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IMPROVING CENTRIFUGAL PUMP SYSTEM EFFICIENCY AND RELIABILITY THROUGH BETTER DESIGN AND OPERATING PRACTICES

by

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DATE: OCTOBER 2015
DECLARATION

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ABSTRACT

IMPROVING CENTRIFUGAL PUMP SYSTEM EFFICIENCY AND RELIABILITY THROUGH BETTER DESIGN AND OPERATING PRACTICES

Significant opportunities exist to reduce the energy consumption of pumped systems through smart design, retrofitting and operating practices (Hydraulic Institute et al., 2004; European Commission, 2001). Besides higher electricity costs and CO2 emissions, inefficient pumps have lower reliability and higher maintenance costs.

Pump efficiency is directly related to the electrical energy consumption, pump reliability and maintenance costs.

The aim of the research is to review design and operating practices currently used in industry to monitor, control, maintain and operate centrifugal pumps. The objectives of the research are as follows:

1. Determine the factors that contribute to pump reliability and mechanical pump efficiency
2. Ascertain to what extent pumps are monitored and controlled in industry
3. Determine what operation and maintenance strategies are used in industry
4. Establish if energy audits are being conducted

A qualitative research design was utilized. The research can be viewed as exploratory.

The aims of the research are achieved through a literature review and interviews, guided by a questionnaire, with industry experts.

In order to increase the reliability of the analysis all data was uploaded into a qualitative data analysis package, ‘Atlas.ti’. This software tracks the progress of the data analysis more carefully than data analysis by hand. The data from the interviews was analysed using thematic analysis.

The interview texts were examined for emerging themes. The analysis followed a data-driven approach, which is appropriate to exploratory case study research where prior examples of themes in the literature are absent. A reliable method described by (Boyatzis, 1998) was used.

A pump system first has to be reviewed and understood before corrective action can be taken. An energy audit is a tool that can be used to review systems and quantify potential savings in a system. Instrumentation must be installed to conduct the audit.

The operating point (flow, head) of a pump determines its efficiency and reliability.

Methods to improve centrifugal pump system performance through design:

1. Change the physical system a pump operates in
2. Change the diameter of the impeller or change the pump itself
3. Change the running speed of the pump
Methods to improve centrifugal pump systems through operating practices:

1. Correct maintenance procedures
2. Correct pump installation and line up
3. Pump monitoring and corrective action taken when a pump operates outside its best efficiency zone

Two of the four interview participants expressed negative views towards reviewing pump systems for energy savings. The first participant did not feel that pumps contributed that much to the overall power consumed by the plant. The second did not have confidence in the audit process.

There is insufficient monitoring (instrumentation) on pump systems to determine the operating point of a pump.

Instrumentation can support operations. The differential pressure indicates where the pump is operating on its curve. If operators are trained on how to read the gauges and manipulate the system to keep the pump operating near its BEP, pump reliability and efficiency would be improved.

Instrumentation can support a maintenance plan. The gradual decrease in pressure indicates that the impeller clearance has widened. The impeller clearance can be adjusted, or the wear ring replaced.

The research provides feasible methods to improve the performance of inefficient centrifugal pump systems and is relevant to all centrifugal pumps in industry. These methods are established through literature reviewed. Research participants provided valuable insight into operating practices currently used in industry.
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GENERAL DEFINITIONS

Best Efficiency Point (BEP): the point on the pump curve where the flow rate at a specific pressure is at its highest possible mechanical efficiency. This is also known as the Best Operating Point.

Centrifugal Pump: used to transport fluids. A centrifugal pump converts energy from a motor or drive, to flow and pressure in a fluid by accelerating the fluid in a revolving device - an impeller.

Cavitation: Cavitation is the formation and subsequent collapse or implosion of vapour bubbles in the pump.

Efficiency: is the relation between the supplied power and the utilised power or output divided by input.

Energy Audit: “systematic analysis of energy use and energy consumption within a defined energy audit scope in order to identify, quantify and report on the opportunities for improved energy performance” SANS 50002:2014.

Life Cycle Cost: All costs relating to a product that occur over its life span.

Overheads: All expenses incurred by manufacturing that are not direct labour or direct materials. Overheads associated with pump operation are electricity or fuel, maintenance, spare parts, lubricants etc.

Procedure: Specified, documented way to carry out an activity or process.

Production Critical System: A system where failure or disruption would result in loss of production.

Pump Curve: The pump curve depicts the flow rate of fluid (Q), the pressure or head (H), efficiency (%) and absorbed power (kW) of a pump.

Pump System: A combination of pump, connected piping, valves, in line components, number of users and other hardware through which flow occurs.

Reliability: The duration or probability of failure-free operation.

System losses: Pressure drop across a system.
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<td>Best Efficiency Point (%)</td>
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<td>TDH</td>
<td>Total Dynamic Head</td>
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<td>CMMS</td>
<td>Computerized Maintenance Management System</td>
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<td>LCC</td>
<td>Life Cycle Cost</td>
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<td>SG</td>
<td>Specific Gravity</td>
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<td>Power Factor</td>
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<td>revolutions per minute</td>
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<td>TDH</td>
<td>Total Dynamic Head</td>
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<tr>
<td>VSD</td>
<td>Variable Speed Drive</td>
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SYMBOLS

A: Amps

A: Cross sectional area of a pipe (m²)

D: Diameter (m)

g: Acceleration due to gravity (m/s²)

H: Head (m)

Hₛ: Static Head (m)

Hᵢ: Friction Head (m)

Hₚ: Pressure Head (m)

Hᵥ: Velocity Head (m)

h: Static height (m)

p: Density (kg/m³)

P: Pressure (kPa)

Q: Flow Rate (m³/h)

v: Fluid Velocity (m/s)

V: Volume (m³)

V: Volts (V)
CHAPTER ONE: INTRODUCTION AND SCOPE OF RESEARCH

1.1 Chapter Overview
Chapter 1 presents the problem of pump performance, efficiency and reliability in context. The problem statement and research questions and objectives are established. The reasons for selecting the particular problem and purpose of the study are also addressed.

1.2 Rationale of the Research
Industry is experiencing rising energy costs and increasing green taxation. (Grundfos, 2013; Whalen, 2014). Reducing energy costs reduces CO₂ emissions (Grundfos, 2013; Whalen, 2014). The energy, or electrical power, required to move a volume of fluid from one point to another is directly dependant on the pump mechanical efficiency.

The potential for energy savings in pump systems is becoming widely recognised and has generated a market for energy auditing products and services (Ahonen et al., 2012).

The European Commission recognised that the largest energy savings are to be made through the better design and control of pump systems.

Centrifugal pumps are used in almost every industry. Pumps move product from one process to another. Pumps are essential, if a pump stops, production may stop.

Studies have shown that pumps are on average 15% to 40% inefficient (Robertson et al., 2008). Besides higher electricity costs, inefficient pumps have lower reliability and higher maintenance costs. These costs can be significantly reduced.

Pump life cycle costs and operational costs can be reduced. The operational cost of a centrifugal pump is in the region of 65%-85% of the total Life Cycle Cost (European Commission 2001)

Every centrifugal pump has a Best Efficiency Point (BEP), also known as the Best Operating Point. This is the point where the pump is most efficient and has the highest reliability. The benefits of operating pumps efficiently are:

- Reduced power consumption
- Improved pump hydraulic performance (Flow and Pressure)
- Lower maintenance costs, longer life expectancy of seals, bearings, impellers and shafts
- Reduced production down time by improving pump reliability

Centrifugal pumps can operate efficiently with few reliability issues. Pumps that are correctly selected, operated and maintained should be perform well and have few reliability issues (Bachus et al., 2003).

1.3 Background
The energy management of pump systems is currently very topical and numerous articles have been written on this topic in the last few years. The US Department of Energy commissioned A Guide to Achieving Operational Efficiency published in 2010 that covers
pump operations. The literature available on this topic is mainly in the form of articles and conference proceedings.

The researcher could only find one relevant quantitative study. A study done in 1996, by the Finnish Technical Research Centre, of close to 1,700 pumps at 20 process plants across multiple industries, found that the average pumping efficiency was below 40%, and more than 10% of pumps were running below 10% efficiency (Kernan, 2009).

Various approaches have been suggested on pump operation management. Of particular interest is Feldman’s article, *Aspects of Energy Efficiency in Water Supply Systems*.

According to Feldman (2009) the main improvements in energy efficiency can be obtained with:

- pump stations design improvement
- systems design improvement
- variable speed drives (VSD) installation
- efficient operation of pumps

In South Africa there are time of day power tariffs, and therefore the potential to change operational strategies to suit the tariff system. Feldman found that major savings would be achieved by shifting the pumps operation from the peak period to the mid and off peak period.

The European Commission (2001) recommended that regardless of operating policies implemented, efforts should continue to be made to raise the general knowledge about pumps and pumping systems.

1.4 Research Aim and Objective

The aim of the research is to review design and operating practices currently used in industry to monitor, control, maintain and operate centrifugal pumps. The objectives of the research are as follows:

1. Determine the factors that contribute to pump reliability and mechanical pump efficiency
2. Ascertain to what extent pumps are monitored and controlled in industry
3. Determine what operation and maintenance strategies are used in industry
4. Establish if energy audits are being conducted

1.5 Scope

Pump selection, operation and maintenance is a broad subject, there are handbooks and literature available on these subjects. This dissertation is not intended to become a handbook for pump selection or operations management.

The literature does not cover how to correctly rebuild and repair pumps.

This paper does not take into account electrical efficiency or methods of improving electrical efficiency such as high performance motors.
The initial purchase price has nothing to do with correct design and operating practices. Many recent studies have focused only on the initial purchase price such as Parbhoo (2012) and excluded life cycle costs. The initial purchase price of the pump is outside the scope of this dissertation.

Pump scheduling is not included in the scope. Pump scheduling is a method of pump energy management. Pump scheduling involves determining the ideal flow rate of a particular pump in a system to suit production requirements. It does not specify how to get the best possible mechanical efficiency out of the pump itself or how to operate the pump at the proposed ideal flow rate.

The scope is limited to key aspects that directly affect mechanical pump reliability and efficiency. It covers the corrective actions that can be taken, to an existing centrifugal pump installation, to improve pump performance and mechanical pump efficiency.

1.6 Research Design and Strategy
A qualitative research design was selected as in-depth understanding of the topic is required. The research looks into the experiences of industry experts with at least 5 years relevant experience.

The research can be viewed as an exploratory. An exploratory design is conducted when there are few or no earlier studies to refer to or rely upon to predict an outcome (Anastas, 1999). Exploratory research approach is useful to gain background information on a particular topic.

Research into the operating practices of centrifugal pump systems and the effect on reliability and efficiency has not been researched in this particular manner before.

Insufficient industry experts with relevant experience could be located to do quantitative research. To select participants without strict criteria would compromise the quality of the research.

The aims of the research are achieved through a literature review and interviews, guided by a questionnaire, with industry experts.

The disadvantage of exploratory research is definitive conclusions about the research findings cannot be made. Findings provide insight but not definitive conclusions (Lynn University, 2015).

1.7 Data Analysis
In order to increase the reliability of the analysis all data was uploaded into a qualitative data analysis package, ‘Atlas.ti’. This software tracks the progress of the data analysis more carefully than data analysis by hand. The data from the interviews was analysed using thematic analysis.

The interview texts were examined for emerging themes. The analysis followed a data-driven approach, which is appropriate to exploratory case study research where prior examples of themes in the literature are absent. A reliable method described by (Boyatzis, 1998) was used. Boyatzis describes a general method for finding initial patterns within the data, called codes, and sorting these codes into larger organising patterns, called themes.
CHAPTER TWO: LITERATURE REVIEW

2.1 Chapter Overview
The focus of the literature review is pump selection, operating practices, pump efficiency and reliability. The pump curve is discussed, as well as how pump performance, efficiency and reliability relate to the pump curve.

Various types of pump monitoring and controlling methods are presented. These methods are used to determine where a pump is operating on its curve.

Different maintenance strategies are discussed.

The chapter concludes with a concise summary of the literature reviewed.

2.2 Reasons Centrifugal Pumps are Inefficient in Industry
Many pumps are poorly operated. Many pumps are run at full speed whilst the flow is controlled through the opening and closing of valves. Whilst this method does control the flow to some extent, it is a complete waste of energy. To make an analogy this is like flooring the accelerator pedal of a car and then controlling the speed of the car with the other foot on the brakes (Bachus et al., 2003).

Commonly capital cost is considered the primary objective to pump selection and little consideration is given to the long-term operation and maintenance costs. Often new production facilities are built on a budget that must be met. The objective is to get the operation up and running, producing products and making money. The thought process is that once profits are being made they can be fed back into the business to improve facilities as required. There is no fault in this method; however pumps that are inefficient or have high maintenance costs should be reviewed.

A pump may be the correct pump for the application at the time of installation; however the system (pipe, valves, in line components and number of users) often changes over the lifespan of the pump. A change that would alter the performance of the pump is a change to the resistance or energy of the system. If there is more resistance the pump has to generate additional pressure to overcome the additional resistance. Changes to the system resistance are a result of the system itself changing over time. There may be scale that builds up on the inside of the pipes that change the system resistance. Valves may be partially closed in error, throttling the system and increasing the system resistance. There are numerous reasons for the system (pipe, valves, in line components and number of users) changing over the lifespan of the pump. Changes in plant operating conditions (expansions, shutdowns, etc.) can cause pumps that were previously well applied to operate at reduced efficiency (Sullivan et al., 2010).

In many pumped systems there is more than one flow rate that a pump must deliver. Flow rates change with demand for products. Many users select a pump that can meet the highest flow rate demand. Most existent pump systems are oversized and many of them by more than 20% (Hydraulic Institute et al., 2004). This can result in the pump operating at points where it is completely inefficient and energy is wasted over the lifespan of the pump (Whalen, 2014).
Pumps systems are dynamic. This means that the pump does not operate at a static point on its pump curve. As levels in suction and discharge tanks change so the pump operating point changes. If the operating point changes so does the pump efficiency. This means that a pump may be efficient at one duty point but become inefficient as the system changes.

The efficiency of a pump will deteriorate over time. As a pump performs its duty fluid passes through the pump, erosion and abrasive action cause the close tolerance parts to wear. As these parts wear, the pump will lose its efficiency (Bachus et al., 2003). The efficiency of an older pump will not match that of the pump when it was new. (European Commission, 2001; Bachus et al., 2003). “Without maintenance, a centrifugal cold water pump can eventually lose about 10% to 15% of its original efficiency" (European Commission, 2001).

Plant maintenance often focuses on ‘just changing parts’ (also known as reactive maintenance) and in the best cases performing preventative maintenance. (Bachus et al, 2003). If a pump is not operating near its Best Efficiency Point it will be inefficient and unreliable. The point at which a pump operates can be determined. It is possible to monitor and control pumps to achieve the best possible efficiency and reliability. If a pump is constantly in the workshop needing repairs then corrective action should be taken. “Just changing parts” is a waste of resources.

2.3 Management’s Responsibly to Improve Pump Efficiency
ISO 50001:2011 states that it is management’s responsibility define, establish and maintain an energy policy. ISO 50001:2011 is an international standard that is used to enable organisations to establish the systems and processes necessary to improve energy performance (including energy efficiency), use and energy consumption. This standard is applicable to all types and sizes of organisations.

The cost of operations or production has a direct link to a company’s profitability. A method to reduce operational costs is to decrease overheads through improving efficiency. It is therefore in management’s best interest to be aware of the various methods or strategies available to improve operational efficiency. One such method is to improve the efficiency of pumps, currently in operation, thereby decreasing overheads.

Life Cycle Costs take into account the running costs as well as the initial investment cost of an asset. The energy consumption of an asset represents a large portion of the life cycle cost (Ferreira et al., 2011; Whalen, 2014).

2.4 Pump Life Cycle Costs
There is a direct link between pump performance, reliability, efficiency, operation and life cycle costs. (European Commission, 2001; Bachus et al., 2003; Grundfos, 2013).
According to the US Department of Energy the life cycle cost of a pump is broken down as follows (Whalen, 2014):

- 10% initial purchase costs
- 7% for installation costs
- 5% environmental costs
- 3% for costs associated with the pump when not in use
- 10% operating costs
- 23% maintenance costs
- 40% for energy costs

\[\text{Figure 1: Life Cycle Costs of Pump (Whalen, 2014)}\]

Based on the figures from the US Department of Energy, 90% of the total life cycle cost (LCC) is accrued after the pump is purchased with a large portion of the life cycle cost (63%) associated with maintenance and energy costs.

According to the European Commission the energy consumption accounts for 85% of the cost of ownership.

\[\text{Figure 2: Life Cycle Costs of Ownership of a pump (European Commission 2001)}\]
LCC is dependent on the pump application. Although there are discrepancies in the LCC breakdown between studies, all studies agree on the fact that most of the LCC is attributed to energy and maintenance costs.

The maintenance and energy costs are directly related to how a pump is operated. In other words the life cycle cost of a pump can be reduced and operational efficiency improved. Refer to Section 2.8 for the relation between Pump Reliability, Performance and Mechanical Pump Efficiency.

2.5 Types of Pumps Available
There are various types of pumps available: see Figure 3. Pump selection is based on application, liquid to be pumped, head and flow requirements.

![Figure 3: Types of Pumps Available (Mobley, 2001)](image)

Centrifugal pumps account for the majority of pumps used in industry (European Commission, 2001) Centrifugal pumps are widely used for water, slurry and process pumping. This mini-dissertation focuses only on centrifugal pumps.

2.6 How a Centrifugal Pump Operates
Pumps are used to move fluids from one place to another through pipes. A pump converts mechanical energy into pressure. Fluid enters the pump suction and leaves at the pump discharge. The shaft is powered by a motor or power source. The shaft, which is attached to the impeller, spins resulting in the impeller rotating. The rotating impeller imparts energy onto a fluid as it passed from the impeller eye toward the outside diameter of the impeller. As the fluid accelerates, a zone of low pressure is created in the eye of the impeller (The Bernoulli Principle, as velocity goes up, pressure goes down). Pumps are used to generate flow (m$^3$/h) at a specific head (m) or pressure (kPa).
2.7 Pump Selection

The pump selection affects reliability and efficiency. The correct pump must be selected for the system. This section covers some of the design considerations when selecting a pump. It covers basic theory and calculations.

General Design Considerations, pump selection is based on the following factors (Metso, 2009):

1. Flow Rate Required
2. Fluid to be Pumped
3. Available Pump Head (pressure required)
4. Economic Evaluation
5. Materials (Wear resistance, corrosion Resistance)

Each of these factors are discussed in the subsequent sections.

2.7.1 Flow Rate

The flow rate (m³/h) is usually determined by the pump application or process. A specific flow is required to make a specific process work or keep a process in balance. This is a variable that can be measured on a flow meter or determined from the pump curve. If a pump does not deliver the required flow or pressure to the process then corrective action is required.

The flow rate is not necessarily a fixed value. The flow requirement may increase or decrease over the life of the pump. For a batch process, where a specific volume is required,
it may be acceptable to increase the flow rate and have the pump run for a shorter period of time, or likewise decrease flow rate and run the pump for a longer period of time.

In South Africa there are time of day power tariffs, and therefore the potential to change operational strategies to suit the tariff system. Feldman (2009) found that major savings would be achieved by shifting the pumps operation from the peak period to the mid and off peak period. This means changing the flow rate to suit the tariff system.

### 2.7.2 Fluid to be pumped

The properties of a fluid affect the pump selection.

Liquids and gasses are referred to as fluids as they can flow and can take the shape of a container into which they are poured. An important property of a fluid to be pumped is its density $\rho \text{ [kg/m}^3\text{]}$.

Slurry is a mixture of solid matter or particles with a liquid carrier (Metso, 2009). These particles can be large or small. The solids concentration and particle size should be taken into consideration when selecting a pump.

Specific gravity is the comparison of the density of a liquid with the density of water. Specific gravity or SG, a dimensionless number is obtained by dividing the density of the material by the density of water.

$$SG = \frac{\text{Density Liquid}}{\text{Density water}}$$  \hfill (2.1)

The specific gravity affects the energy required to transport the fluid. (da Cunha et al., 2008). The SG therefore affects the power requirements.

Over the lifespan of the pump the fluid properties, such as the density and SG, may change as the process changes.

### 2.7.3 Pump Head

The Pump head can be measured in either meters (m) of fluid or in pressure (kPa).

The conversion between Pressure (kPa) and meters or head is as per Equation 2.2 below:

$$h \text{ [m]} = \frac{P \text{[kPa]}}{1000 \times \rho \times g}$$  \hfill (2.2)

The conversion between pressure units for water at 20°C, density 997 kg/m$^3$:

- 100kPa = 1 bar = 10.2m

There are software packages available that can calculate the TDH of a pump. AFT Fathom is an engineering software package. Some pump companies, such as Curo Pumps, provide free software packages, to assist in TDH calculations.

The Total Dynamic Head (TDH) is determined by the system in which the pump will be installed (Ivor da Cunha et al., 2008)

The TDH is made up of the following components:
1. The elevation differential or static head \( (H_s) \)
2. The pressure differential or pressure head \( (H_p) \)
3. The velocity Head \( (H_v) \)
4. The pipe friction losses or friction head \( (H_f) \)

\[
TDH = H_s + H_p + H_v + H_f
\]

The pressure generated by the pump must be sufficient to overcome the friction and pressure losses in the system.

Each component of the TDH is reviewed in the subsequent sections.

2.7.3.1 Static Head \( (H_s) \)

The static head is the change in elevation. For example, if the pump is pumping from ground level, to a tank that is 5m higher than the pump, then the static head is 5m. The static head is a characteristic of the specific system and it is generally not practical to reduce the static head of an existing system.

2.7.3.2 Pressure Head \( (H_p) \)

The pressure head is the pressure change across the system. If both the suction vessel / tank and the discharge vessel / tank are at the same pressure (whether high pressure, atmospheric pressure or vacuum) then there is no pressure differential. If a pump pumps from an open tank at atmospheric pressure (101 kPa) to a vessel at 300kPa then the differential pressure across the system is 199 kPa. The pump must generate additional energy, called pressure head \( (H_p) \) to overcome the pressure differential.

2.7.3.3 Velocity Head \( (H_v) \)

The velocity head is the energy required to create and maintain fluid velocity in the pipes. The velocity head is dependent on the fluid velocity.

\[
H_v = \frac{v^2}{2g}
\]

2.7.3.4 Pipe Friction Head \( (H_f) \)

The friction losses that the pump has to overcome are caused by the friction between the fluid and the internal surface of the pipes and fittings. There are various methods for estimating the friction losses. The Darcy Weisbach equation or Hazen-Williams equation can be used to estimate the pipe friction losses (WEIR, 2007).

The Darcy Weisbach \( (Equation \ 2.5) \) can be used to estimate the pipe friction losses:

\[
H_f = \frac{k \times L \times v^2}{2gD}
\]

Where:

- \( k \) is a dimensionless coefficient called the Darcy Friction Factor. The Darcy friction factor can be determined by solving the Colebrook equation or from a Moody diagram.
- \( L \) is the actual pipe length (m)
As can be seen from *Equation 2.5* the friction head is dependent on the velocity of the fluid in the pipes. The larger the inside diameter of the pipe, the lower velocity will be, the lower the friction losses will be. If the velocity and pipe size is known, the flow rate can be calculated from *Equation 2.6* below.

\[
Q = vA
\]

*Equation 2.6*

Settling slurries have a minimum flow velocity required to keep the particles in suspension. The minimum velocity of settling slurries is calculated using *Durand's Equation*.

As power consumption depends on head or pressure, see *Section 2.7*, the lower the TDH the lower the operational cost. Friction head losses contribute to the TDH and can be reduced by choosing larger diameter pipes or reducing the number of fittings. (Hydraulic Institute et al., 2004).

### 2.7.4 Materials

The pump materials are selected based on application, pressure rating, chemical compatibility etc. Efficiency of the pump cannot be greatly improved through changing pump materials. However, if incorrect materials are selected the system could have reliability problems (Weir, 2007).

Pump Materials are application specific and considered to be outside of the scope of this dissertation.

### 2.8 The Centrifugal Pump Curve

The pump curve depicts the flow rate of fluid (Q), the pressure or head (H), efficiency (%) and absorbed power (kW) of a pump.

Pumps systems are dynamic. This means that the pump does not operate at a static point on its pump curve. As levels in suction and discharge tanks change so the pump operating point changes. If the operating point changes so does the pump efficiency. This means that a pump may be efficient at one duty point but become inefficient as the system changes.

The pump curve can be broken down into three curves:

1. The Head (H) – Flow (Q) Curve
2. The Efficiency curve
3. The Pumps Net positive Suction Head Required (NPSHr)

These curves are shown in *Figure 4*. The pump curve has a descending profile. This means that for an increase in flow, the corresponding pressure or head decreases. The shape of a centrifugal pump curve is always a descending curve. The shape of the curve is different between pumps, some curves are steeper and some curves flatter than others.

Pump efficiency can be determined from the efficiency curve. Efficiency is defined as output divided by input, refer *Section 2.7*.

The point on the pump curve where efficiency is the highest is known as the Best Efficiency Point (BEP). The BEP occurs when the angle of the fluid entering the eye of the impeller is parallel to the impeller blade (Dabbs et al., 2012; Vogel, 2013).
Most pump manufactures provide pump curves for the pumps sold in their range.

### 2.9 Mechanical Pump Efficiency

The mechanical pump efficiency is a function of the pump itself, it determines how much energy or electricity is required to operate the pump.

The efficiency can be read of the pump curve or calculated mathematically (Vogel, 2013).

The pump efficiency is the relationship between the power that the pump produces (energy of the fluid that is being pumped) to the input power (power absorbed by the pump motor)

\[
Pump\ efficiency = \frac{Output\ Power\ [kW]}{Input\ Power\ [kW]} \times 100\% \quad \text{2.7}
\]

The output kW is a function of the pump head (h) the flow (Q) and the specific gravity of the fluid being pumped (SG)

\[
Output\ Power\ [kW] = \frac{\rho [kg/m^3] \times g [m/s^2] \times Q [m^3/s] \times H [m]}{1000} \quad \text{2.8}
\]

The input power is the power that the pump requires from the motor to operate.

\[
Input\ Power\ [kW] = \frac{\sqrt{3} \times V \times A \times PF \times Motor\ Efficiency}{1000} \quad \text{2.9}
\]

The physical system (pipes, valves, friction losses, static heights etc.) dictate where on the pump curve a pump will operate. The power requirements and mechanical pump efficiency is dependent on the pump operating point.
2.10 Relation between Pump Reliability, Performance and Mechanical Pump Efficiency

As discussed Section 2.6 there is a Best Operating Point or Best Efficiency Point (BEP) on the centrifugal pump curve. Operation of the pump should be as close to this point as possible for best possible pump efficiency, reliability and pump life (Vogel, 2013). The effect on pump life and reliability is more severe the further away from the BEP the pump operates (Barringer, 2003).

The BEP is a key factor to assess whether a pump is being operated properly (Kernan, 2009). Few pumps operate at their exact BEP all of the time. This is because of process variables and energy in the system changing. A correctly sized pump should operate near its BEP in a range of 10% left to 5% right of BEP.

*Figure 4* shows that operating a pump at:

- BEP 100% life is expected
- 10% left to 5% right of BEP 92% life is expected
- 20% left to 10% right of BEP 53% life is expected
- 30% left to 15% right of BEP 10% life is expected

![Pump Curve Sensitivity For Pump Reliability](image)

*Figure 4: Pump Curve Sensitivity for Pump Reliability (Barringer, 2003)*

Operating to the left of BEP occurs when the discharge flow is restricted; at a flow lower than the pump was designed to maintain, resulting in fluid recirculating within the pump (Kernan, 2009). For flows lower than BEP flow:

- Higher vibration
- Lower pump efficiency
- Recirculation cavitation
- Side forces on impeller that stress the pump shaft
- High forces on mechanical seal or gland packing
Operating to the right of BEP means that the flow rate is higher than the pump was designed to maintain (Kernan, 2009). For flows higher than BEP flow:

- Higher vibration
- Lower pump efficiency
- Overload on the motor
- Classic cavitation
- Side forces on the impeller that stress the pump shaft
- High forces on the mechanical seal or gland packing

The types of failure that are typical of operating the pump too far away from its BEP, whether too far to the left or too far to the right of BEP, are:

- Bearing failure
- Mechanical seal failure
- Holes through the impeller vanes as a result of cavitation
- Fatigue breakage of the pump shaft

The life expectancy of a pump is difficult to quantify as it is directly related to the fluid that is being pumped, the pump design and the materials selected. In other words a clear water pump should last longer than a pump that pumps abrasive slurry. The European Commission suggested as an estimate lifetime of 20 years for centrifugal pump sets in clear water application that are correctly operated and maintained.

Many pumps do not operate near their BEP. A study done in 1996, by the Finnish Technical Research Centre, of close to 1,700 pumps at 20 process plants across multiple industries, found that the average pumping efficiency was below 40%, and more than 10% of pumps were running below 10% efficiency (Kernan, 2009).

If a pump operates at or below 30% of its BEP then the life expectancy of the pump is reduced to 10% of total pump life. In other words if the life expectancy of a water pump is in the region of 20 years (European Commission, 2001), but the pump is operated at or below 30% of its BEP, then the pump should only last 2 years before catastrophic failure.

### 2.11 Methods to Control Flow Rate

It may be beneficial to change the flow rate of a pump. If demand of a product changes, then operations could be sped up or slowed down to meet the product demand. In South Africa there are time of day power tariffs, and therefore the potential to change operational strategies to suit the tariff system.

Besides changing the pump (or impeller), there are three ways to control the flow rate of a pump:

- The first is by increasing the friction of the system (one common method is partially closing a valve or "throttling" the system). By “throttling valves” the system head increases and power consumed is not reduced. “Throttling valves” increases pressure in the pump casing which increases maintenance costs.
• The second is to have a bypass line which diverts some of the flow back to the source. This allows the flow through the pump to remain constant, if sized and utilized correctly, a bypass line allows the pump to run near its BEP whilst modulating the flow downstream.

• The third is to control the speed of the pump. Controlling the speed of the pump is the most efficient way to control the flow because when the speed is reduced the power consumption is reduced (da Cunha et al., 2008).

2.9.1 Pump Motors to Control Flow Rate

Pump performance is directly linked to the pump speed. A change in speed would bring about a corresponding change in the pressure (head), flow, and power requirements (kW) of the pump.

Most industrial pumps are directly coupled to an electric motor. This means that the motor speed is also the pump speed. In South Africa, fixed speed 2-pole electric motor rotates at 3000 rpm, a 4-pole motor rotates at 1500 rpm, a 6-pole motor rotates at 1000 rpm and an 8 pole motor at 750 rpm.

There may be benefit to operate a pump at a speed other than the motor speed. The pump speed and performance is directly linked to the speed of the motor. The pump speed can be adjusted up or down by:

• Installing a gear box
• Installing a clutch
• Changing the pulleys
• Installing belts between the pump shaft and motor shaft
• Using a Variable Speed Drive (VSD)

About 30 years ago electric motor companies developed a method to vary the motor frequency (Hz). These devices are referred to as ‘Variable Frequency Drives’ (VFD) or ‘Variable Speed Drives’ (VSD).

A VSD allows a pump to operate close to its BEP over a range of flows by changing the speed of the motor or driver. (Dabbs et al. 2012)

According to Geem (2009) VSD drives have the potential to save 10 to 20% of the total pumping energy. Kiselychnyk (2009) indicates a possible energy reduction of 27% only with a 10% pump speed decrease

Fernando (2011) concluded that the use of the VSDs instead of throttle valves to regulate the flow can produce a substantial reduction in both the environmental impact and the Life Cycle Cost. Other advantages of VSD drives are better process control and less wear and tear in the mechanical components (Fernando et al., 2011).

Automation or an intelligent VSD can be used in conjunction with a programmable logic controller (PLC) to direct the pumps to operate at an optimized efficiency.
In the cases with no flow rate variation, the use of VSD is not the best choice for saving energy costs (Hydraulic Institute et al., 2004; Fernando et al., 2011). If the speed of a pump is reduced there is a corresponding loss of pressure, as per the pump affinity laws. The system has to be assessed to insure that the loss of pressure does not result in system problems (Fernando et al., 2011). In other words VSD drives are not suitable for all applications.

2.12 Pump Affinity Laws
Affinity laws are used to predict the effects of changing the speed of a pump and trimming an impeller. Affinity laws are also referred to as Laws of Conformity. Affinity laws are based on the principles of physics.

Pump systems are often oversized, resulting in the pump operating away from its BEP. Recommendations made by the US Department of Energy (2006) to lower operating costs and improve system reliability, without replacing the entire pump/motor assembly include:

1. Replace the pump impeller with a smaller impeller
2. Reduce the outside diameter of the existing impeller
3. Use a Variable Speed Drive (VSD)

If a VSD is being used to adjust the speed of the motor, as discussed in Section 2.9.1 Pump Motors to Control Flow, then the affinity laws are applicable.

Affinity Law 1: Flow is proportional to speed:

\[
\text{New Flow} = \text{Initial Flow} \times \left(\frac{\text{New rpm}}{\text{Initial rpm}}\right)\nonumber \tag{2.10}
\]

Affinity Law 2: Head change is proportional to the square of the change in speed:

\[
\text{New Head} = \text{Initial Head} \times \left(\frac{\text{New rpm}}{\text{Initial rpm}}\right)^2\nonumber \tag{2.11}
\]

Affinity Law 3: The change in power is proportional to the cube of the change in speed:

\[
\text{New Power (kW)} = \text{Initial Power} \times \left(\frac{\text{New rpm}}{\text{Initial rpm}}\right)^3\nonumber \tag{2.12}
\]

Based on the affinity laws reducing pump speed by 10% will reduce the flow rate by 10%, reduce the head or pressure by 19% and reduce the energy consumption by 27.1%.

If for example production needed 30% addition flow to meet production requirements the pump could be sped up by 30%. This would result in a pressure increase of 69% and an increase in the power consumption of 119.7%. This means more than twice the original power consumption. The increase in pressure in the pump would also cause addition wear and tear on the pump and result in additional maintenance costs. If the pump was not designed to operate at this higher pressure breakdown would be expected.
2.10.1. **Affinity Laws for change in Impeller Diameter**

The impeller can be ‘trimmed’ to change pump performance. A pump can be supplied with more than one impeller size.

Affinity Law 4: The flow change is directly proportional to the change in impeller diameter:

\[ \text{New Flow} = \text{Initial Flow} \times \left( \frac{\text{New Diameter}}{\text{Initial Diameter}} \right) \] ................................. 2.13

Affinity Law 5: The head change is directly proportional to the square of the change in impeller diameter:

\[ \text{New Head} = \text{Initial Head} \times \left( \frac{\text{New Diameter}}{\text{Initial Diameter}} \right)^2 \] ................................. 2.14

Affinity Law 6: The power change is directly proportional to the cube of the change in impeller diameter:

\[ \text{New Power} = \text{Initial Power} \times \left( \frac{\text{New Diameter}}{\text{Initial Diameter}} \right)^3 \] ................................. 2.15

A pump impeller can be trimmed, resulting in a smaller impeller. An impeller trim results in lower flow, pressure and power consumption.

Pump casings are designed to fit a range of impeller sizes. It is possible to purchase more than one impeller size for the same pump casing. This allows flexibility as impellers can be changed to accommodate different flow requirements.

### 2.13 Decreasing Power Requirements

The power required by the pump is directly related to the TDH, see Section 2.7 on Mechanical Pump Efficiency. A component of the TDH is pipe friction losses or friction Head \((H_f)\).

The physical system (pipes, valves, friction losses, static heights etc.) dictate where on the pump curve a pump will operate. If friction losses increase, because of a partially closed valve or a blockage, then the pump must produce more pressure to overcome the additional friction losses. The pump moves to the left on its curve, thereby decreasing the pump flow rate and increasing the pump pressure. This illustrates that the system can be manipulated in order to change the operating point of a pump.

It may be possible to reduce friction losses in the system. Friction losses in the system can be reduced through:

- Ensuring all valves are completely open
- Remove any scale build up
- Clean clogged screens, filters
- Remove blockages
- Removing entrapped air
2.11.1. Removing Entrapped Air

Pockets of air in a pipeline cause restrictions in the pipeline. In order to overcome this restriction, the pump must run at a higher head, this means that the pump use additional electrical energy to overcome the restriction in the pipeline.

“Proper location of air valves in a pressurized liquid conveyance system can improve flow performance greatly, thereby providing efficient energy saving as well as dependable and safe supply. Poor air valve location can cause problems, damage and hazards.” (Bhatia, 2014)

Air, in the form of bubbles, will migrate to high points in a pipeline. If there is no method to remove these air bubbles, these air pockets will grow, creating a throttling effect in the pipeline.

The presence of air in piped systems is caused by:

- Before a pipe is filled air is present in the system. As the pipe is filled air is pushed out of the system. If there is no means for the air to escape air pockets will collect at high points in the pipeline.
- Air can be drawn into the pipeline if a vacuum forms
- Water contains about 2% dissolved air by volume; this dissolved air will come out of solution if there is a pressure drop or a rise in temperature.

No quantitative means exist to determine the presence of entrapped air in pipelines. A method to remove entrapped air is air release valves located at the high points system.

2.14 Pump Controls

Pumps are controlled using one, or a combination of the three basic controls listed below (Feldman; 2009):

1. Pressure Control; starting and stopping pumps based on pressure in the system
2. Level Control; starting and stopping pumps based on the fluid level in the reservoir
3. Time Control; starting and stopping pumps at fixed times in the day

The above controls do not take into account the operating point of the pump. The pump itself can be controlled using a throttling valve, a bypass line or a VSD as discussed in Section 2.9.

2.15 Pump Monitoring

Monitoring a pump can support a condition based maintenance plan, assist operations in correctly operating a pump and gives an indication of the potential energy savings during an energy assessment. Monitoring pump performance provides users the ability to remotely monitor the health of a pumped system, and support predictive maintenance strategies (Whalen, 2014).

If a pump operates at a fixed duty, then measuring and noting only increases in current can be sufficient to determine a deterioration in efficiency (European Commission, 2001).
Brito (2011) states that preventative maintenance practices should include as a minimum monitoring of the following:

- Bearing and lubricant condition
- Shaft seal condition
- Overall pump vibration
- Differential pressure

The differential pressure can be used to calculate the pump TDH, see Equation 2.18. A gradual decrease in TDH indicates that the impeller clearance has widened. (Brito, 2011). The impeller clearance can be adjusted or the wear ring replaced to restore the pump to its intended design performance.

Lax (2014) states that permanent flow meters often are the best option for effective flow monitoring.

\[
H = \frac{p_2 - p_1}{\rho \times g} + (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2g} \quad \text{Equation 2.16}
\]

Where the velocity at the suction and discharge is a function of the pipe area and flow rate

\[
v = \frac{Q}{A} = \frac{4}{\pi D^2} \times Q \quad \text{Equation 2.17}
\]

As the flow rate is constant at the suction and discharge flanges, Equation 2.16 and Equation 2.17 can be combined:
\[ TDH = \frac{P_2 - P_1}{\rho \times g} + (h_2 - h_1) + \frac{8 \times Q^2}{g \times \pi^2} \times \left( \frac{1}{D_2^4} - \frac{1}{D_1^4} \right) \]  \hspace{1cm} 2.18

Monitoring can be done on an intermittent basis such as visually inspecting pumps on a once or twice a week basis. Or monitoring can be done on a continuous “live” basis where results are taken with various instrumentation and fed directly into a control room. Both methods can be used to support operation and maintenance.

2.13.1. Vibration Monitoring

The moving parts of the pump generate a distinct pattern and level of vibration. A vibration analyser measures the amplitude of the vibration. The amplitude is compared to trended readings. Changes in the readings are indicative of changes in the equipment condition.

Unwanted vibration can occur due to (Brito, 2011):

- A change in pump alignment
- Imminent bearing failure
- Presence of cavitation
- Resonance between the pump and its foundation or in-line equipment

2.13.2. Thermography

Thermography is an infrared thermometer or camera that allows for an accurate, non-contact assessment of temperature. Temperature assessment can be done on bearing assemblies at the impeller housing and motor system connections. (Sullivan et al., 2010)

2.13.3. Thermodynamic Method for Continuous Pump Monitoring

In situ measurement of pump efficiency is costly, but in some cases economically viable (European Commission, 2001). The thermodynamic method of pump efficiency determination is used in particular by water companies. This technique needs to be done by trained personnel, and so is often done by consultants rather than company personnel (European Commission, 2001).

The thermodynamic method measures the inefficiency of the pump based on the temperature increase in the fluid.

This method uses immersion temperature probes that are inserted into the piping. One is fitted on the pump suction side and one on the pump discharge side. Recent developments are surface temperature probes that are strapped onto the outside of pipelines and covered with thermal insulating material (Robertson et al., 2008).

There are a few of disadvantages with the thermodynamic method. Equipment has to be protected from weather, especially rain. It is often unsuitable for slurry systems (Robertson et al., 2008).

The method is based on the first law of thermodynamics. It requires measurement of both the differential pressure and differential temperature. Once the pump efficiency has been determined the flow rate can be calculated.
2.13.4. Ultrasonic Analyser
A pump has many moving parts and therefore emits distinct sound patterns. These sounds are not audible. An ultrasonic analyser is able to isolate the frequency of sound being emitted. The ultrasonic wave emissions are indicative of the equipment condition.

2.16 Pump Installation
Pump installation should be done according to API 686 – Machinery Installation and Installation Design, Second Edition, standard by American Petroleum Institute. The Hydraulic institute has also published tolerances for pump installation.

Mobley 2001 stated that “…it should not be a surprise that centrifugal pump applications often exhibit chronic reliability and maintenance problems. Many of these chronic problems are the direct result of improper installation”.

The design of the pumps takes into account the following rules for proper installation of pumps to ensure long term, trouble-free operation of pumping systems (Mobley, 2001; Foszcz, 1998)

- Provide pump sufficient NPSH
- No elbows in the pump suction line
- Prevent air or vapour entering the suction line
- Correct alignment of piping
- Use the right pipe fittings
- Adequate foundation

Some of these points, raised by Mobley, should be taken into account during the design or layout of the system. For example “no elbows in the suction line” and “use the correct pipe fittings”. It is the responsibility of the designer to insure that the correct fittings are specified and the system can be installed correctly.

Dabbs (2012) recommends a rigid flat concrete foundation that weighs approximately two to three times as much as the pump. The foundation has to be adequate to absorb vibrations and prevent distortion when the foundation bolts are tightened (Foszcz, 1998).

Inadequate foundation can cause the shifting of the pump feet resulting in misalignment between the pump and motor. Therefore pump alignment should be checked periodically. Alignment can be checked using a dial indicator that measures the total indicated runout (Hydraulic Institute, 2006) or a laser measurement system.

2.17 Pump Maintenance
Maintenance is essential to minimise Life Cycle Costs and to minimise unplanned downtime. The maintenance strategy is determined by the criticality of the process and consequences of failure. (European Commission, 2001):

The European Commission (2001) found that pumps are often poorly maintained, and are not given attention until they start to cause problems or stop working altogether. As fluid passes through the pump, erosion and abrasive action cause close tolerance parts to wear. As these parts wear, the pump will lose its efficiency and ability to pump (Bachus et al.,
“Without maintenance, a centrifugal cold water pump can eventually lose about 10% - 15% of its original efficiency” (European Commission, 2001).

There are three approaches to maintenance (European Commission, 2001):

1. Do nothing until something goes wrong. This approach is generally not recommended. However, may be appropriate for less critical applications.

2. Periodic strip-down.

3. Condition-based maintenance (regular or continuous monitoring of the pump condition). Monitoring equipment gives an accurate indication of when maintenance is required.

Condition-based maintenance is arguably the best method, but investment in monitoring equipment is required to generate data (European Commission, 2001).

Centrifugal pumps require periodic maintenance that should include (Foszcz, 1998):

- Gland adjustment
- Gland re-packing
- Mechanical Seal Adjustments
- Gland lubrication
- Bearing lubrication
- Impeller adjustment
- Labyrinth grease purging
- Bolt tightening

If a pump is used in “severe-service” conditions, such as highly corrosive liquids or slurries then the maintenance and monitoring intervals should be shortened (Brito, 2011). It is the operator that determines the maintenance routine; i.e. whether there are less frequent but more major repairs, or more frequent but simpler servicing. (Brito, 2011)

Routine maintenance procedures are described in detail in the maintenance instructions that are supplied with the pumps. These maintenance instructions can often be located on the manufactures websites or requested directly from the pump manufacturer.

Preventative and protective maintenance should include, as a minimum, the monitoring of the following (Brito, 2011; Dabbs et al. 2012):

- Bearing and lubricant condition
- Shaft seal condition
- Overall pump vibration
- Differential pressure

Refer to Section 2.13 for the methods used to monitor pumps.
Computerized Maintenance Management System (CMMS) can be used to support a preventative maintenance program. A CMMS software package is a database of maintenance information. It typically determines which equipment requires maintenance, the parts that are required and in some cases if stock of those parts are available.

2.18 Cavitation
Cavitation affects pump performance and efficiency. The result is lower pump pressure and flow. A vapour bubble is a bubble of air. Bubbles take up space within the pump. The energy produced by the motor is wasted expanding and compressing bubbles, instead of moving liquid.

Cavitation is one of reasons a pump may be inefficient and unreliable. The damage caused by cavitation is visible when the pump is disassembled.

Cavitation in a pump occurs if the pressure in the eye of the impeller falls below the vapour pressure of the fluid. At this point, the fluid “boils,” changing from a liquid to a vapour. Cavitation is the formation and subsequent collapse or implosion of vapour bubbles in the pump (Detloff C, 2013).

If a pump operates under cavitation conditions for enough time, one or more of the following shall occur: (Bachus et al., 2003)

- Decreased pump efficiency
- Reduced pump performance (flow and pressure output drops)
- Problems with pump packing, leaking
- Premature mechanical seal failure
- Premature bearing failure
- Pitting marks on the impeller blades and on the pump casing
- Scratches, gouges and track marks on impeller blades and pump casing
- Shaft breakage and other fatigue failures in the pump

There are five types of cavitation (Bachus et al., 2003)

1. Vaporization Cavitation
2. Internal Recirculation Cavitation
3. Vane Passing Syndrome Cavitation
4. Air Aspiration Cavitation
5. Turbulence Cavitation

Vaporization cavitation represents about 70% of all cavitation (Bachus et al., 2003).
<table>
<thead>
<tr>
<th>Type of Cavitation</th>
<th>Cause</th>
<th>Damage to Pump</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vaporization</td>
<td>Inadequate suction pressure available (NPSHa)</td>
<td>Damage occurs behind the impeller blades toward the eye of the impeller</td>
<td>• Reduce friction in suction pipe&lt;br&gt; • Lower the fluid temperature&lt;br&gt; • Raise the liquid level in the suction tank&lt;br&gt; • Reduce the pump speed&lt;br&gt; • Use a larger pump</td>
</tr>
<tr>
<td></td>
<td>Or</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pump suction is restricted (Obstruction or sharp elbows in the suction piping)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Or</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inadequate or incorrectly sized pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Internal Recirculation</td>
<td>Pump discharge is restricted</td>
<td>Damage occurs on the leading edge of the impeller blades toward the eye of the impeller</td>
<td>• Reduce friction losses in discharge pipe&lt;br&gt; • Use a different pump</td>
</tr>
<tr>
<td>3. Vane passing Syndrome</td>
<td>Impeller outer diameter is too large for pump casing</td>
<td>Damage occurs on impeller blade tips and just behind the cutwater or on the internal volute wall</td>
<td>• Use a smaller Impeller if possible&lt;br&gt; • Use a different pump</td>
</tr>
<tr>
<td>4. Air Aspiration</td>
<td>Air drawn into the system Or</td>
<td>Same damage as Vaporization Cavitation</td>
<td>Seal or tighten all points that air can enter the system this includes:&lt;br&gt; • Flanges&lt;br&gt; • Packing rings&lt;br&gt; Review pump suction arrangement</td>
</tr>
<tr>
<td></td>
<td>Improper suction pipe (fluid velocity too high)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Turbulence</td>
<td>Formation of vortexes in the suction flow Or Suction piping arrangement is inadequate</td>
<td>Same damage as Vaporization Cavitation</td>
<td>• Review pump suction arrangement</td>
</tr>
</tbody>
</table>

*Table 1: Types of Cavitation*

**2.19 Identifying Pump Systems to be Optimised**

Most pump optimisation of industrial pumps follow an 80:20 rule; about 80% of energy savings will come from optimising 20% of the pumps (da Cunha et al., 2008). The initial focus or priority should be on optimising pump systems that will result in the largest energy savings.
In order to identify systems most in need of review are: (da Cunha et al., 2008; European Commission, 2001)

- large systems i.e. systems that have large power requirements
- Systems with high annual operating hours
- Problem systems, systems with high maintenance or poor reliability
- Systems that have been changed from the original design
- Oversized pumps that run in a throttled condition
- Systems where recirculation lines are used to control the flow
- Pump systems that have large variation in flow or pressure
- Production Critical Systems

The following are the typical symptoms of a system that can be optimised

- High energy costs
- Throttle valves that are usually partially or completely closed
- Bypass lines that are usually open
- Cavitation in pumps
- High maintenance requirements or systems with frequent failures
- High operating noise levels
- Vibrations in the system

The US departments Industrial Technologies Program assisted in the development of the Pumping System Assessment Tool (PSAT) software. This software is available at no cost. PSAT software is used to estimate potential energy savings in industrial pump systems. It requires input data such as the pump head, flow rate, and motor power. PSAT software can be used to identify systems that are likely to offer savings.

An energy assessment as per the requirements of ASME/ANSI EA-2-2009 can be used to identify pump systems in need of review and quantify the expected savings against investment costs.

2.20 Energy Assessment and Audits

SANS 50001:2011 is an international standard that is used to enable organisations to establish the systems and processes necessary to improve energy performance (including energy efficiency). ISO 50001:2011 is applicable all types and sizes of organisations. ISO 50001:2011 specifies energy management system requirements and the responsibilities of top management.

SANS 5002:2014 entitled Energy audits – requirements with guidance for use defines an energy audit as a detailed analysis of the energy performance of an organization, equipment, system or processes. SANS 5002:2014 covers the general requirements and framework common to all energy audits.
ASME/ANSI EA-2-2009 – Energy Assessment for Pumping Systems sets the requirements for conducting and reporting the results of a pumping system assessment. The assessment considers the entire pumping system including pumps, piping drives and other in line components. The purpose of an ASME assessment is to identify efficiency improvement opportunities in a pumped system. The purpose of the standard is to provide a standardized method of executing and documenting energy assessments of pumping systems.

EA-2-2009 defines three different levels of pump system assessment, refer to Table 3. As the assessment level increases so the time, resources, data gathering and analysis requirements increase.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Assessment Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prescreening opportunities</td>
<td>1</td>
</tr>
<tr>
<td>Walk through</td>
<td>2</td>
</tr>
<tr>
<td>Identify systems with potential saving opportunities</td>
<td>3</td>
</tr>
<tr>
<td>Evaluate systems with potential saving opportunities</td>
<td></td>
</tr>
<tr>
<td>Snapshot type measurement of flow, head and power data</td>
<td></td>
</tr>
<tr>
<td>Measurement/data logging of systems with flow conditions that vary over time*</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Verify and use data from plant historical information where applicable

Table 2: Assessment Levels (ASME, 2010)

The three EA-2-2009 levels of assessment:

1. Level 1 (pre-screening) assessment is a qualitative investigation
2. Level 2 assessment is a quantitative, measurement-based investigation
3. Level 3 assessment is a quantitative investigation, requires measurements to be taken over an extended period of time in order to develop a system load profile

Level 2 and Level 3 assessments require pump monitoring equipment such as such as flow meters, pressure sensors, and power sensors to estimate the potential energy savings of the system.

EA-2-2009 has a limited review of the common causes of high energy use in pump systems and solutions, limited to (Towsley, 2010):

- System head reduction
- System flow reduction
- Maximize component efficiencies
- Pump system run time

ASME has also published a guidance document (ASME TR EA-2G-2010) which supports ASME EA-2-2009 standard. The guidance document provides background, supporting information and basic guidance on how to fulfil the requirements of the ASME EA-2 standard.
2.21 Summary of the Literature Review

Centrifugal pumps account for the majority of pumps used in industry. Opportunities exist to reduce the energy consumption of a pumped system through smart design, retrofitting, and operating practices (Hydraulic Institute et al., 2004). Studies have shown that pumps are on average 15% to 40% inefficient (European Commission 2001; Robertson et al., 2008). Besides higher electricity costs, inefficient pumps have lower reliability and higher maintenance costs (Kernan, 2009).

The operating point of a pump determines the pump reliability and efficiency. The closer the pump operates to its BEP (Best Efficiency Point) the higher the pump mechanical efficiency will be and the greater the pump reliability will be (Kernan, 2009; Barringer, 2003).

Many pumps do not operate near their BEP. A study done in 1996, by the Finnish Technical Research Centre, of close to 1,700 pumps at 20 process plants across multiple industries, found that the average pumping efficiency was below 40%, and more than 10% of pumps were running below 10% efficiency (Kernan, 2009).

If a pump operates at or below 30% of its BEP then the life expectancy of the pump is reduced to 10% of total pump life. In other words if the life expectancy of a water pump is in the region of 15 to 20 years (U.S. Department of Energy’s Industrial Technologies Program and the Hydraulic Institute, 2006), but the pump is operated at or below 30% of its BEP, then the pump should only last 1.5 to 2 years before catastrophic failure. Pump systems with high maintenance requirements are often the result of improper design and operation (U.S. Department of Energy’s Industrial Technologies Program (ITP) et al., 2006)

In order to determine the operating point of a pump, the flow rate and TDH is required. The TDH is the total pressure or head the pump must produce to overcome pressure and friction losses in the system. Pressure is often converted to head (m). The various components of the TDH are discussed in the literature.

The operating point can be plotted on the pump curve. The pump curve indicates the operating range of a pump in terms of flow and pressure (head). The pump curve also indicates the pump mechanical efficiency and NPSH required at various operating points. The pump curve predicts the performance of a pump at a specific head and flow.

Pump performance is directly linked to the speed of production; pumps move product from one process to another. If a pump stops, production may stop.

It may be beneficial to change the flow rate in order to change the speed of production. If demand of a product changes, then operations can be sped up or slowed down to meet the product demand. In South Africa there are time of day power tariffs and therefore the potential to change operational strategies to suit the tariff system.

Pump performance is directly linked to the pump speed. A change in speed would bring about a corresponding change in the pressure (head), flow and power requirements (kW) of the pump.
There are three ways to change the operating point of a centrifugal pump namely:

1. Change the physical system the pump operates in
2. Change the pump itself by changing the impeller or replacing the pump
3. Change the speed at which the pump runs

The physical system (pipes, valves, friction losses, static heights etc.) dictate where on the pump curve a pump will operate. For example, closing a valve increases the friction losses in the system. The pump must produce more pressure to overcome the additional friction losses. The pump moves to the left on its curve, thereby decreasing the pump flow rate and increasing the pump pressure. This example directly shows that the system can be manipulated in order to change the operating point of a pump. One common method to change the flow rate of the pump is to partially close a valve or “throttle” the system. By “throttling” the system the TDH increases and the power consumed is not reduced. “Throttling valves” increases pressure in the pump casing which increases maintenance costs. This shows pump performance, efficiency and reliability can be manipulated by manipulating the system.

The pump speed and performance is directly linked to the speed of the motor. The speed at which a pump operates can be changed by:

- Installing a gear box
- Installing a clutch
- Changing the pulleys
- Installing belts between the pump shaft and motor shaft
- Variable Speed Drive (VSD)

Controlling the speed of the pump is the most efficient way to control the flow because when the speed is reduced the power consumption is reduced (da Cunha et al., 2008). However the system has to be assessed to ensure that the corresponding loss of pressure does not result in system problems (Fernando et al., 2011). In other words controlling the speed of a pump is not suitable for all applications.

The pump itself can be permanently altered by trimming the pump impeller. By trimming the pump impeller the pressure that a pump is able to produce is decreased. Affinity laws are used to predict the effects of changing the speed of a pump or trimming the pump impeller.

Corrective action cannot be taken unless the current operating point of a pump is known. The literature reviews methods of pump monitoring to determine the operating point of a pump. Pump monitoring can also be used to support a maintenance plan.

In order to assess the performance of a pump that is in operation the following measurements are required (Bachus et al., 2003):

- Differential pressure or Pressure at the suction and discharge flanges (kPa/bar)
- Flow rate (m³/h)
- Power Input to the pump shaft (kW)
The above measurements can be obtained from a pump in operation, using basic and readily available equipment (Bachus et al., 2003). However no amount of instrumentation can prevent equipment failure if the data is not correctly interpreted and used.

Preventative and protective maintenance should include, as a minimum, the monitoring of the following (Brito, 2011; Dabbs et al. 2012):

- Bearing and lubricant condition
- Shaft seal condition
- Overall pump vibration
- Differential pressure

ASME/ANSI EA-2-2009 – Energy Assessment for Pumping Systems (EA-2-2009) sets requirements for conducting and reporting the results of a pumping system assessment. An ASME assessment considers the entire pumping system including pumps, piping drives and other in line components. The purpose of an ASME assessment is to identify efficiency improvement opportunities in a pumped system. The purpose of the standard is to provide a standardized method of executing and documenting energy assessments of pumped systems.

Most pump optimisation follows an 80:20 rule; about 80% of energy savings will come from optimising 20% of the pumps (da Cunha et al., 2008). The initial focus or priority should be on optimising pump systems that will result in the largest energy savings.

ASME/ANSI EA-2-2009 has three different levels of assessment. A Level 2 and Level 3 assessments requires pump monitoring equipment such as such as flow meters, pressure sensors, and power sensors to estimate the potential energy savings of the system.

Significant opportunities exist to reduce the energy consumption of existing pumped systems and improve system reliability.
CHAPTER THREE: RESEARCH DESIGN AND METHODOLOGY

3.1 Chapter Overview
This Chapter describes the approach taken to the research. A qualitative research design was utilized. The research can be viewed as exploratory. Experts with specialist knowledge were selected and Interview questions set. The Chapter further describes the data collection and data analysis methodologies.

3.2 Qualitative vs. Quantitative Research Strategy
A quantitative research strategy would not be appropriate to answer the research questions.

A quantitative study using data sets or laboratory-based methods would not be practical. Definitive figures and generalizable data cannot be determined without conducting a full energy audit as per the requirements of ASME/ANSI EA-2-2009.

Conducting an energy audit was not viable for the following reasons:

- Each system is has many different variables (pump size, head, flow, age, type, fluid etc.).
- Multiple systems would have to be reviewed from multiple organisations to obtain information relevant to the dissertation.
- Conducting multiple energy audits would be time consuming.
- The researcher has a full time job and was unable to get access to any of the process plants.
- Would not be appropriate to mini-dissertation level of research

Insufficient industry experts could be located to do quantitative research strategy. To select participants without strict criteria would compromise the quality of the research.

Structured interviews, questionnaires or surveys would have limited the responses from participants.

A qualitative research strategy involves the collection, analysis, and interpretation of data that are not easily reduced to numbers (Anderson, 2010).

Advantage of qualitative research strategy (Anderson, 2010):

- Issues can be examined in detail and in depth
- Subtleties and complexities about the research subjects and topic are discovered that are often missed by more positivistic enquiries
- Data is collected from a few individuals; findings cannot be generalized to a larger population. Findings can however be transferable to another setting.

Qualitative research requires a small sample because of the detailed work required for the study (Anderson, 2010).
A qualitative research design was selected as in-depth understanding of the topic is required. The aim of the research is to look into design and operating practices currently used in industry. The research looks into the experiences industry experts currently working with centrifugal pumps. The research is supported by a literature review.

3.3 Exploratory Research Design

The research can be viewed as an exploratory. Exploratory research is useful to determine if a problem or issue even exists. Exploratory research approach is useful to gain background information on a particular topic.

An exploratory design is conducted when there are few or no earlier studies to refer to or rely upon to predict an outcome (Anastas, 1999)

Research into the operating practices of centrifugal pump systems and the effect on reliability and efficiency has not been researched in this particular manner before.

Exploratory research is intended to produce the following possible insights (Lynn University, 2015):

- Investigate basic details, settings, and concerns.
- Represent the situation being investigated.
- Generate new ideas and assumptions.
- Develop tentative theories or hypotheses.
- Determine whether further study is feasible in the future.
- Refine issues for more systematic investigation
- Formulation of new research questions.

An advantage of exploratory research is that it is flexible and can address all types of research questions (what, why, how).

The disadvantage of exploratory research is definitive conclusions about the research findings cannot be made. Findings provide insight but not definitive conclusions (Lynn University, 2015).

3.4 Sampling Method

A non-probability sampling method is required as experts with specialist knowledge are required to get relevant, appropriate data. Purposive sampling technique was used to select participants, in other words the researcher used judgement to select the participants.

Centrifugal pumps are used in almost every industry, the sizes and duties vary; therefore experiences may be slightly different between participants. Participants were chosen based on having broad experience with centrifugal pumps. In the mining industry all sizes of pumps are used with varying duties. A typical mine or process plant has a wide variety of pumps both in size and duty. A typical mine or process plant has clean water pumps, chemical pumps, process pumps and slurry pumps. Participants with experience on mines or process plants were therefore considered preferable.
Participants with a minimum of five years of relevant experience on mines or processing plants were selected.

In order to remove bias and improve the validity of the findings, participants were selected with experience in different processes plants from different geographic locations.

3.5 Ethics
Participants in the research signed a letter of informed consent (Wiles, 2013). Participants also signed consent forms permitting the researcher to audio tape them during the interview.

The participants are all over the age of 18, the research is not of a highly sensitive nature, and participants’ details are kept confidential (Wiles, 2013). Pseudonyms are used to protect the participants’ privacy and identity.

3.6 Questionnaire Developments for Data Collection
Open-ended interview questions were formulated to allow the researcher maximum flexibility when interacting with the participants. Open ended response is non-restrictive to any answers and allows the researcher to capture comprehensive viewpoints.

In order to increase the validity of the interview questions a technique suggested by Mason (1996) that recommended that the research objectives be used as a brainstorming tool for generating interview questions, was used.

Direct observations could not be utilised, as interviews were conducted in Johannesburg, some of the process plants that the participants worked on were not in South Africa.

Questions are set in this section with the aim to establish the methods currently used in industry to maintain, monitor and control pumps and its effectiveness.

During data collection different strategies to manage pump operations may emerge. The questions are as follows:

• Have you had experience with unreliable pumps?
• Is there any kind of pump monitoring currently in place?
• What factors do you believe contribute to pumps being unreliable?
• Have any energy audits been carried out and if so what was the outcome of those audits?

3.7 Data Collection Methods
Once the author had a general idea of which questions to ask, the selected participants were invited to take part in a 15 to 30 minute interview. The interviews were audio recorded using a freely available online software package, called ‘Audacity’. An Audacity is capable of capturing sound at very high quality.

3.8 Data Analysis Measures
In order to increase the reliability of the analysis all data was uploaded into a qualitative data analysis package, ‘Atlas.ti’. This software tracks the progress of the data analysis more carefully than data analysis by hand. The data from the interviews was analysed using thematic analysis.
Thematic analysis is a process of segmentation, categorisation and re-linking of aspects from the database using the researcher’s judgements. It focuses on repeated words and phrases from the data collected in order to answer the research questions. It is a repetitive review of the information to identify recurrent patterns, themes or categories.

The interview texts were examined for emerging themes (Boyatzis, 1998). The analysis followed a data-driven approach, which is appropriate to exploratory case study research where prior examples of themes in the literature are absent. Instead of relying solely on the researcher for a framework for searching for the themes, a reliable method described by (Boyatzis, 1998) was used it describes a general method for finding initial patterns within the data, called codes, and sorting these codes into larger organising patterns, called themes. Bruan and Clarke’s (2006) methodology follows four steps.

1. Familiarising yourself with your data
2. Generating initial codes
3. Searching for themes
4. Reviewing themes
5. Defining and naming themes

These steps were applied to the interview transcriptions as follows:

1. The data was read a few times
2. An initial list of codes was generated
3. Codes were reviewed and sorted into themes and sub-themes
4. These themes were reviewed to ensure that all the codes had been sorted into themes, and that no additional themes could be found, a process known as saturation
5. The central idea behind each theme was written down in a sentence, and a name chosen for each theme. Once the themes and sub-themes emerged a visual representation of the relationship between themes and sub-themes was produced
CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Chapter Overview
This chapter discusses the findings of the interviews. The data from the interviews was analysed using thematic analysis. The themes emerging from the interviews are discussed and compared to the literature reviewed in Chapter Two.

4.2 Participants
The interview topic is such that it requires knowledgeable participants. All participants had at least seven years of relevant experience on mines or processing plants. Participants worked in different geographic locations, in different industries. All were able to discuss the methods currently used in industry to maintain, monitor and control pumps. The relevant experience of participants in the research is presented below in Table 3.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Number of Years Relevant Experience</th>
<th>Industry</th>
<th>Work Experience Geographic Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>7</td>
<td>Process Plants (Gold, Copper)</td>
<td>South Africa Zimbabwe Botswana</td>
</tr>
<tr>
<td>B</td>
<td>15</td>
<td>Process Plants (Gold, Copper)</td>
<td>Australia Ghana Liberia Botswana</td>
</tr>
<tr>
<td>C</td>
<td>7</td>
<td>Petro Chemical Process Plant (Copper)</td>
<td>South Africa</td>
</tr>
<tr>
<td>D</td>
<td>30</td>
<td>Power Generation Process Plants (Sugar Brewery Dairy)</td>
<td>South Africa</td>
</tr>
</tbody>
</table>

Table 3: Participants in the Research

4.3 Themes Emerging from Research
The developments of themes emerging from the research are shown in Table 4. The pump reliability or Mean Time Between Failure (MTBF) was central to the interviews.

Although reliability, power consumption and pump efficiency were discussed in the interviews, none of the participants linked the concepts. However the literature reviewed clearly describes the direct relationship between reliability, power consumption and efficiency, refer to Section 2.8.

Two of the four interview participants expressed negative views towards reviewing pump systems for energy savings. These views are in line with the findings made in 2001 by the European commission: “For most users, energy saving is treated as if it is less important than either first cost, ease of maintenance or reliability”.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Reliability</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Installation</td>
<td>✓</td>
</tr>
<tr>
<td>A</td>
<td>Maintenance</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Pump Selection</td>
<td>✓</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>“the only problem is if they are not sized properly it could be a problem it’s mainly to do with the pump selection side”</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“think that if you do not have a sensible lubrication schedule in place you then you will lose pumps more frequently than not”</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“As well pumps used incorrectly, so the pump is under is basically under designed for what it is trying to do, hence it just doesn’t last. So you’re running the pump so far off its curve all the time that there is just no reliability factor in it anymore”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“reliability of the pump its only as good as what the maintenance personnel are so in other words operations people do they do um timeous preventative maintenance, do they have a program where they go every once a week, twice a week and go and actually check the operation of the pump, see what it’s doing, is it just standing there cavitating and nobody knows about it”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“the reasons I’ve found that they were unreliable is incorrect installations, incorrect line up…”</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“They are unreliable if they haven’t been designed or sized properly and also you if they are not maintained, simple as that”</td>
</tr>
</tbody>
</table>

Table 4: Themes Developed in the Research

As seen in Table 4 it was indicated during the interviews that reliability is a function if the installation, the maintenance being done and the pump selection. This is in line with the literature reviewed in Chapter Two.

Themes and their relation to one another are depicted in Figure 5 and explained in Sections 4.3.1 to 4.3.3
4.3.1 Installation
Based on the interviews, refer to Table 4, it is known in industry that installation affects pump reliability, particularly pump line up. Correct pipe line up was raised during the interview with Participant C. Equipment such as laser alignment tools were used on all sites that Participant C had worked on, laser alignment ensures correct pump line up.

Pump installation is discussed in the literature review Section 2.14. Mobley (2001) stated that many chronic problems of centrifugal pumps are a direct result of improper installation.

4.3.2 Maintenance
Three of the four participants noted that maintenance affects pump reliability, refer to Table 4. Maintenance is essential to minimise Life Cycle Costs and to minimise unplanned downtime. (European Commission, 2001).

It was noted by Participant D that in some instances the maintenance team is aware of items that need to be maintained or repaired; however as a result of production deadlines they are unable to do the necessary preventative maintenance or repairs.

Participant D: “... any mechanical item on in the plant is down time against production time and the sometimes sacrifice, alright, the mechanical component against production cus they don’t want to stop production because they got production deadlines to meet, do you understand what I’m saying, so they f*ing run those mechanical items into the ground and then afterwards the whole pump is destroyed, or whatever component is destroyed, then they are forced to shut down. Instead of replacing a mechanical seal or whatever they replace the whole unit. “
Based on the response from Participant D maintenance is dependent on plant shutdowns, operation management and the production deadlines.

Based on the response from interviews, the do nothing until something goes wrong approach to maintenance is the most common approach to maintenance in industry. The European Commission (2001) found that pumps are often poorly maintained, and are not given attention until they start to cause problems or stop working altogether. Therefore findings from the interviews are in line with the literature reviewed.

4.3.3 Pump Selection
It is well known in industry that pump selection and design affects pump reliability. Three of the four participants stated that pump selection affects pump reliability. Refer to Table 4 for quotations used during the interviews. It was specifically stated that incorrect pump size can affect pump reliability.

In Section 2.8 it was shown that the pump should be selected so that the operating point is as close to its BEP as possible. The operating point of a pump determines the pump reliability and efficiency. The closer the pump operates to its BEP (Best Efficiency Point) the higher the pump mechanical efficiency will be and the greater the pump reliability will be (Kernan, 2009; Barringer, 2003).

Pumps systems are dynamic. This means that the pump does not operate at a static point on its pump curve. As the system the pump operates in changes so the pump operating point changes. For example if the number of users changes then the operating changes. If the operating point changes so does the pump efficiency. This means that a pump may be efficient at one duty point but become inefficient as the system changes.

All participants confirmed that on most of the pump systems, in their experience, there is no pressure or flow indication. Without instrumentation there is no simple way to determine the flowrate of the pump or the pressure in the system.

In order to review a system or conduct an ASME EA-2-2009 energy assessment, Level 2 or Level 3, flow meters, pressure sensors, and power sensors are required. There is insufficient instrumentation installed in pump systems to determine if the pump is the correct size for the system.
CHAPTER FIVE CONCLUSIONS AND RECOMMENDATIONS

5.1 Chapter Overview

Chapter 5 presents the key findings from the interviews and answers the research questions. The importance of this research is discussed. The limitations and areas for further research are presented.

5.2 Research Objective One

- **Determine the factors that contribute to pump reliability and mechanical pump efficiency**

The operating point (head vs. flow) of a pump determines the pump reliability and efficiency. This operating point can be plotted on the pump curve. The closer the pump operates to its BEP (Best Efficiency Point) the higher the efficiency and the reliability will be. The point at which the pump operates on its curve is dependent on the system in which it operates.

The life expectancy of a centrifugal pump depends on where it is operating on its curve (Barringer, 2003):

- BEP 100% life is expected
- 10% left to 5% right of BEP 92% life is expected
- 20% left to 10% right of BEP 53% life is expected
- 30% left to 15% right of BEP 10% life is expected

If a pump operates at its BEP the life expectancy is 100% whereas if it operates at or below 30% of its BEP then the life expectancy of the pump is reduced to 10% of total pump life. In other words if the life expectancy of a water pump is in the region of 20 years (U.S. Department of Energy’s Industrial Technologies Program and the Hydraulic Institute, 2006), but the pump is operated at or below 30% of its BEP, then the pump should only last 2 years before catastrophic failure.

The point at which the pump operates on its curve is dependent on the pump size and the properties of the system in which it operates. Three of the four research participants stated that pump size was a contributor to pump reliability. However, in the participants’ experience, insufficient instrumentation is installed in the system to determine if the pump is correctly sized, or operating near its BEP.

Based on the literature reviewed, corrective action can be taken if a pump is not operating near its BEP. There are three ways to change the operating point of a centrifugal pump:

1. Change the physical system the pump operates in
2. Change the pump itself; by changing the impeller or replacing the pump
3. Change the speed at which the pump runs

The installation of the pump determines the pump reliability. The pump line to the motor, foundation and pipework must be correct.
Maintenance practices contribute to pump reliability. Three of the four participants stated that pump reliability is dependent on the maintenance being done. These statements are in line with the literature reviewed.

Pump efficiency and reliability is a function of the installation, maintenance and the pump selection or operating point.

5.3 Research Objective Two

- *Ascertain to what extent pumps are monitored and controlled in industry*

The pump reliability is a function of where the pump operates on its curve. In order to determine where a pump is operating on its curve a reading of the differential pressure across the pump is required as a minimum. However based on the experience of the research participants these measurements are not taken.

The Participant A was asked specifically if the operating point of the pump could be determined, the response was as follows “If the pump is running then you don’t worry about it, but if a pump is not meeting its duty then people check.” In other words the pump has to be running far to the left on its curve (not producing enough flow or pressure) before any concern is raised. Instrumentation in general is not utilized during pump operation.

Participant C “in certain of the process streams yes there is they do have continuous um analysis installed on the pump i.e. excessive vibration temperature and stuff like that but in general no these things are not installed on most process plants”

All participants stated that the only monitoring done on the smaller pumps is in the form of a visual inspection. Larger pumps and pumps that are production critical are monitored on a more regular basis.

Based on the response from interviews most pumps are visually inspected on a weekly basis. Pumps are checked for bearing noise and cavitation (by listening to the pump), checked for V-belt slippage and the condition of the seals are visually inspected.

The participants were asked specifically if temperatures and pressures were monitored. None of the participants had known of instances of pressure monitoring. Temperature was checked during commissioning using a temperature scanner; however temperatures were not monitored during normal plant operation.

Monitoring most commonly done is routine inspection. Records of the repairs done on the pumps and which parts required replacement are recorded in a maintenance program to develop a maintenance trend. Little to no condition based monitoring is done. Monitoring is mostly in the form of visual inspection. Condition based monitoring is not used in to control centrifugal pumps in industry.

5.4 Research Objective Three

- *Determine what operation and maintenance strategies are used in industry*

Interview candidates were asked about maintenance procedures that are currently used on site. Participants stated that the type of maintenance procedure used depends on the size of
the equipment and how critical the equipment is to the process. In other words, larger pumps and process critical pumps were more closely monitored and better maintained.

Based on the response from interviews, most industrial pumps are visually inspected on a weekly basis. The visual inspection consists of checking for bearing noise and cavitation (by listening to the pump), visually inspecting for V-belt slippage and checking the condition of the seals. No instrumentation or monitoring equipment is used. In other words, no condition based monitoring is done. If a problem with a pump is picked up during an inspection, the problem is raised and put into the maintenance schedule.

If repairs are done to the pump, the date of repair and parts required are noted in a predictive maintenance program. After running for a while a trend develops. This trend is used to predict the future maintenance requirements.

A predictive maintenance plan is used to predict the potential future date equipment will fail based on a trend. This is used to schedule maintenance to avoid breakdowns. Predictive maintenance does not diagnose why failures occur, or how to get better life out of equipment, it only predicts the next failure date if maintenance does not occur.

For larger and process critical pumps the approach to maintenance is a periodic strip down during plant shut downs. The periodic strip down is dependent on production deadlines and on the number of plant shutdowns.

Only one instance of condition based monitoring was noted by Participant C, in the power generation industry. Condition based monitoring is used on the water supply pumps feeding the boiler as these are process critical pumps and due to the process, the flow rate has to be accurate.

It was noted by Participant D that in some instances the maintenance team is aware of items that need to be maintained or repaired; however as a result of production deadlines they are unable to do the necessary preventative maintenance or repairs.

Based on the response from Participant D maintenance is dependent on plant shutdowns, operation management and the production deadlines.

Based on the response from the interviews the first approach to maintenance, which is do nothing until something goes wrong is the most common approach to pump maintenance currently used in industry. Little to no condition based monitoring is done.

Maintenance is dependent on plant shutdowns, operation management and the production deadlines.

5.5 Research Objective Four

- Establish if energy audits are being conducted in Industry

Participant A and C had known energy audits to take place, but were not directly involved in those audits. Both had positive views towards energy audits. Participant C stated that there was benefit to such audits and more audits had been happening in recent years.

Participants B had not known of any energy audit being conducted on centrifugal pumps and had a negative perception of audit.
“I think that the pumps would be the last thing that I would look at I'd look at the mills first”, Participant B then went on to clarify “I think that if you're going to look for energy look for things that are pulling the power”

Participant D likewise had negative views regarding energy audits.

“Although I've heard about these guys that....... with these good and wonderful plans on how to save kW on the performance of plants, to be honest with you I haven't heard of one successful story.”

All participants agreed that saving energy is important, even those that expressed negative views towards the energy audits. Participant D said that working in Africa, diesel generated power is often cheaper than power off a grid. This means that immediate, evident savings would be realised if power consumption was reduced.

There are energy audits being conducted but not necessarily in all industries. The viewpoints expressed towards such audits are mixed.

5.6 Discussion and Implications of the Findings
There is direct relationship between pump reliability (life) and the operating point of the pump (how close it operates to its BEP). The BEP is the best efficiency point, or the point at which the pump has the highest mechanical efficiency.

Based on the response from interviews, the operating point and condition of a pump cannot be determined, as currently there is insufficient instrumentation installed in pumped systems. The significance is that corrective action cannot be taken as the operating point cannot be determined.

Participant D stated that the maintenance team may be aware of items that need repairs; however repairs are not done as production cannot be interrupted. The plant referred to by Participant D, had running and standby pumps. The layout is such that one pump runs whilst the other is connected, ready to operate in the event of the first pump failing. Valves are used to switch between the two pumps. Therefore the plant has the ability to do maintenance or repair pumps without disrupting the process. Production deadlines should not prevent repairs from being done, however it seems that production deadlines take precedence over good operational practices.

The research participant responses are in line with the European Commission (2001) findings that the most common approach to maintenance is to do nothing until something goes wrong. Maintenance done is also dependent on plant shutdowns, operation management and the production deadlines.

The research indicated that energy audits are being conducted however participants had mixed views towards pump energy audits.

Participant B did not consider industrial pumps to use significant power when compared to other larger pieces of plant equipment such as mills. Pumps are often operated inefficiently whilst larger pieces of plant equipment are closely monitored and are operated near their best possible efficiency (U.S. Department of Energy's Industrial Technologies Program and the Hydraulic Institute, 2006).
Participant D appeared to lack confidence in the consultants that conduct energy audits and mistrusts the results of energy audits:

“Although I’ve heard about these guys that……. with these good and wonderful plans on how to save kW on the performance of plants, to be honest with you I haven’t heard of one successful story.”

This perception needs to be overcome, because, even though audits are being conducted, findings are not necessarily implemented.

There are numerous published success stories available where energy savings have been realised through conducting energy audits and implementing the findings.

5.7 Limitations
The researcher was unable to interview a suitable candidate that had been directly involved in an energy audit. It would have added value to the research if the findings of an energy audit were included. The cost implications, both in terms of capital investment and in terms of energy savings realised. It would also have been relevant whether or not the findings of such audits are being implemented.

5.8 Recommendations for Further Research
The research has determined the need to optimise pump efficiency for both the potential in energy savings and the potential to improve pump reliability and decrease maintenance costs. Further research could be done to determine the findings of energy audits are being implemented and the results thereof.

Larry Bachus proposes a strategy to assist operations; monitoring pump pressure and training operators to manipulate the system to keep the pump operating in its optimum zone. Research could be conducted to determine if the Mean time Between Failure (MTBF) changes with the implementation of Larry Bachus’ strategy.

The MTBF statistics could be compared between pumps that have similar duties but managed and maintained using different strategies. The total Life Cycle Costs (LCC) could then be compared based on the different operating strategies.

5.9 Recommendations
The European Commission (2001) stated that the largest energy savings to made are through better design and control of pump systems.

5.9.1 Recommendations for Better Design of Centrifugal Pump Systems
There is no single method to better design pump systems. In some cases installing VSD is appropriate whilst in other cases a smaller pump impeller is appropriate. The system itself has to be reviewed for energy savings including the pumps, piping, drives and other in line components. An energy assessment is a tool that can be used to identify the major energy efficiency opportunities and identify potential design improvements.

It is recommended that an energy audit or assessment be conducted as per the requirements of SANS 50002:2014 in order to identify, quantify and report on the
opportunities for improved energy performance. The energy audit should take into account life cycle costs and payback periods. ASME EA-2-2009 sets requirements for conducting and reporting the results of a pumping system assessment.

Many systems do not have instrumentation or monitoring equipment. Instrumentation is required to conduct an ASME EA-2-2009 Level 2 and Level 3 assessments. Pump monitoring equipment such as flow meters, pressure sensors, and power sensors are required to estimate the potential energy savings of the system. It is recommended that as minimum pressure gauges or pressure transmitters are installed.

5.9.2 Recommendations for Better Control and Operation of Centrifugal Pump Systems

In most cases the pump operating point cannot be determined as insufficient instrumentation is in place. It is recommended that pressure gauges or pressure transmitters be installed. The research participants were asked specifically if pressure was measured, in their experience pressure is not generally measured.

Larry Bachus (2014) strongly recommends measuring the differential pressure across the pump. The differential pressure indicates where the pump is operating on its curve. If operators are trained on how to read the gauges and manipulate the system to keep the pump operating near its BEP, pump reliability and efficiency would be improved.

Measuring the pressure whether using pressure gauge or pressure transmitters can support a maintenance plan. The gradual decrease in TDH (pressure) indicates that the impeller clearance has widened. (Brito, 2011). The impeller clearance can be adjusted, or the wear ring replaced, to restore the pump to its intended design performance.

Preventative and protective maintenance should include, as a minimum, the monitoring of the following (Brito, 2011; Dabbs et al. 2012):

- Bearing and lubricant condition
- Shaft seal condition
- Overall pump vibration
- Differential pressure

Acceptable ranges should be established for each of the instrument readings and compared to actual readings. Measurements should be trended over time. Many CMMS are able to provide trend charts for these measurements.

5.10 Conclusions

Centrifugal pumps account for the majority of pumps used in industry (European Commission, 2001). As a whole centrifugal pumps in industry consume a large amount of energy.

A qualitative research design was utilized. The research can be viewed as exploratory. The aims of the research are achieved through a literature review and interviews, guided by a questionnaire, with industry experts.
The operating point (flow, head) of a pump determines its efficiency and reliability.

Methods to improve centrifugal pump system performance through design:

1. Change the physical system a pump operates in
2. Change the diameter of the impeller or change the pump itself
3. Change the running speed of the pump

Methods to improve centrifugal pump systems through operating practices:

1. Correct maintenance procedures
2. Correct pump installation and line up
3. Pump monitoring and corrective action taken when a pump operates outside its best efficiency zone

Maintenance procedure most commonly used is a visual inspection and then do nothing until something goes wrong approach. The European Commission (2001) found that pumps are often poorly maintained, and are not given attention until they start to cause problems or stop working altogether. Findings from the interviews are in line with the literature reviewed. There is insufficient monitoring (instrumentation) on pump systems to determine the operating point of a pump. Pump pressure is not monitored and the condition of a pump cannot be determined. There is opportunity to improve pump operating practices.

Instrumentation can support operations. The differential pressure indicates where the pump is operating on its curve. If operators are trained on how to read the gauges and manipulate the system to keep the pump operating near its BEP, pump reliability and efficiency would be improved.

Instrumentation can support a maintenance plan. The gradual decrease in pressure indicates that the impeller clearance has widened. The impeller clearance can be adjusted, or the wear ring replaced.

An energy audit is a tool that can be used to review systems and quantify potential savings in a system. Instrumentation must be installed to conduct the audit.

Most pump optimisation of industrial pumps follow an 80:20 rule; about 80 of energy savings will come from optimising 20% of the pumps (da Cunha et al., 2008). The initial focus or priority should be on optimising pump systems that will result in the largest energy savings, refer to Section 2.17. to identify systems most in need of review.

In order to assess the commercial viability of optimising pump systems a payback period can be calculated. A payback period is the period of time required to for the outlay cost to equal the savings or to "break even". A payback period method is an approximation that does not take into the account all benefits (U.S. Department of Energy’s Industrial Technologies Program and the Hydraulic Institute, 2006).
In addition to energy savings, other benefits of optimising pump systems include (U.S. Department of Energy’s Industrial Technologies Program and the Hydraulic Institute, 2006):

- Increased productivity
- Lower maintenance costs
- Lower production costs
- Better product quality
- Improved capacity utilization
- Less down time
- Better reliability

Two of the four interview participants expressed negative views towards reviewing pump systems for energy savings. The first participant did not feel that pumps contributed that much to the overall power consumed by the plant. The second did not have confidence in the audit process.

The objectives of the study have been achieved as specified in Section 5.2 through to Section 5.5 i.e.

- Determine the factors that contribute to pump reliability and mechanical pump efficiency
- Determine what operation and maintenance strategies are used in industry
- Ascertain to what extent pumps are monitored and controlled in industry
- Establish if energy audits are being conducted in Industry

The largest energy savings to be made are through better design and control of pump systems, however there may be lack of expertise available (European Commission, 2001).

The research provides feasible recommendations to improve the performance of inefficient centrifugal pump systems and is relevant to all centrifugal pumps in industry. These methods are validated through literature reviewed. Research participants provided valuable insight into operating practices currently used in industry.
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APPENDIX 1 QUESTIONS FOR INTERVIEW DURING INITIAL DATA COLLECTIONS
Date:
Participant Name
Position
Job Function
Years of experience
Contacts

**Interview Questions**

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**Objectives:**

1. Determine the factors that contribute to pump reliability and mechanical pump efficiency
2. Determine what operation and maintenance strategies are used in industry
3. Ascertain to what extent pumps are monitored and controlled in industry
4. Establish if energy audits are being conducted in Industry

**Questions:**

- Have you had experience with unreliable pumps?  
  __________________________________________________________________________
  __________________________________________________________________________
  __________________________________________________________________________

- Is there any kind of pump monitoring currently in place?  
  __________________________________________________________________________
  __________________________________________________________________________

- What factors do you believe contribute to pumps being unreliable?  
  __________________________________________________________________________
  __________________________________________________________________________

- Have any energy audits been carried out and if so what was the outcome of those audits?  
  __________________________________________________________________________