. The mechanical seals, since they are not subjected to harsh working conditions, can be made of less costly material (Allan & Budris, 2014). Additionally, the casings are smaller and have fewer machined parts that when combined with the smaller engines make the pumps much lighter in weight (Figure 9).

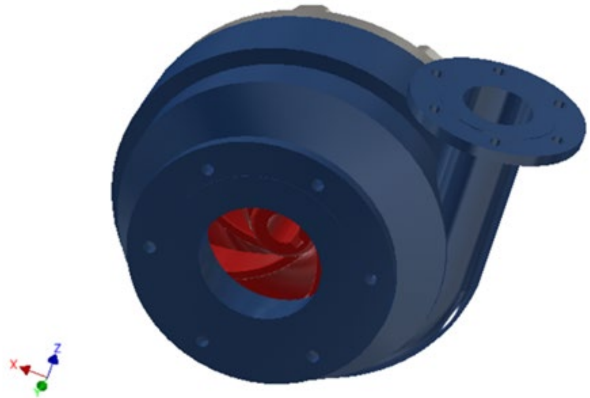

Figure 9: Standard Centrifugal Pumps.

4.4.2. Model Second Variant: High-pressure Centrifugal Pumps

High-pressure centrifugal pump was chosen because it is designed for use in applications requiring high-discharge pressures and low flows. The impellers used on these pumps are a closed design (Figure 10) and not open like those used on other types of centrifugal pumps. These are exactly the type of centrifugal pump currently being use at Rand Water. These pumps by design are not capable of handling any types of solids or even sandy water. Silt, sand or debris would almost immediately clog the pump if allowed to enter into the casing.

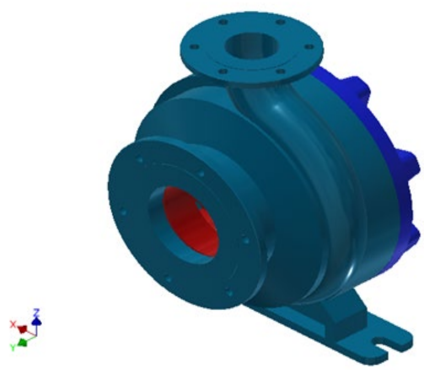

Figure 10: High-pressure Centrifugal Pumps.

5. Design of Solid Model of Centrifugal Pump

5.1. Detailed Design Description

Table 1 contains the specifications of the main design. These specifications were obtained through reasonable specifications and calculations using appropriate equations.

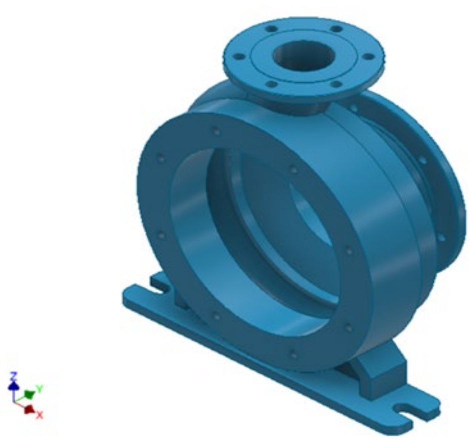

Figure 11: 3D isometric model for Casing.

Table 1. Design Specification

Parameters	Symbol	Models	Units
Atmospheric pressure	P_{atm}	101.325	kpa
Rotational Speed	N	1453	rpm
Mass flow rate	Q	2.1	m^3/sec
Net positive suction head available	NPSH (available)	10.02	m
Net positive suction head required	$(NPSH)_{required}$	9.5	m
Pump head	H	6	m
Suction pressure	P_s	58.68	kpa
Discharge pressure	P_d	90	kpa
Suction diameter	D_1	556	mm
Discharge diameter	D_2	345	mm
Efficiency	η	86	%
Impeller outside diameter	d_o	1120	mm
Impeller inner diameter/ hub diameter	d_h	672	mm
Specific Speed	N_s	534	rpm
Number of blades	Z	6	
Clearance	Δ	1.12	mm
Input Power (Shaft power)	P_s	835.90	kW
Blade outlet angle	β_1	34°	
Blade inlet angle	β_1	16°	

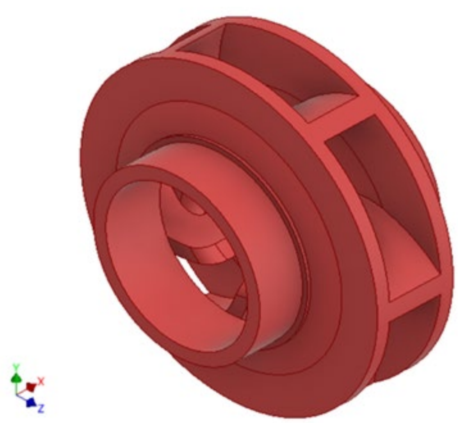

Figure 12: 3D isometric Model of Impeller.

Figure 13: 3D isometric Model of back plate.

5.2. Cost Analysis

The design of a pump is made in two stages. The first stage is the design and selection of different concepts based on desired technical properties. After this stage, economic evaluation of the chosen concept from budget quotations and firm bid quotations gathered from different suppliers takes place. In this project, Life Cycle Cost (LCC) was used to develop an economic model of the centrifugal pump. This involves its total "lifetime" cost to purchase, install, operate, maintain, and dispose of that equipment (Husain, 2008; Allan & Budris, 2014). Determining LCC involves following a methodology to identify and quantify all of the components of the LCC equation. Table 2 shows all estimated costs of the centrifugal pump.

Table 2. Estimated life cycle cost of the centrifugal pump

Cost contributor	Pump
Design, Build and Installation	R180 000
Maintenance cost per year	R80 000
Mean time between failure (years)	1.5
Mean time to repair (hour)	35
Routine maintenance cost per year	R15 000
Associated costs per failure	0
Energy price (Rs/kWh)	4
Weighted average power (kW)	836
Average operating hours per year	4000

5.3. Maintenance and Repair

There are several diagnostic methods that are very helpful in monitoring centrifugal pumps. Well-implemented programs can often recognize degradation in the incipient stage. In some cases, the root cause of the problem can be identified and mitigated before further damage is done. In others, developing problems can be monitored carefully and tended to, allowing preventive or corrective actions to be initiated in a planned environment instead of having to address failures that cause unplanned outages. The following is the Pump Troubleshooting Guide adopted from MULTIQUIP INC., (2011) which can be used to determine the problem when the pump is not functioning properly; Every six months the impeller should be checked for wear, and for clearance should be checked between the impeller face and the volute. The manufacturer's recommendations should be referred to make a proper diagnosis. The shaft seal should be checked for wear, as well as the shaft sleeve. The casing and volute passages should be cleaned (INC, 2011; Pauk & Cho, 2018).

6. Conclusion

A centrifugal pump was designed through calculations using appropriate equations to develop technical 3D drawings using Autodesk inventor. The designed centrifugal pump had an efficiency of 86% which requires an input power (Shaft power) of 835.90 kW to produce a discharge pressure and pressure head of 90 kPa and 35 m respectively. A normal and steady pressure distribution results were used to show the pump casing and the impeller are in good condition when the pump is running with the impeller at the given rotational speed. Cavitation will occur if the pressure is too low and this will damage the impeller, thus, reducing its life cycle. However, in this project to avoid cavitation the pump was designed to have a NPSH (Net Positive Suction Head) available that is greater than NPSH (Net Positive Suction Head) required. The results were taken in varying axis and cross sections for pressure distribution of centrifugal pump (Assembly of pump casing and impeller), pressure distribution of centrifugal pump impeller and velocity distribution of centrifugal pump (Assembly of pump casing and impeller). As expected, the pressure appears to be low at inlet when compared to the pressure at outlet. The pump casing and the impeller had a maximum pressure of 7.623 MPa and a minimum pressure of -2.092 MPa. The pressure at the inlet of the pump is -0.473 MPa. The outlet of the impeller has a pressure of 1.686 MPa. As expected, the velocity appears to be high at inlet when compared to the pressure at outlet. The velocity also appears to be relatively high at the rotating section of the pump, where the impeller is rotating. The simulation results of velocity distribution showed that the pump casing and the impeller has a maximum velocity of 212.6 m/s and a minimum pressure of 11.81 m/s. The velocity at the inlet of the pump is 35.44 m/s. The outlet of the pump has a pressure of 11.81 m/s.

7. References

Matlakala M.E. A Computational Model for the Efficiency of Centrifugal Pump. Masters dissertation submitted to the University of Johannesburg. 2021

Board Rand Water, "About Us," 24 March 2019. [Online]. Available:
http://www.randwater.coza/AboutUs/Pages/CoreBussiness.aspx.

E. J. Ncube, K. Voyi and d. H. Preez, "Implementing a protocol for selection and prioritisation of organic contaminants in the drinking water value chain:," *Water SA,* vol. 38, no. 4, 2011.

K. Fernandez, B. Pyzdrowski, D. Schiller and M. Smith, Understand the Basics of centrifugal pump operation, Fluids/Solids Handling, 2002.

I. McGuire, J. Karassik and Terry, Centrifugal Pump, New York: International Thomson Publishing Asia, 1998.

Kallon D.V.V, Matlakala M.E. Effect of Discharge Diameter on Centrifugal Pump Performance. *SAIEE*. 2019. Pp. 721-730.

Matlakala M.E, Kallon D.V.V. Influence of Impeller Blade Count on The Performance Centrifugal Pumps. *SAIEE.* 2019. Pp. 603-612.

Matlakala M.E, Kallon D.V.V, Simelane S.P, Mashinini P.M, "Effect of Design Parameters on Performance of Centrifugal Pumps," in *Proceedings of the Second International Conference on Sustainable Materials Processing and Manufacturing*, Sun City, 2019.

S. Moran, "Pump Sizing: Bridging the Gap Between Theory and Practice," American Institute of Chemica Engineers (ALChE), 2016. [Online]. Available: https://www.aiche.org/cep. [Accessed 22 June 2019].

J. Evans, "Centrifugal Pump Efficiency – What, How, Why & When?.," Pump ED 101., 2005. [Online]. Available: http://www.pumped101.com. [Accessed 4 June 2019].

Kallon D.V.V, Matlakala M.E, Nkoana K.F, Mafu B.D, Mkhwanazi S.B. Effect of Suction Diameter Variations on Performance of Centrifugal Pump. *OIC.* 2019. Pp. 170 - 173.

Matlakala M.E, Kallon D.V.V, Mogapi K.F, Mabelane I.M, Makgopa D.M. Influence of Impeller Diameter on Performance of Centrifugal Pumps. *IOP Conference Series: Meterials Scicne and Engineering.* 655, (1). 2019. Pp. 009 – 012.

[T. Baumeister, Fans, New York: McGraw Hills, 1935.

S. Moran, "Pump Sizing: Bridging the Gap Between Theory and Practice," American Institute of Chemica Engineers (ALChE), 2016. [Online]. Available: https://www.aiche.org/cep. [Accessed 22 June 2019].

Z. E. A. Husain, Basic fluid mechanics and hydraulic machines, Hyderadad: BS Publications, 2008.

R. Allan and P. E. Budris, "The Impact of Component Material Selection on Pump Reliability," Water world," 2014.

[Online]. Available: https://www.waterworld.com/municipal/technologies/pumps/article/16192827/the-impact-of-component-material-selection-on-pump-reliability. [Accessed 2019 June 2019].

M. INC, "Pump Selection Handbook," MULTIQUIP INC, 2011. [Online]. Available: https://www.multiquip.com. [Accessed 22 July 2019].

P. Pauk and C. K. Cho, "Design Calculation of Impeller for Axial Flow Pump," *International Journal of Scientific and* Research *Publications,* vol. 8, no. 8, p. 8104, 2018.

8. Biographies

Mr Arnold Ripfumelo Matiane is a South African holder of a Bachelor of Engineering Technology (BEngTech) degree in Mechanical Engineering, from the University of Johannesburg. This degree equipped him with skills to apply scientific and engineering theories to technical areas such as product design and development, production, manufacturing, power and control of machinery, materials, quality control and cost analysis through projects, labs work and assignments. He is also a holder of Master of Science degree in Geology from University of Johannesburg and multidisciplinary Bachelor of Earth Sciences degree, from the University of Venda. During his Masters studies, he published one paper with International Journal of Coal Geology and he also published one paper with Journal of African Earth Sciences during his Honours studies. Both papers were about the Coal quality from different coal fields in South Africa.

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.

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 five (5) papers and was also selected as a reviewer of paper in two (2) 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 Candidate Technologist with ECSA. Mr Matlakala's primary research areas are System Analysis and Dynamics, Optimization, Computational Fluid Dynamics, Finate Element Analysis and Water Research.