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Department of Physics

PERFORMANCE OF A RESIDENTIAL SWIMMING POOL AIR SOURCE HEAT PUMP WATER HEATER INSTALLED IN FORT BUEAFORT, SOUTH AFRICA

BY

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(201214270)

Dissertation submitted in partial fulfilment of an Award of a Master's of Science degree in Physics

Supervisor: Dr M. Simon

DECLARATION

I declare that this project on “Performance of a residential swimming pool, air source heat pump water heater installed in Fort Beaufort, South Africa” is an original work done by me under the supervision of Dr Michael Simon and team leader Engr Stephen Loh Tangwe at the Faculty of Science and Agriculture, Department of Physics, University of Fort Hare. It has not been submitted to any other University or Institution for evaluation purposes for the award of any degree. All the information herein has been duly acknowledged at the reference section.

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Singatha Mqhayi (Student)

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Dr Micheal Simon (Supervisor)

DEDICATION

I dedicate my work to my family, my late loving parents, Mr and Mrs Nobonke Mqhayi and Eric Mqophiso Mqhayi whose words of encouragement pushed me up to this level. Not leaving out my very special sisters and brothers, who have never left my side, hence served as a source of encouragement and the drive needed to stand out in every endeavor. Also, I would like to dedicate this work to my best friend Noluthando Mzolo and my wonderful daughter, Akuwe Minentle Maputle for being there for me throughout the entire journey.

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LIST OF ABBREVIATIONS AND SYMBOLS

ASHP:	Air source heat pump
DAS:	Data acquisition system
COP:	Coefficient of performance
ESKOM:	South African electricity public utility
IDM:	Integrated Demand Management
FC:	Forcing constant
HP:	Heat Pump

WP:	Water circulation pump
Rh:	Relative humidity [%]
VCRC:	Vapour compression refrigeration cycle
T_{amb}	Ambient temperature (℃)
T_{in}	Temperature of water at the inlet of the swimming pool ASHP (℃)
T_{out}	Temperature of water at the outlet of the swimming pool ASHP (℃)
V_{tot}	Total volume of heated water (litres)
Q:	Thermal energy (kWh)
E:	Electrical energy (kWh)
P:	Power consumption (kW)
t:	Time taken (h)

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CHAPTER ONE

INTRODUCTION

1.1 BACK GROUND

For several years, fossil fuels have been used as the primary source of energy [International Energy Agency, 2013]. Even today, 82% of the primary energy requirements are satisfied by non-renewable generating techniques such as gas and oil, which are very costly and non-environmentally friendly [Department of Environmental Affairs, 2013]. In addition, it is also reckoned that the world's power source of energy generation is from coal [European Heat Pump Assn, 2005].

Precisely in South Africa, electricity is predominantly derived from the non-renewable energy source (coal), which is associated with both environmental pollution and exhaustibility [Tangwe *et al*., 2014]. Moreover, there has been a drastic increase in the energy use worldwide, and without loss of generality, more than 85% of Eskom generated electrical energy from the coal thermal power plant are likely insufficient to meet Eskom's peak demand [Eskom, 2011]. This further compounds the existing energy crisis or challenge.

Consequently, these challenges have led to a global interest in seeking renewable and energy efficient methods to satisfy our electricity and heating needs [Department of Environmental Affairs, 2013]. Clearly, these shortcomings have driven the South African government in collaboration with Eskom and the Department of Energy to promote the utilization of renewable energy efficient technologies in the country. In this light, the government is focused on the reduction of greenhouse gas emissions that leads to global warming. Also, Eskom has initiated a strategic plan as from 2010 to 2030 with the anticipation to achieve over 20% reduction of electricity production from coal, to be used in the residential sector [Digest of SA Energy Statistics, 2009]. In addition, it embarked on the heat pump rebate program to promote the use of renewable and efficient energy technologies (heat pumps, water heaters) in a bid to provide a demand reduction in the residential sector [Eskom, 2011].

Globally, water heating contributes a substantial percentage of energy consumption in all the sectors cutting across industrial, commercial and residential sectors [Tangwe *et al*., 2015]; but residential water heating could account for about 50% of the monthly electricity consumption in South Africa [Tangwe *et al*.,2015]. The conventional method of residential water heating employs the use of boilers; a technique which is faced with high fuel consumption and carbon dioxide emissions. Accordingly, Martin (2008) proposed the utilization of heat pumps for heating and demonstrated that they could cut down fuel and energy consumption as well as carbon dioxide emission.

Interestingly, based on energy-related measurements, heat pumps have been viewed as one of the renewable energy-efficient technologies for water heating and can be used to heat water at a swimming pool as well as for domestic sanitary hot water production. [Bobble, 1974; Buston *et al.*, 1985; Kim and Fluck, 1977]. The main advantage of using heat pump technology is that waste heat can be extracted from its natural surroundings, from various sources and then transported to heat or cool domestic, commercial and industrial buildings elsewhere. The waste heat source is free and of low-grade energy. There are many different types of heat pump technologies, including the ground source HPs, air source heat pumps (ASHPs), gas-engine-driven heat pumps, chemical source heat pumps, hybrid heat pumps and, water-source heat pumps.

Of interest, the performance of the heat pump is characteristic of its efficiency and it is known as the coefficient of performance (COP). The COP is the basic performance parameter used to analyse the efficiency of the heat pump system. It is defined as the ratio of the total useful thermal power that is released from the heat pump to the total input electrical power used by the heat pump during vapour compression refrigeration cycle (VCRC). The higher the COP, the more efficient the heat pumps. It is noteworthy that the estimated energy savings when this particular system was operated was found to be up to 65-75% [Tangwe *et al.*, 2016].

1.2 PROBLEM STATEMENT

Globally, there is growing concern about energy consumption and its diverse effects on the environment. In South Africa, the current status quo is unfavourable in the domain of energy, hence the Department of Energy, Eskom and NERSA have embarked on supporting energy efficiency technologies nationwide as a strategic goal in reducing demand on the national grid. Due to the non-conservative consumption of electricity from the grid and the insufficient supply to meet its demand, the importation of crude oil is very certain.

In addition, the current and most popular technology for pool water heating in the said country is the resistive element which is inefficient and non-cost-effective. The energy consumption of residential swimming pool water heating is very massive, and tariff structure shows a constant rise. Furthermore, there's a current electricity crisis during the Eskom evening peak. Hence, a reliable, efficient, cost-effective and renewable energy technology such as an air source heat pump is required as a retrofit to the existing resistive element.

Furthermore, mathematical modelling is a tool that can be used to mimic the dynamic behaviour of a physical or process system. It is a computational language or mathematical equation used to predict the dynamic behaviour of physical systems [Tangwe *et al*., 2015]. Various methods such as numerical methods have been considered as the particular types of mathematical modelling which have been employed to predict the performance of swimming pool ASHP water heater. However, they were unreliable and expensive. Consequently, this research focused on the experimental determination of the viability and development of a mathematical model to predict the performance of swimming pool ASHP water heater. The benefit of the development and building of this model was attributed to its low cost and credibility to forecast the performance of swimming pool ASHP water heater. Also, this robust mathematical model can be used by an energy service company and system manufacturer to compute the dynamic coefficient of performance of the swimming pool ASHP water heater.

Following the above-mentioned information, the research sought to provide a permanent solution to the Eskom evening peak constraint. This is because energy-efficiency, serves as the bridging block between conventional and renewable energy sources needed by Eskom in a bid to provide a balance energy mix and sustainable energy. The implementation of a swimming pool ASHP water heater guaranteed a conducive environment for the population due to the reduction in environmental pollution.

1.3 RESEARCH OBJECTIVES

1.3.1 OVERALL OBJECTIVES

The main aim of this study was to design and build a data acquisition system required for the investigation of parameters relevant to forecast the performance of a residential swimming pool ASHP.

1.3.2 SPECIFIC OBJECTIVES

The primary objectives of the study were;

i. To determine the variation of critical predictors (power consumption of the water circulation pump, temperature of water at the inlet of the swimming pool ASHP and ambient temperature) to the desired power consumption of the swimming pool ASHP unit.
ii. To determine the simple payback period of the swimming pool ASHP using the experimentally determined average COP.
iii. To derive a multiple linear regression mathematical model which could be used to predict the power consumption of the swimming pool ASHP using the following predictors: Power consumption of the water circulation pump, temperature of water at the inlet of the swimming pool ASHP and ambient temperature.

1.4 RESEARCH QUESTIONS

i. How does the variation of the critical predictors (power consumption of the water circulation pump, temperature of water at the inlet of swimming pool ASHP and ambient temperature) influence the performance of the swimming pool ASHP power consumption?
ii. Can the simple payback period of the swimming pool ASHP water heater be determined from the economic analysis based on the experimentally collected data?
iii. Can a mathematical model be used to accurately forecast the performance of a swimming pool ASHP water heater?

1.5 SIGNIFICANCE AND MOTIVATION OF THE STUDY

The research provided insights into the typical performance of the swimming pool ASHP water heater operated under different seasons and weather conditions, which was located in a residential home in Fort Beaufort in the Eastern Cape Province. Development of a mathematical model aided in the characterization of the COP using predictors' parameter such as ambient temperature, the power consumption of the water circulation pump and water temperature at the inlet of the swimming pool ASHP. The primary significance of this mathematical model was its uniqueness and simplicity compared to other complex computational methods that have been employed to determine performance.

In addition, the mathematical model has been described as a very economically friendly tool which is available in many affordable data analysis packages. It could be used by energy companies and manufacturers to predict the performance of heat pump water heaters.

Nevertheless, the quest to provide a lasting, sustainable solution to the current crisis is the implementation of an energy efficiency initiative. Accordingly, this study was centered on energy efficiency, thus, it can provide a potential solution in reducing electricity demand in the residential sector.

1.6 DELINEATION AND LIMITATIONS

a. The research dealt with the experimental analysis of critical input parameters (power consumption of water circulation pump, water temperature at the inlet of the swimming pool ASHP and ambient temperature) and the output parameter (power consumption of swimming pool ASHP water heater).
b. It also embodied the development of the multiple regression model using experimentally obtained data for both the predictors and desired response.
c. The research was limited to experimental study from one site and hence not a full weather condition of the whole regions in the country.

1.7 THESIS STATEMENT

The operation of the swimming pool ASHP water heater can be estimated with over 90% confidence level by the use of a multiple linear regression model and the simple payback period of the swimming pool ASHP unit was under 1.5 years based on economic analysis of experimental data.

1.8 OVERVIEW OF CHAPTERS

The thesis is made up of six chapters with each chapter unravelling different aspects of the research as follows;

Chapter 1 introduces the topic of the research, explains the background information and significance of the study. Also, the problems to be solved by this study, aim and objectives implemented and respected in order to achieve a successful completion of this study are clearly presented herein.

Chapter 2 covers similar comprehensive work done by other researchers (literature) including the recent development of the heat pumps. Clearly, a review of the performance of the swimming pool ASHP water heater as well as the existing heat pump technologies, their application and performance has been elaborated. Also, the summary of parameters that influence the performance of the heat pumps is discussed

Chapter 3 entails the details or full description of the materials used to obtain the data collected from various experiments done during the monitoring period. The methods employed for data collection and data analysis were discussed in this chapter as well as the mathematical models were introduced. Unique parameters and specifications of different sensors are highlighted, such as ambient temperature and relative humidity sensors, temperature sensors, flow meters as well as the power track analysers.

Chapter 4 encompasses information on the observations and results obtained from the experiments and data analysis of the study. These are consistent results obtained from the performance monitoring period of three months. Plots representing measured parameters as well as the predictors are presented through graphical analysis. Also, a techno-economic analysis of the technology was conducted to ascertain the potential viability.

Chapter 5 deals with the building and development of the mathematical model that was aimed at predicting the dynamic desired response of the swimming pool ASHP water heater. The accuracy of prediction of the developed model was also validated based on core statistical parameters such as the determination coefficient and the mean bias error.

Chapter 6 provides the summary of the major findings of the research, and their contributions to the science domain and society. The conclusions drawn from the discussions in chapter 4 and 5, the recommendations based on the findings of the research and suggestions for further work beyond the scope of this investigation are discussed in this chapter.

CHAPTER TWO

FUNDAMENTAL PRINCIPLES AND LITERATURE REVIEW

2.1 THE HEAT PUMP WATER HEATER TECHNOLOGY

The heat pump water heater is an electro-mechanical system comprising of a heat pump and a hot water storage system. In ASHP water heater, the heating action of the water is achieved by the heat pump while the storage tank serves as a reservoir for the hot water [Tangwe *et al*., 2015]. On the other hand, in a swimming pool ASHP water heater, the heat pump still performs the heating action while the swimming pool acts as the reservoir [Tangwe *et al*., 2016]. It is paramount to understand that lots of work has been done on the residential ASHP water heaters whereby the geyser functions as a storage tank but very limited literature can be found in swimming pool ASHP water heater with the swimming pool serving as the storage system.

Moreover, the heat pump operates on a vapour compression refrigeration cycle similar to the air conditioning unit (i.e. Reverse Rankine cycle) even though the conditioning unit is being used for air cooling purposes. Generally, if a heat pump is designed for the sole purpose of hot water production, it is called a heat pump water heater. In addition, heat pump unit in a heat pump water heater transfers the renewable aero-thermal energy from the environment to the water stored in the tank. Heat pump water heaters are categorized based on the source from which it extracts its renewable energy. Relying on this criterion, if renewable energy is from the ground (geothermal energy), it is called a ground source heat pump (GSHP), if the source is from the air, that is called an air source heat pump (ASHP), if the source is directly from the sun (solar energy), it is called a solar assisted heat pump (SAHP) water heater and if the source is from water (hydrothermal), it is called water source heat pump (WSHP). The ASHP water heater is the type that was implemented in this research, but with the specific objective of heating water in a swimming pool to the desired set point temperature.

2.2 DESCRIPTION OF AN ASHP WATER HEATER

The ASHP water heater transports thermal energy during its vapour compression refrigeration cycle from ambient air to heat water in a storage system and in turn causing cooling and dehumidification of the air [Morrison *et al*., 2001]. An efficiently installed ASHP water heater has a COP which ranged between 2 and 4 whereas typical conventional water heaters (i.e. electrical resistance element, coal, gas, kerosene stove, etc.) have a performance energy factor less than or equal to 1 [Levins, 1982; Bodzin, 1997; Oak Ridge National laboratory, 2009].

In addition, in an ASHP water heater, heat is being transferred from the air (cold reservoir) to heat water (hot reservoir) and this process can only be possible with the input of energy (electrical) to the heat pump (cyclic engine). This is in conformity with Cluasuis statements which are in accordance with the second law of thermodynamics. Figure 2.1 shows a block diagram of energy distribution in a typical ASHP water heater and figure 2.2 shows a schematic block diagram of the components involved in the vapour compression refrigeration cycle process that occurs in the ASHP unit.

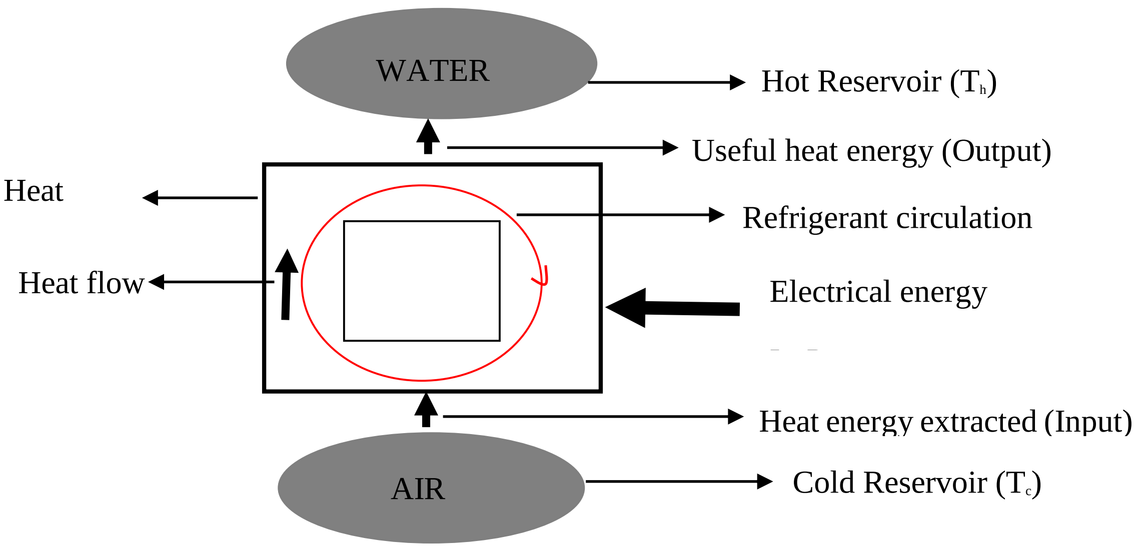

Figure 2.1: A block diagram of energy distribution for typical ASHP water heater

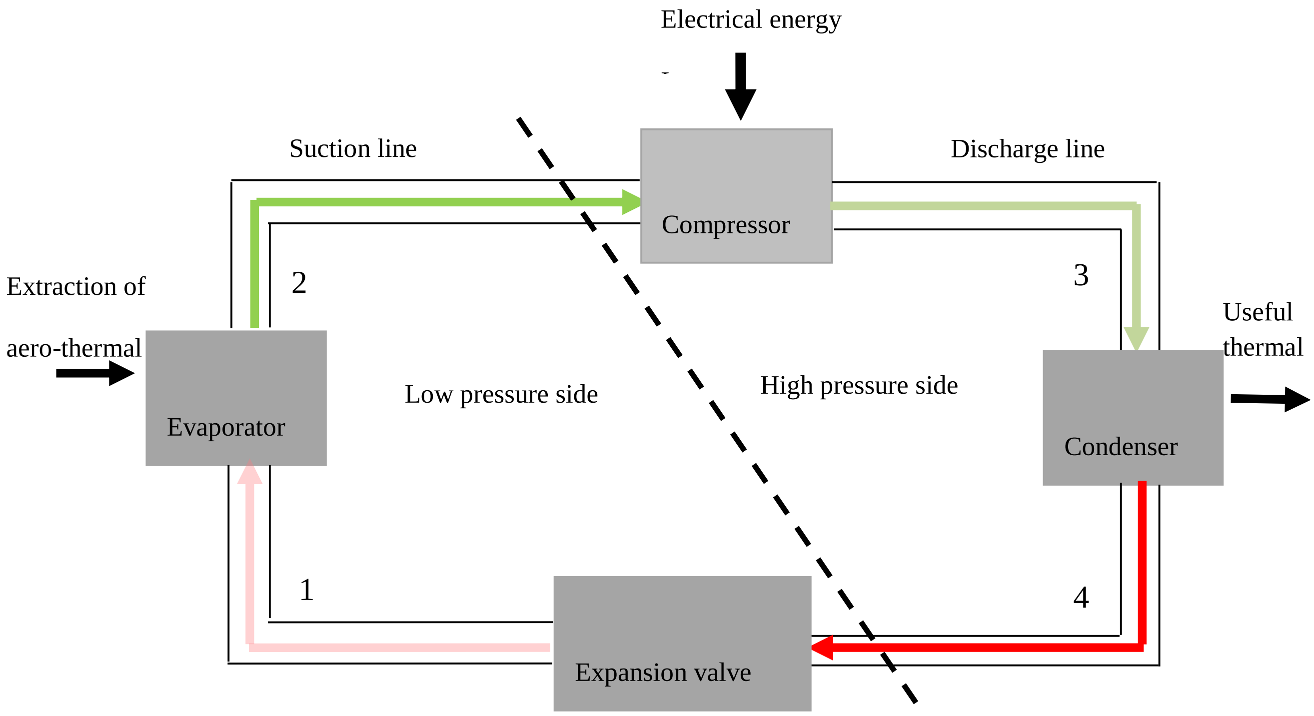

Figure 2.2: A schematic block diagram of the ASHP main components

2.3 MAJOR COMPONENTS OF ASHP UNIT AND HOW IT WORKS

2.3.1 COMPONENTS

The ASHP (standalone system) constitutes of the following principal components:

(a) An evaporator (metallic tube coils) which acts as a heat exchanger between the ambient air and the refrigerant (liquid and vapour coexist). Heat is transmitted from the ambient air to the refrigerant.

(b) A compressor that functions in compressing lower pressure and temperature refrigerant vapour to a high temperature and pressure super-heated refrigerant vapour.

(c) A condenser (metallic tube in tube coils) which acts as heat exchanger between a high temperature and pressure refrigerant and the water circulating inside the water pipes embedded in the condenser compartment.

(d) A thermal expansion valve which carries out the process of throttling whereby a high pressure and high temperature saturated refrigerant liquid is converted to a low temperature and low pressure refrigerant (liquid and vapour coexist).

In addition to the mentioned primary components, there are also:

(e) A simple propeller axial fan situated at the rear end of the evaporator which is responsible for forceful convection of ambient air to enhance the rate of heat extraction.

(f) An electric induction motor which drives the crack shaft of the compressor during the vapour compression refrigeration cycle.

(g) The refrigerant is the working (primary) fluid and undergoes phase changes during the compression and expansion cycles. The refrigerant fluid (primarily) used in heat pumps must be able to possess very good thermo-physical properties to allow for efficient expansion and compression cycles. It should equally be non-toxic, non-flammable, with zero ozone depletion potential, minimal global warming potential and with a very low boiling point.

(h) A water circulation pump to facilitate the flow of water (secondary fluid) circulating between the tank and the condenser of the ASHP unit.

2.3.2 THE PROCESS OF VAPOUR COMPRESSION REFRIGERATION CYCLE

The overall process can be illustrated as shown in figure 2.2. A salient and better understanding of refrigeration cycle of heat pump water heater was given by Ashdown *et al*. (2004) and Sinha and Dysarkar, (2008). During a vapour compression refrigeration cycle, aero-thermal energy extracted from the evaporator end is absorbed by the refrigerant (liquid and vapour coexist). This changes the phase of the liquid portion to vapour without any change in the refrigerant temperature (latent heat) and also sensible heat is gained by the refrigerant. The process is isothermal.

Owing to the pressure difference between the suction line and the discharge line shown in figure 2.2, the refrigerant vapour (dry and low temperature and pressure refrigerant vapour) flows to the compressor, where the vapour is compressed to a super-heated vapour which exits along the discharge line. The process is isentropic. As the super-heated refrigerant vapour flows into the condenser, the refrigerant is cooled and a saturated refrigerant liquid is formed and heat is dissipated to heat up the water flowing inside the inner tube of the condenser. At this stage (3 – 4), the temperature of the super-heated vapour drops to form a desuper-heated vapour, which in turn losses heat to become a saturated refrigerant liquid. At the expansion valve, the pressure and temperature decrease and saturated refrigerant vapour becomes a low pressure liquid refrigerant (isenthalpic process).

2.3.3 TECHNOLOGY AND TYPES OF RESIDENTIAL ASHP WATER HEATER

Although, there is a substantial growth in the technology of the ASHP water heater, it is not yet economically ascertaining due to its market price, limitation of public awareness of the product, and a wrong conception of system durability [Douglas, 2008]. Also, poor installation and lack of routine maintenance can lead to inefficiency of the system.

Nevertheless, heat pump water heaters also render an extra benefit of dehumidifying and space cooling because during operation, it pulls warm vapour from the air [Baxter *et al*., 2005].

In Japan, there are already manufactured innovative heat pump that exploits carbon dioxide as the refrigerant fluid and is more than 300 % energy efficient. This was made possible due to the government and private partnership rebate initiatives [Hashimoto, 2006; Maruyamma, 2008].

The residential ASHP water heater can be used for both sanitary hot water heating and for swimming pool water heating. There exists limited literature on swimming pool ASHP water heater. It is paramount to mention that residential ASHP water heater for sanitary hot water production can be divided into two categories; namely the split and integrated type ASHP water heater [Marrison *at al*., 2001].

More elaborately, there are two types of residential ASHP water heater namely;

i. Integral ASHP water heater – This is a heat pump water heater with the condenser immersed as an essential part of the tank or mounted inside the tank. Heat is delivered to the water in the tank by free convection over the tank wall or condenser tubing inside the tank [Tangwe *et al.,* 2016]. It is also known as a hybrid or 'drop in' heat pump water heater. Figure 2.3 illustrates a schematic diagram of an integrated type ASHP water heater.

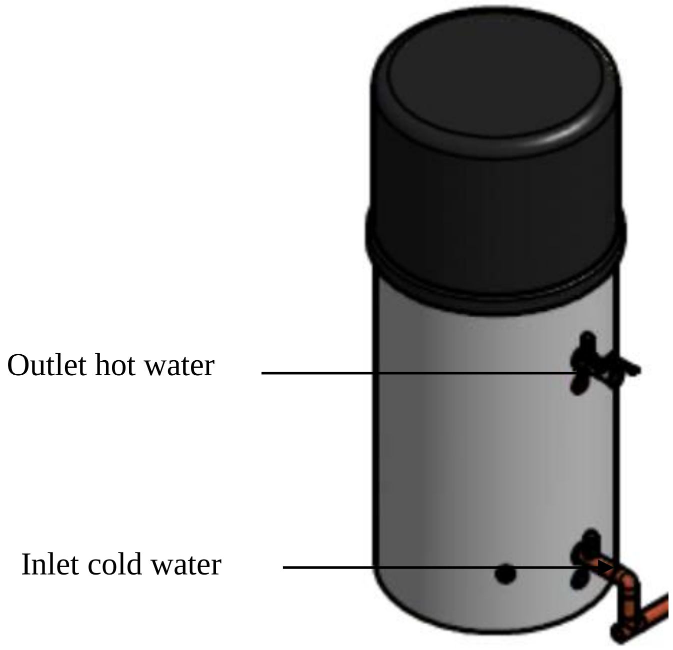

Figure 2.3: Schematic diagram of a residential integrated type ASHP water heater (Tangwe *el al*., 2016)

ii. Split (Standalone) heat pump water heater: This is a heat pump water heater without the heat pump unit directly mounted together with the storage tank. Heat is being delivered to the water flowing through the condenser of the heat pump. It is also known as the retrofit heat pump water heater.

In addition, the Split type systems can be grouped into re-circulating and once-through as described below:

(a) Re-circulating split type heat pump water heater: Heat pump water heater that requires recirculation of water between the tank and the heat pump in order to attain the required set point temperature before the heating up cycle can be terminated. These types of systems are also known as multi-pass systems [Bodzin, 1997].

(b) Once-through split type heat pump water heater: Heat pump water heater that the heat pump is capable to deliver water at the required set point temperature (usually 55°C or higher) in one pass through the heat pump. Figure 2.4 shows the schematic diagram of a residential split type ASHP water heater.

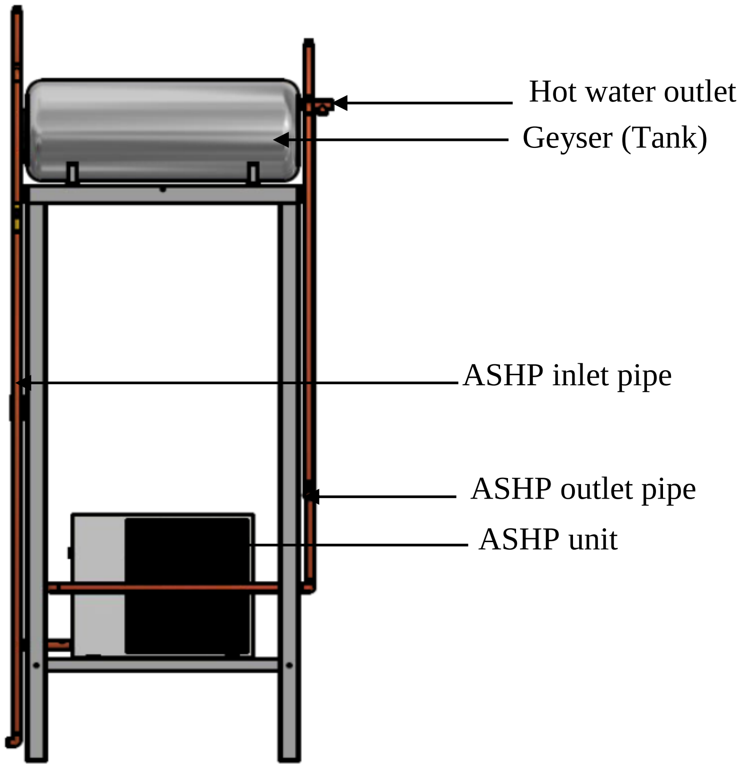

Figure 2.4: Schematic diagram of a residential split type ASHP water heater (Tangwe *el al.*, 2016)

The overall classification of heat pump water heater is as shown in figure 2.5 with special emphasis on the ASHP water heater which is critically monitored under this research.

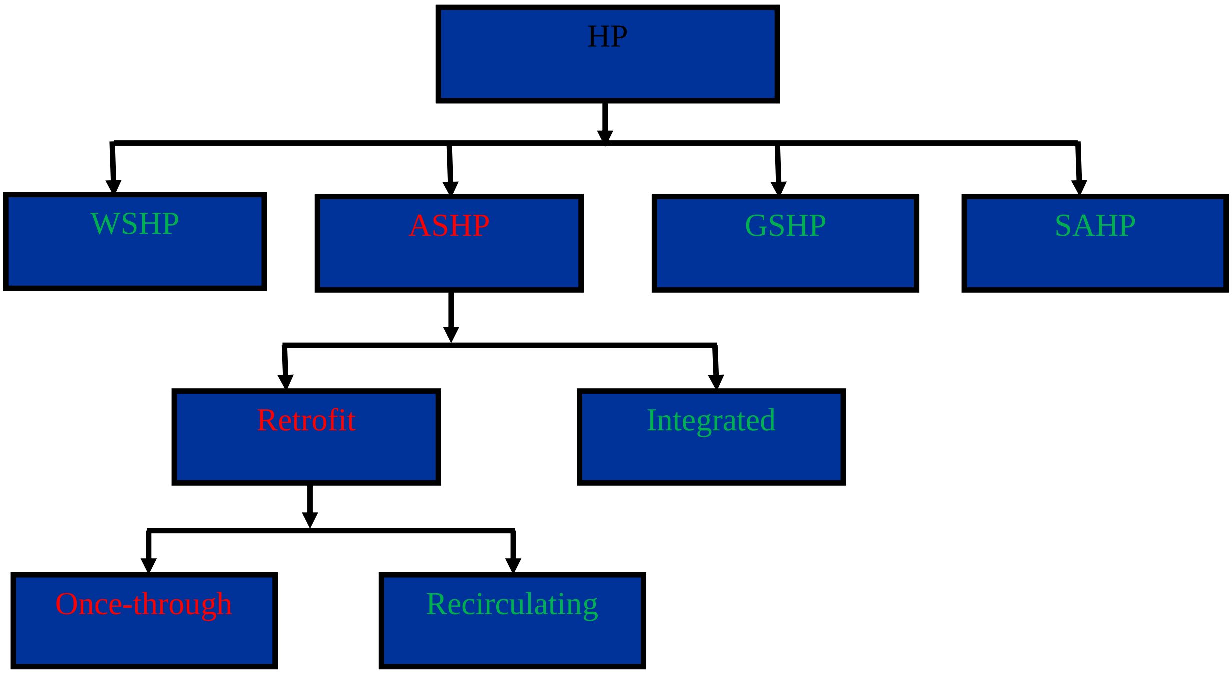

Figure 2.5: Flow chart classification of heat pump water heater

2.3.4 Swimming Pool ASHP Water Heater Performance and Basic Components Functionality

The recent and most popular technology for pool water heating in South Africa is the resistive electrical element which is an inefficient conventional geyser [Tangwe *et al.*, 2015]. Traditionally, the seasonal performance of heat pump water heating is usually determined by instantaneous performance rating and climate condition analysis method [Schinuola, 2000]. Swimming pool ASHP operates by utilizing aero-thermal energy to heat pool water to a desirable set point temperature and maintain a pool temperature at 27-35℃ for swimming comfortability [Tangwe *et al.* 2016].

The swimming pool ASHP is energy efficient and renewable device that is used to heat pool water from an initial temperature of around 24°C to desirable set point temperature (27-35 °C). The use of this heating technology could save up to 80% of power consumption compared to other conventional electrical heaters [Tangwe *et al.*, 2016a]. Like residential ASHP, it operates by the principle of vapour-compression refrigeration cycle (VCRC). The swimming pool

ASHP water heater uses electricity to operate. It comprises of the following primary components; swimming pool as a reservoir, filter which is chlorinated with chemicals to kill germs and bacteria.

Generally, the ASHP unit which is a closed loop circuit system comprises of the major components that make up the vapour compression refrigeration cycle and consists of the compressor, evaporator, refrigerator and an expansion valve [Tangwe *et al.,* 2016b].

It uses fan to draw in air over an evaporator coil filled with liquid refrigerant. The ambient heat in the air is absorbed by the refrigerant. The refrigerant is then pumped into a compressor which amplifies the heat. The extremely hot refrigerant is pumped into a heat exchanger (condenser) where the heat is transferred to the water supply. The refrigerant turns into a liquid state and is pumped through an expansion valve to cool and then sent back into the evaporator coil. Figure 2.6 shows a full schematic layout of a residential swimming pool ASHP water heater system.

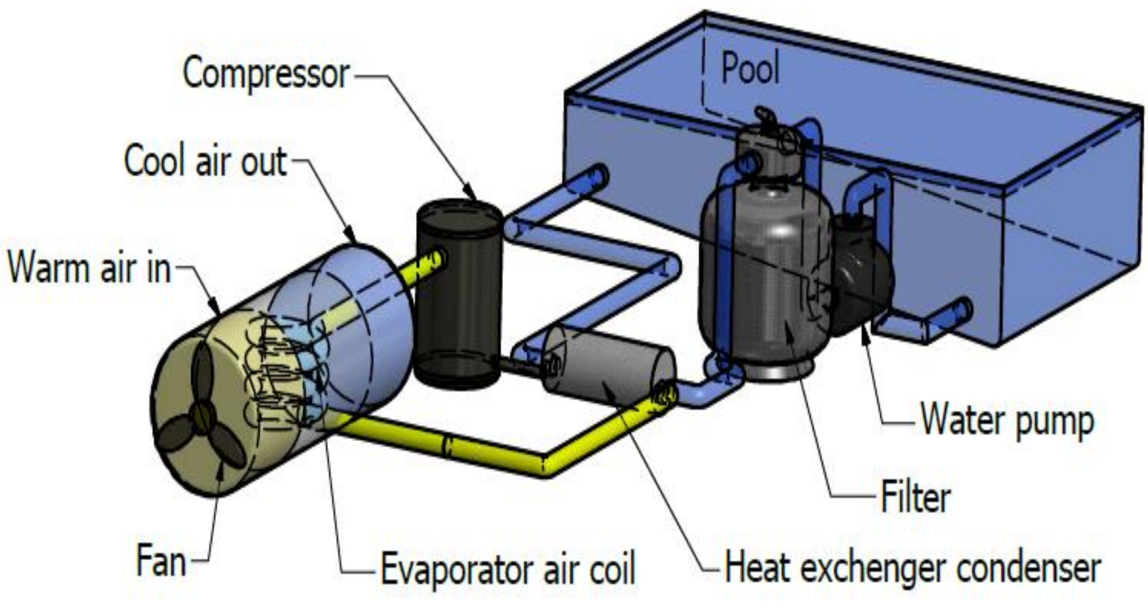

Figure 2.6: Full schematic layout of a residential swimming pool ASHP system

The components of the swimming pool ASHP close loop circuit are hereby described briefly as follows;

a. Compressor: It is a prime mover and an electro-mechanical device in which its performance is reduced when the operating temperature is too high. Basically, the performance of the compressor depends on the temperature range between the evaporator and the condenser. In the previous studies from researchers, much research has been undertaken to improve energy efficiency of the compressor [Wang *et al*., 2009].

b. Evaporator: This acts as the first heat exchanger during the vapour compression refrigeration cycle. Ambient warm air is drawn from the surroundings and transferred directly to the first heat exchanger which is the evaporator whereby the aero-thermal energy in the surrounding of the evaporator is absorbed by the refrigerant to convert the refrigerant from saturated liquid to saturated vapour.

c. Expansion valve: It is the key element of a heat pump that controls the amount of refrigerant that flows into the evaporator thereby controls the superheating at the outlet of the evaporator. Expansion valves are flow restricting devices that cause pressure drops of the working refrigerant [Rankin and Eldik, 2008].

d. Condenser: It removes heat given off during liquefaction of vapourized refrigerant. Heat is said to be given off when there is a temperature drop in condensation temperature. In order to remove excess heat, the refrigerant is forced through the condenser.

e. Refrigerants- They are the working fluids in the heat pump cycle. It is important at this junction to point out that of great concern is their environmental pollution and ozone depletion potential. The most common refrigerant used in the swimming pool ASHP water heaters is the R407C refrigerant because it has less impact on the environment. It has zero ozone depletion and moderate global warming potential compared to other refrigerants like R22 [Tangwe *et al.,* 2016].

2.4 OPERATION OF A SWIMMING POOL ASHP SYSTEM

Taking into consideration figure 2.6, a swimming pool ASHP system composes of an air source swimming pool heat pump unit, a filter, a circulation water pump and the swimming pool. The swimming pool acts as a reservoir and functions both as a source and sink for the desired water to be heated by the swimming pool ASHP unit. All the major components of the air source swimming pool heat pump are connected to form a close system by plastic tubing (PVC).
The swimming pool ASHP unit is an electro-mechanical renewable device that operates in the reverse vapour compression refrigeration cycle in the process of heating up the water in the pool to the set point temperature. Furthermore, the filter prevents debris from entering the heat pump as swimming pool water circulates between the pool and the heat pump. The water circulation pump imparts the water pressure on the water reticulation pipelines connecting the swimming pool and the air source swimming pool heat pump unit.

In addition to the aforementioned components, the system also contains a skimmer which acts as the primary channel, from where the swimming pool water leaves the pool into the air source swimming pool heat pump unit. The skimmer also contains a fine filter that collects large particles prior to the pool water, which is intended to be heated flows into the swimming pool

ASHP unit. There also exist the return ducts, which serve as the channel for the heated water to be pushed back into the swimming pool. The bottom drains provide the passage where swimming pool water could be drained out. Nevertheless, the light emitting diode (LED) lamps installed in the swimming pool make it possible for the pool to be used at night and the vacuum ports remove carbon dioxide building up inside the swimming pool. The pool is protected from heat losses by the use of a pool blanket.

2.5 PERFORMANCE AND LOSSES OF GEYSER AND ASHP WATER HEATER

The characteristic feature which gives the heat pump water an efficiency of more than 300% is known as the coefficient of performance [De Swardt and Meyer, 2000]. A dynamic performance of water heater driven by heat pump was proposed and designed to model the coefficient of performance of heat pump water heater [Kim *et al*., 2004]. The coefficient of performance of heat pump water heater can be enhanced by using R11 (Chlorofluorocarbon compound) and R22 (Hydrochlorofluorocarbon compound) as the thermo-physical refrigerant in the heat pump unit [Zhang *et al*., 2007]. Heat pump water heater with dual tank gives better performance than the corresponding system with a single tank and the hot water usually attained a much higher temperature [Carl, 1996]. The instantaneous, seasonal or annual COP can be determined using the TRYSYN simulation software package [Klinge *et al*., 2000]. Itoe *et al*. (1999) presented an analytical, mathematical model of the performance of a solar assisted heat pump water heater correlating ambient temperature and hot water set point temperature.

The average energy factor of a geyser is 0.92 owing to the standby losses in the hot water cylinder [Haung and Lin, 1997]. The standby losses of the geyser were determined by the multi-level expert modelling and evaluation of geyser load management opportunities in South Africa [Deport. and Van Harmelen, 1999]. Similarly, an experimental method was conducted to determine the geyser standby losses [Beute., 1999]. Optimized geyser control switching method was equally used to minimize the geyser standby losses [Zhang and Xia, 2007]. In addition, the standby losses of the integrated heat pump water heater were evaluated using a laboratory benchmark approach [Sparn *et al*., 2011].

2.6 MATHEMATICAL MODELING OF ASHP WATER HEATER

A mathematical modelling is the use of mathematical language or equations to describe the dynamic behaviour of a system, taking into considerations some predictors in order to forecast the response. A mathematical model can be of great benefit in optimization and control of the system under different scenarios. Different regression models have been developed and built to model the performance of an air source heat pump water heater in the different heating up cycles. Precisely, a multiple linear regression model was used as the mathematical model to predict the performance of the ASHP water heater at the first hour heating rating [Tangwe *et al*., 2014]. In addition, mathematical models embedded in the multi-dimensional unit contour plots simulation in the MATLAB statistical tool was used to illustrate how each of the predictors (ambient temperature, relative humidity and heat pump COP) varied with the COP of the system while all the other predictors were held constant [Meyers and Montgomery, 1995]. Furthermore, the multiple comparison test was performed to evaluate any mean significant difference based on comparing the interval between the difference of the 95% mean confidence interval and the true mean of one particular heating up cycle to the other for all the possibilities in the heating up operation. This was done by employing the analysis of variance approach [Goodall, 1993; Hochberg and Tamhane, 1987].

2.7 COMPARISON OF RESIDENTIAL ASHP WATER HEATER AND A RESIDENTIAL SWIMMING POOL ASHP WATER HEATER.

Domestic ASHP water heater used for sanitary hot water heating (hot water set point temperature 55°C) is commonly known as the residential ASHP water heater. Seemingly, domestic ASHP water heater used for swimming pool water heating (Hot water set point temperature 27-35°C) is also known as residential swimming pool ASHP water heater. The table 2.1 shows a comparative analysis of the two systems.

Table 2.1: Comparative analysis of residential and swimming pool ASHP water heater

Quantity	Residential ASHP Water heater	Swimming pool ASHP Water heater
Water set point temperature	55°C-60°C	27°C-35°C
COP	2-4	3-8
Typical storage capacity	200 l	65000 l
Input power	1.2 kW	5.6 kW
Typical capita cost	R 15000	R56000
Installation cost	R4000	R12000
Simple payback period	3- 6 years	1-2 years
System life span	15 years	15 years

2.8 FACTORS AFFECTING THE POWER CONSUMPTION OF SWIMMING POOL ASHP WATER HEATER.

The key factors that can influence the power consumption of a swimming pool ASHP water heater are ambient temperature, relative humidity, wind speed, heat losses, initial water temperature of the pool and the sizing of the entire system according to our experimental study. These outcomes can be supported from our analysed results and discussion which have been presented in chapter 4.

a. Ambient temperature: It is the air temperature in the vicinity of an outdoor system. The power consumption of the swimming pool ASHP water heater could increase with an increase in the ambient temperature.
b. Relative humidity: It is the amount of water vapour present in the air expressed as a percentage of the amount needed for saturation at the same temperature. The power consumption of the swimming pool ASHP system turns to increase with a corresponding increase in the relative humidity. But, it should be alluded that an increase in relative humidity often accompanies a decrease in ambient temperature.
c. Wind speed: It is the rate at which the air is moving in a particular area. The power consumption of the swimming pool is likely to increase with a corresponding increase in the wind speed in the vicinity of the swimming pool ASHP system.
d. System sizing: The capacity of the swimming pool if optimally sized to the input power of the swimming pool ASHP unit could result in better performance and efficient operation of the system.
e. Initial swimming pool water temperature – The total power consumption of the swimming pool strongly depends on the initial temperature of water in the swimming

pool. The power consumption of the swimming pool ASHP water heater would increase with an increase in the initial water temperature of water in the swimming pool.

f. Heat losses at the surface of the swimming pool – The power consumption of the swimming pool ASHP water heater is also affected by the rate of heat losses on the surface of the swimming pool. The power consumption of the swimming pool ASHP can increase as the heat losses of water in the swimming pool increases.

g. Power consumption of the water circulation pump: The water circulation pump assisted to impart the pressure of the water flowing in and out of the inlet and outlet of the swimming pool ASHP water heater during VCRC. An increase in the power consumption of the water circulation pump can result in an increase in the power consumption of the swimming pool ASHP system.

The research was limited to the swimming pool ASHP water heater with focus on;

a) Experimental monitoring of the variation of some key input parameters that could influence the power consumption of the system.

b) Determination of simple payback period based on the experimental data collected from the operation and performance of the system.

c) Classification of the predictors (the selected key parameters) according to their relative weight of contribution to the power consumption of the swimming pool ASHP water heater.

d) Development and building of a multiple linear regression model that correlates the predictors (temperature of water at the inlet of the swimming pool ASHP, power consumption of water circulating pump and ambient temperature) to the power consumption of the swimming pool ASHP water heater.

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter demonstrates the protocol that was adopted to investigate the targets expressed as the objectives of this study. The full performance monitoring of the system was conducted in a residential swimming pool ASHP water heater located in Fort Beaufort in the Eastern Cape Province of South Africa. Also, included in this chapter are the descriptions of the equipment that were used to assemble the data acquisition system needed for the monitoring procedure. The sensors and transducers employed for the critical measurements were also discussed. A multiple linear regression model was also developed and built that was used to predict the power consumption of the swimming pool ASHP water heater. In the development of this model, all the predictors were assumed to have a linear dynamic relationship with the output.

3.2 RESEARCH METHODS AND DESIGN

3.2.1 Study/experimental design

This research was conducted through the use of quantitative methods to achieve relevant information. The methodology was divided into three; the data acquisition system, architectural design and full schematic layout of the swimming pool ASHP water heater including the installation of the system and sensors. The swimming pool ASHP water heater was operated in the autumn season. The monitoring process was done for three consecutive months (August to October 2014). The system was operated without interruption for 24 hours on a daily basis. It is worth mentioning that due to the cost of Eskom bill, the system was not allowed to operate for the complete winter and summer seasons. Notwithstanding, based on the performance of the autumn period, it was adequate to justify the viability of swimming pool ASHP water heater in the field of swimming pool water heating. The table 3.1 and figure 3.1 present the heating intervals and the full installation of the swimming pool ASHP system.

Table 3.1: Three heating time intervals

Months	Operations times	Average time intervals
August, September October	Morning	04:00-05:00
	Afternoon	13:30-16:00
	Evening	18:00-23:30

Figure 3.1: Illustrates the complete setup of the swimming pool ASHP system

3.2.2 Methods and Materials

Data Acquisition system

The data acquisition system comprised of power track analysers, S-TMB 12 bits temperature sensors, T-MINOL- 130 flow meter, 12 bits S-THB ambient and relative humidity (RH) sensor, 5 channels hobo U30-NRC data logger. The U30-NRC data logger was used as a reliable data logger because it consisted of jack ports which were used to connect the sensors to the data logger to ensure that all the measurement via every sensor was recorded correctly [Tangwe *et al*., 2015]. The main input parameters measured were power consumption of the water circulation pump, ambient temperature and temperature of water at swimming pool ASHP. Data was collected and stored in hobo U30-NRC data logger and downloaded into the PC for further analysis using the hobo ware pro software.

The flow meter was connected to the inlet of ASHP to measure the flow rate of the water into the ASHP unit. The power track analysers were used to measure power consumption. The temperature sensors, the ambient temperature and relative humidity sensor and flow meter were connected to the data logger using smart jack ports. A logging interval of one minute was set for all the sensors. The S-TMB 12 bits temperature sensors were connected to the inlet and outlet pipes of the ASHP unit to monitor the temperature of water flowing into and out of the swimming pool ASHP unit, respectively. The temperature sensors were isolated from external interference by wrapping them at their point of contact to the designated piping line with insulated tape.

The S-THB 12 bits relative humidity (RH) and ambient temperature sensor was used to measure relative humidity and ambient temperature of the system. The ambient temperature and relative humidity sensors were insulated using a solar radiation shield that prevented the reading from external interference. The equipment used for the design and building of the data acquisition system is listed in table 3.2.

Table 3.2: List of equipment and sensors used in the Data acquisition system (DAS)

Materials	**Quantity**
Power track analysers	2
T-SMB 12 bits temperature sensors	2
T-MINOL Flow meter	1
T-SHB 12 bits Relative humidity(RH) and ambient temperature sensor	1
U30-NRC (5channels) data logger	1

Figure 3.2 shows the complete schematic layout of the swimming pool ASHP water heater and the enclosure accommodating the data acquisition system. All the major components of the swimming pool ASHP were connected to form a complete system that makes up the vapour-compression refrigeration cycle.

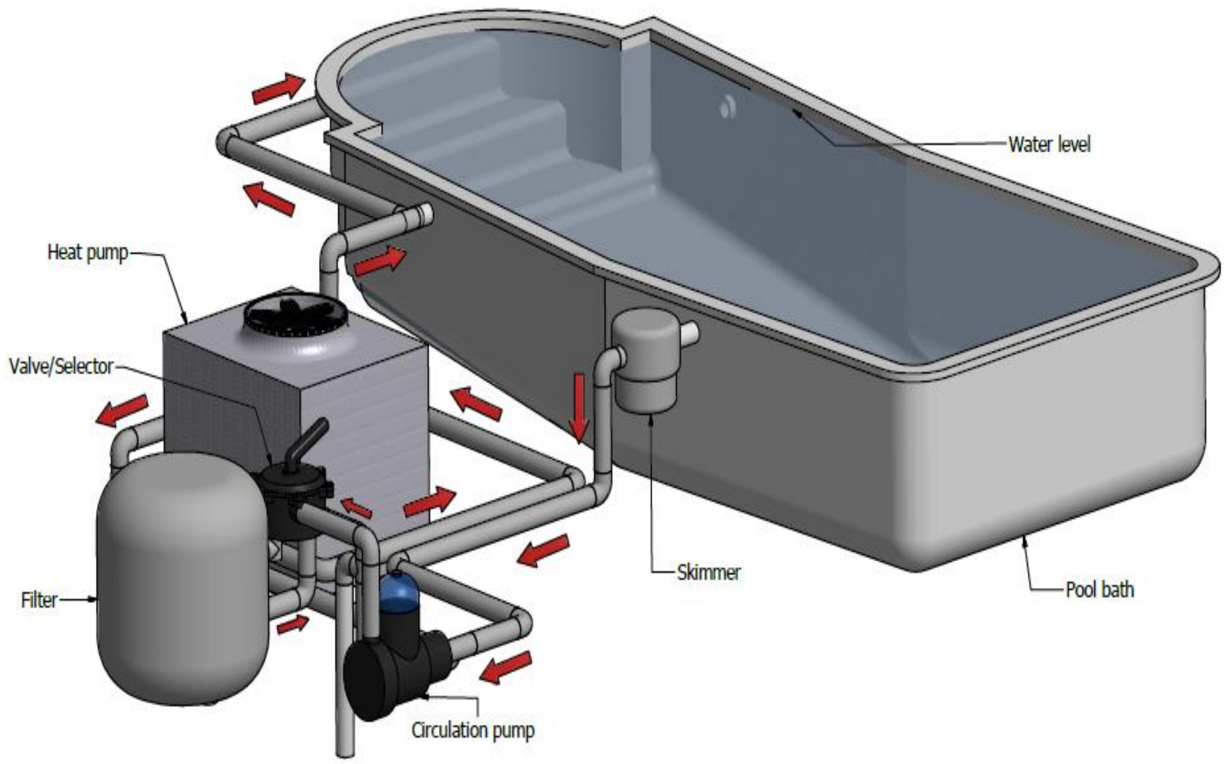

Figure 3.2: Illustrates the schematic layout of the swimming pool, air source heat pump system

3.3 DESCRIPTION OF SENSORS AND SPECIFICATIONS

3.3.1 Relative humidity (RH) and ambient temperature sensor

This is a 2-channel smart sensor capable of measuring ambient temperature and relative humidity with resolutions of 0.02°C and 0.1% respectively, at room temperature (25°C). It had a measurement range of -40°C to 75°C for temperature and 0-100% for RH. The measurements occurred within an accuracy range of ±0. 21°C (ambient temperature) and ±2. 5% (RH) provided the sensor was kept operational within the specified manufacturer's range. For security purposes, this smart sensor was protected with a solar radiation shield (M-RSA). Figure 3.3 shows the relative humidity and ambient temperature sensor.

Figure 3.3: Relative humidity and ambient temperature sensor

3.3.2 T-MINOL 130 Flow Meter

This is a nickel-plated brass pulse output water flow meter that was used to measure the rate at which water circulates into the ASHP unit during the heating cycle. It had a measurement range between 0.25 and 22.0 counts and a measurement accuracy of 97-103%. Each pulse output represented 1US gallon, which for the sake of convenience was converted into m/s by multiplying the total number of pulse outputs by 3.785. The flow meter used is illustrated in figure 3.4.

Figure 3.4: T-MINOL 130 flow meter

3.3.3 Input Pulse Adapters

Generally, input pulse adapters work as a model. It converted analogue signals recorded by the sensors to digital signals. It comprised of smart jack ports which were used to store the collected data in U30-NRC data logger. The adapter had a plug in the connector which allowed its connection to the smart jack port of U30-NRC data logger. Figure 3.5 shows input pulse adapters.

Figure 3.5: Input pulse adapters with modular jack

3.3.4 Power Tack Analyser

The power track analysers are described as class A type power and energy meters used to measure electrical power consumption, current, voltage and power factor of the swimming pool ASHP unit and the water circulation pump. The power track analysers are phase power analysers with an inbuilt data logger which logged every one-minute interval with a prediction of about 99% accuracy. Power track analyser is shown in figure 3.6.

Figure 3.6: Power track analyser

3.3.5 Temperature Sensors

It could be described as a robust smart surface contact sensor. It was a single channel 12-bit device that stored all useful parameters within itself and they were retrieved by the use of an external HOBO station. It had a stainless steel waterproof sensor tip, which measured the temperature of samples with an accuracy of less than 0.2°C and a resolution of less than 0.03°C at a temperature range of 0-50°C. It was operated reliably within a temperature range of -40°C to 75°C and was used in the experiment to record the temperature of water both at the inlet and outlet of the swimming pool ASHP. Figure 3.7 shows 12 bits S-TMB smart temperature sensor.

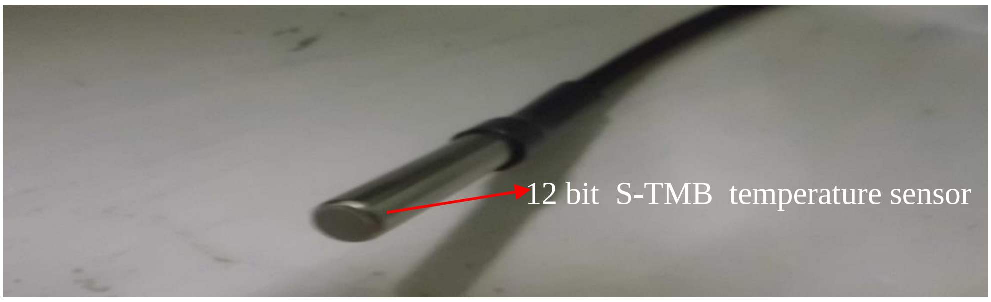

Figure 3.7: Shows 12 bits S-TMB smart temperature sensor

3.3.6 U30-NRC Data Logger

The U30-NRC data logger was a vigorous and reliable data logger with 5 digital smart jack ports for connecting the sensors. It logged and stored data for further analysis, just like any other device. It used battery as the source of power. U30-NRC data logger logged various temperatures, counts from water flowing into the ASHP unit as well as the relative humidity and ambient temperature per minute. Figure 3.8 shows HOBO U30-NRC data logger.

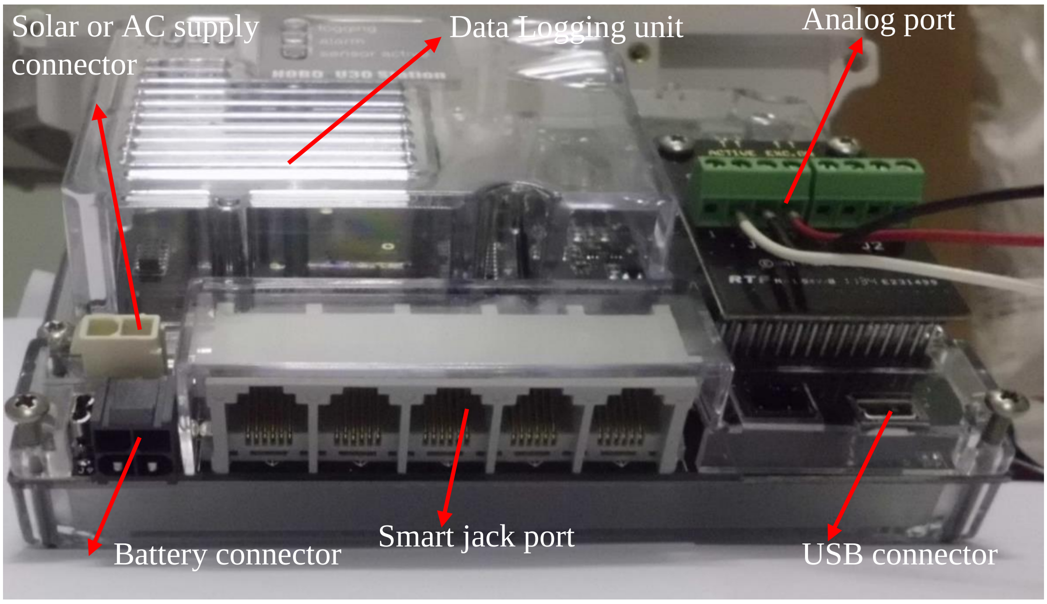

Figure 3.8: shows U30-NRC data logger

3.4 DATA COLLECTION AND ANALYSIS

The data were logged for the three-consecutive months involved in monitoring of the performance. During the monitoring period, both the desired output and input parameters were measured. The data was collected and stored in the U30-NRC hobo data logger. This data was extracted via the Hobo ware pro software to Microsoft excel and finally exported to the MATLAB software for further analysis.

3.5 MATHEMATICAL MODELLING

One major objective of the study was to develop a mathematical model that would forecast the performance of a swimming pool ASHP water heater under changing weather conditions. A mathematical model is a computational language or mathematical equation used to predict the dynamic behaviour of a physical system [Robnik-Sikonja *et al*., 2003]. The development of the model involved the selection of the primary parameters employed as predictors to determine the performance. In this study the predictors that were selected were the power consumption of the water circulation pump (kW), temperature of water at the inlet of the swimming pool ASHP (℃) and the ambient temperature (℃).

CHAPTER FOUR

AN EXPERIMENTAL STUDY TO DETERMINE THE PERFORMANCE OF A SWIMMING POOL AIR SOURCE HEAT PUMP WATER HEATER

4.1 INTRODUCTION

This chapter harbours the results of the performance monitoring of the system operated under the meteorological conditions of Fort Beaufort in the Eastern Cape Province. It also consists of the results of the changes of the critical predictors during the particular VCRC and the impact on power consumption of the swimming pool ASHP. In addition, a comparative analysis was done, and the results of the data analysis are hereby presented. The performance of the swimming pool ASHP water heater was monitored during the autumn season (August to October) in 2014.

Two fundamental goals guided the collection of data and subsequent data analysis. These included; to build a simple data acquisition system and to determine the coefficient of performance of the swimming pool ASHP in addition to the simple payback period of the system. These objectives were accomplished and the corresponding COP of the data was determined. The findings interpreted from the analysis outlined in this chapter demonstrated the potential for consolidating theoretical framework with practice in respect to the efficiency of the employed technology for heating of the water in the swimming pool.

4.1.1 CALCULATIONS

The useful output thermal energy gained by the stored water of the swimming pool is given by equation 4.1.

$$Q = mc\Delta\theta \tag{4.1}$$

Where:

Q = Useful thermal energy gained by water in kWh

m= Mass of water heated in kg

c= Specific heat capacity of water = 4.2 kJ/kg^{o}C

$\Delta\theta$ = Temperature difference of water at the outlet and inlet of the swimming pool ASHP

The input electrical energy consumed by the swimming ASHP water heater is given by equation 4.2.

$$E = Pt \tag{4.2}$$

E= Input electrical energy in kWh

P=Electrical power consumption in kW

t= 5 minutes' time interval in minutes

The coefficient of performance of the swimming pool ASHP water heater is the ratio of the output useful thermal energy gained and the input electrical energy used and is given in equation 4.3.

$$\text{COP} = \frac{\text{Q}}{\text{E}} \tag{4.3}$$

Where:

Q= Useful thermal energy gained by water in the pool in kWh

E = Input electrical energy consumed in kWh

COP = Coefficient of performance during VCRC

In addition, the simple payback period is defined as the ratio of the capital cost and the product of the annual energy saving in kWh and the tariff per unit kWh is given by equation 4.4.

$$\text{SPP} = \frac{\text{Capital cost}}{\text{annual saving x tarrif}} \tag{4.4}$$

Where:

SPP= Simple payback period

4.2 COMPARATIVE ANALYSIS OF PREDICTORS DURING SPECIFIC VCRC

The results of the power consumptions for the swimming pool ASHP water heater and the water circulation pump showed that the swimming pool heating up cycles were consistent over the entire monitoring period. The analyses of the power consumption of the swimming pool ASHP water heater, the power consumption of the water circulation pump, the ambient temperature and the temperature of the water at the inlet of the swimming pool heat pump were performed for an average month from August to October. It was depicted from the results that the swimming pool ASHP system functioned in all the three set time intervals (from 07:00-

10:45, 13:55-16:45 and 20:50-22:40). It can be observed that the swimming pool ASHP water heater took a longer time to heat the water to the set point in the morning period (270 minutes) as opposed to that in the afternoon session (180 minutes). This is strongly governed by the factors that influenced the cooling rate of the swimming pool (ambient temperature, relative humidity, wind speed). The figure 4.1 shows the average monthly power consumption of the swimming pool heat pump during the three heating up sessions.

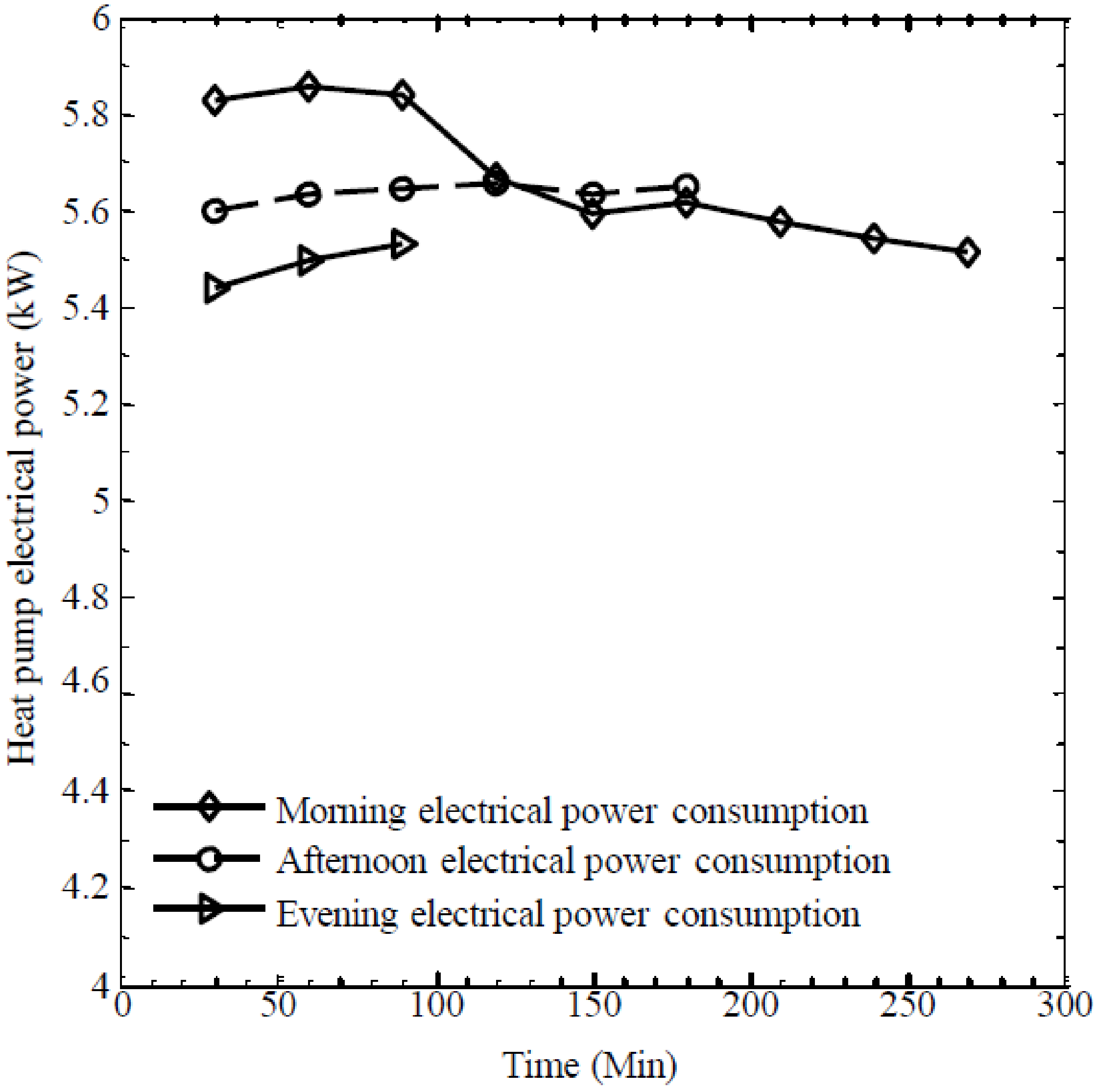

Figure 4.1: power consumption of the swimming pool ASHP

From the figure 4.1, it can be depicted that the electrical power consumption of the swimming pool ASHP fluctuated between 5.43kW to 5.86 kW. There was a slight increase in the power consumption of the swimming pool ASHP during the afternoon operation interval (13:55-16:45) due to the increase in ambient temperature and the load of water heated. Furthermore, the figure 4.2 shows the average power profiles of the water circulation pump during the three-desired heating up cycles. It can be delineated that the power consumption of the water circulation pump in the morning heating up session was slightly higher as compared to the other profiles.

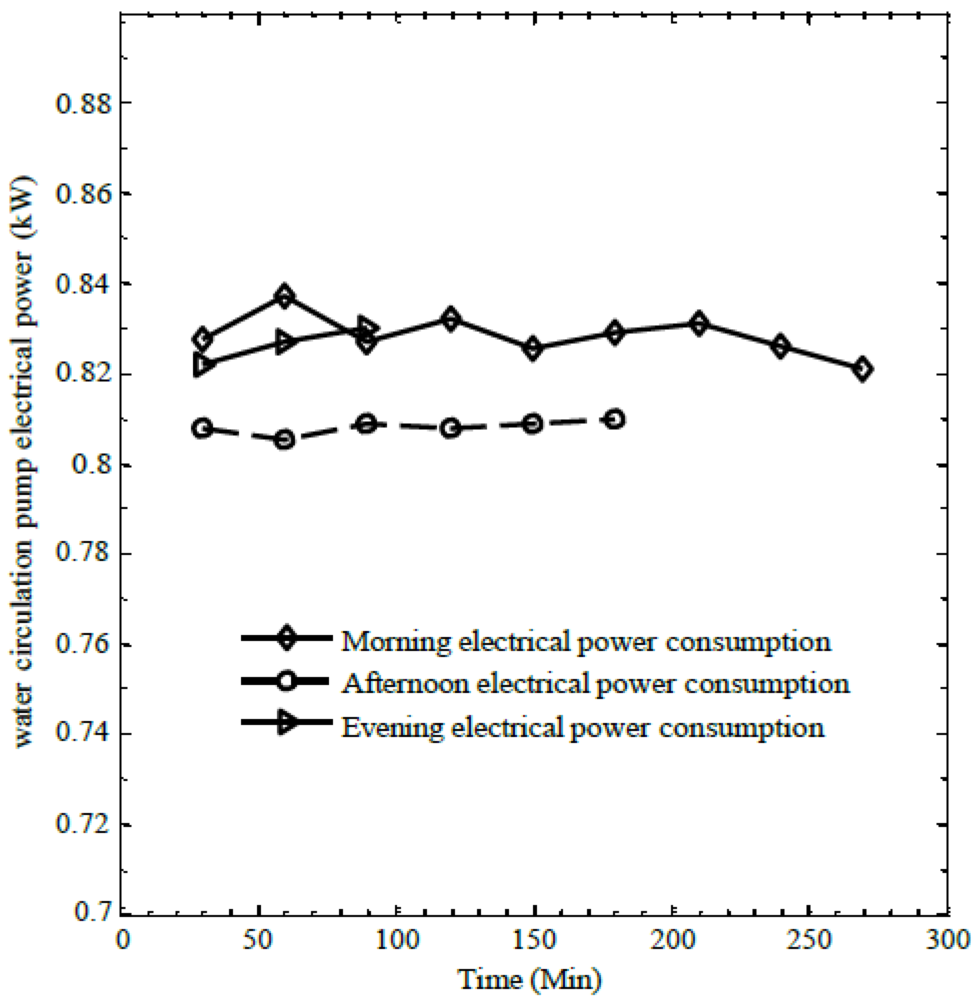

Figure 4.2: The power consumption of the water circulation pump

The current of the water circulation pump also fluctuated and ranged from 3.3A-3.5A. The power consumption of the water circulation pump ranged from 0.75 kW-0.8 kW as specified on the nameplate.

The figure 4.3 shows the temperature of water at the inlet of the swimming pool ASHP and can be observed that the temperature was fairly constant throughout the heating up cycle and ranged between 23.5 and 24.0 °C.

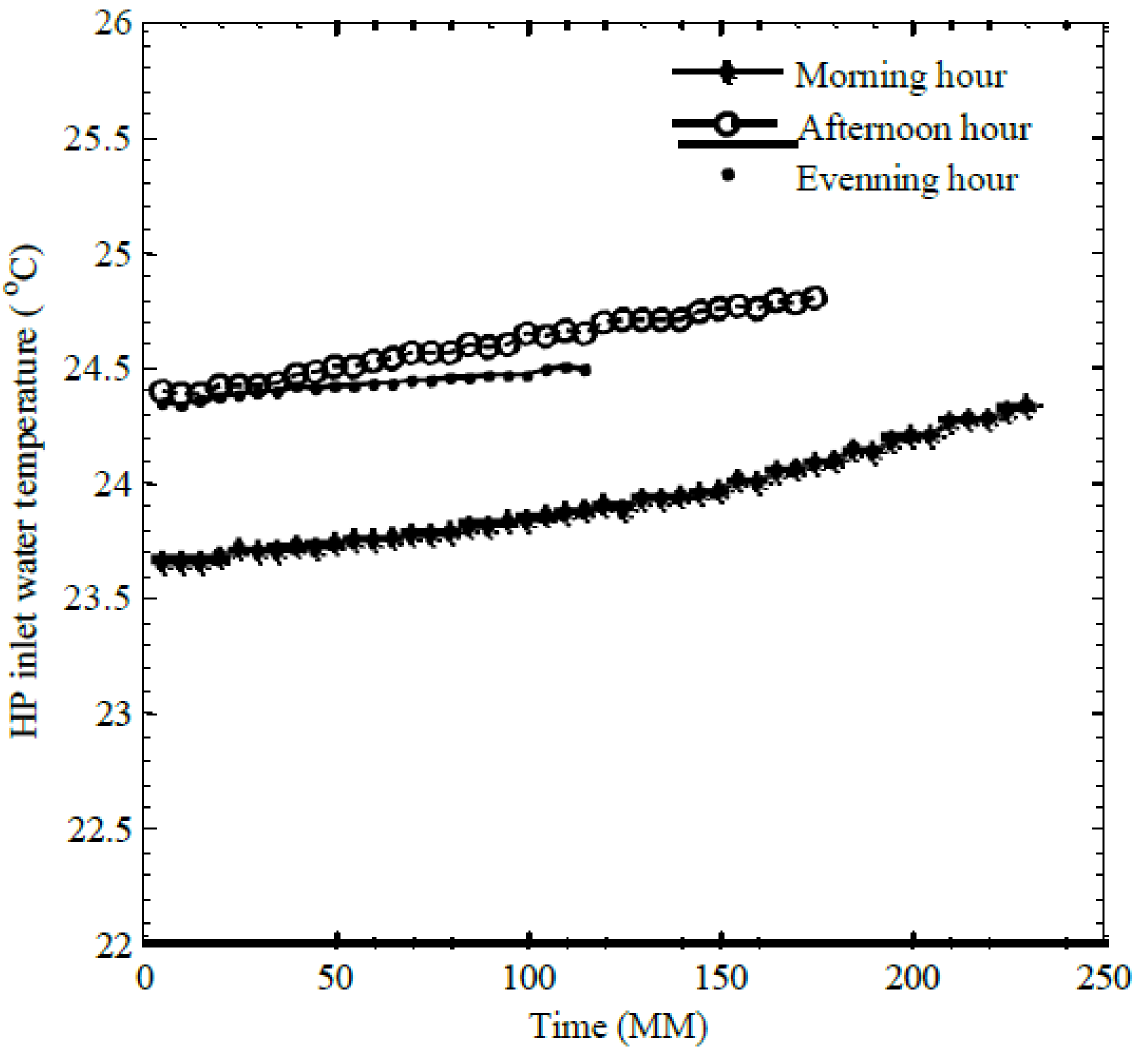

Figure 4.3: Swimming pool heat pump inlet water temperature

Figure 4.4 shows the ambient temperature profiles over the three heating up cycles. The ambient temperature ranged from 12- 18ºC and the noted slight difference in the ambient temperature could produce changes in the power consumption of the swimming pool ASHP, however, it was of no significant difference.

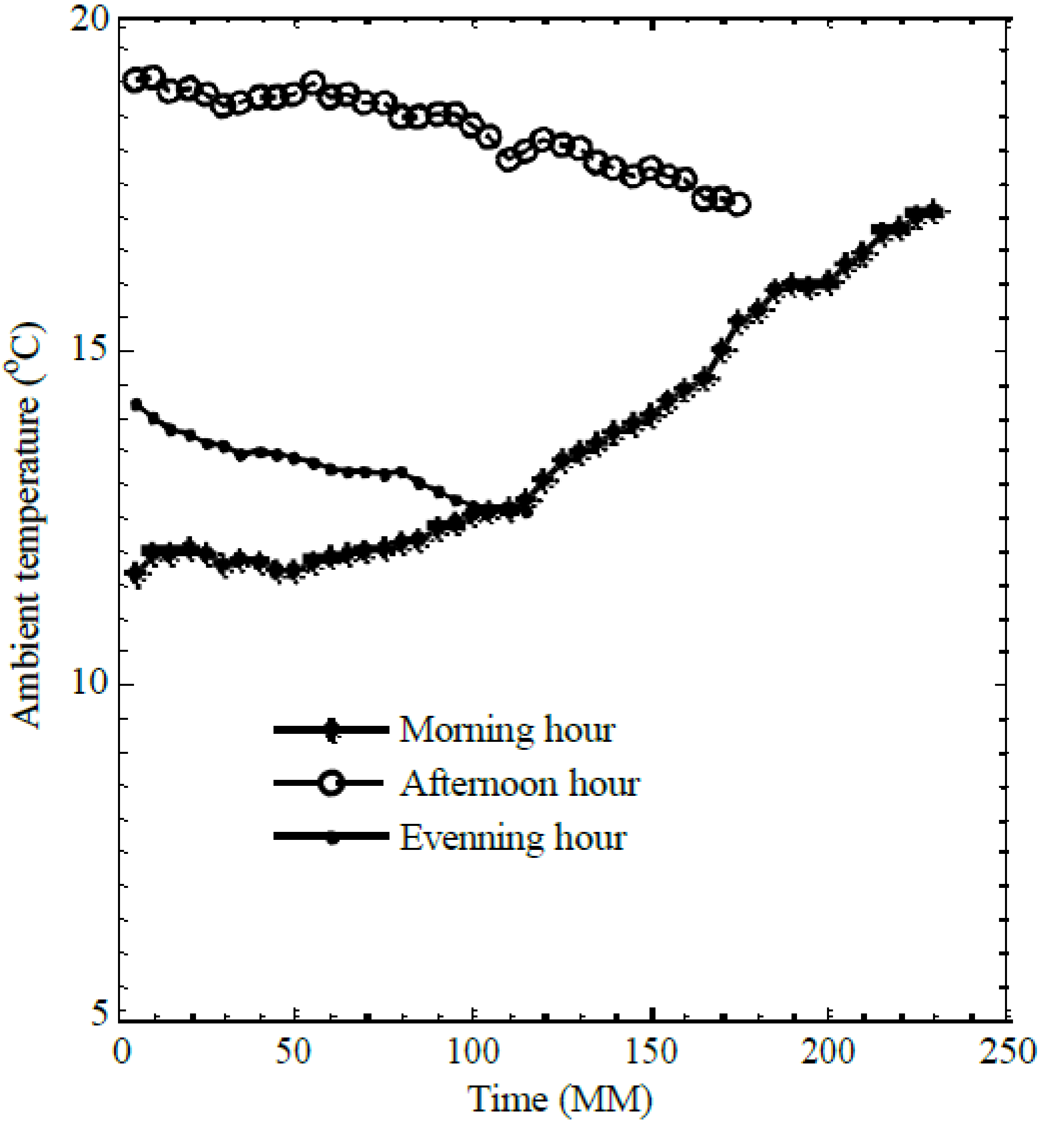

Figure 4.4: The ambient temperature profiles

4.3 DETERMINATION OF SIMPLE PAYBACK PERIOD

Following the chronicles of reviewing information, and based on this study, the most efficient way of heating a swimming pool has been noted by using renewable resources such as ASHP. It operated with a coefficient of performance of about three to eight which indicates an excellent efficiency. Due to the very high efficiency of the heating technology governed by its distinctive characteristics known as COP, the heat pumps can be termed to be very relatively low operating cost system when compared to other non-renewable system like the electrically resistive element. A simple economic analysis was conducted to evaluate the feasibility of incorporating water heating of the swimming pool via the use of ASHP system. From previous studies, the payback period is the time required to recover the initial investment of the system from operation [Harwell, 2012]. Table 4.1 shows crucial measured and calculated parameters relevant to the determination of the simple payback duration.

Table 4.1: crucial measured and calculated parameters

Ambient temperature °C	Inlet ASHP temperature °C	Outlet ASHP temperature °C	Volume of water heater Litres	Electrical energy kWh	Q kWh	COP
10.948	28.291	31.200	2934.990	3.161	9.958	3.150
10.927	28.295	31.200	2928.910	3.181	9.925	3.120
20.828	29.376	32.100	3729.024	3.201	11.846	3.700
20.610	29.399	32.100	3780.692	3.218	11.909	3.700
20.796	29.424	32.100	3823.609	3.225	11.934	3.700
20.777	29.425	32.100	3716.215	3.221	11.596	3.600
20.351	29.407	32.100	3494.493	3.228	10.976	3.400
17.236	29.222	32.020	3464.774	3.326	11.308	3.400
16.460	29.174	32.020	3326.661	3.347	11.045	3.300
15.799	29.127	32.020	3208.879	3.332	10.829	3.250
15.107	29.088	32.020	3059.210	3.249	10.463	3.220
14.408	29.069	32.020	3000.772	3.207	10.329	3.220
13.368	29.056	32.020	2991.890	3.222	10.344	3.210
12.812	29.058	32.020	2975.965	3.203	10.283	3.210
12.525	29.061	31.900	3104.330	3.182	10.279	3.230

12.181	29.056	31.900	3072.519	3.165	10.193	3.220
11.911	29.056	31.900	3068.255	3.161	10.179	3.220
11.577	29.055	31.900	3033.037	3.135	10.066	3.210

In addition, the table 4.2 demonstrated the complete breakdown of the simple payback period economic analysis of the swimming pool ASHP system.

Table 4.2: Layout of the simple payback period analysis of the systems

Item	Description	Electrical Energy kWh	Unit cost ZAR	Total cost ZAR
Systems	Up front cost			56000.00
Maintenance	Sustainability			2000.00
Thermal energy	Equivalent electrical element energy	82312.30	1.30	107006.00
Electrical energy	Systems electrical energy consume	24626.90	1.30	32015.08
Avoided energy	Electrical energy saved	57685.40		74990.95

From the table 4.2 above, it can be deduced that the tariff structure was equal to 1.30 Rand, the annual cost of the efficient electrical energy consumption of the swimming pool ASHP water heater was R32, 015.08, and that of the total electricity cost projected by the implementation of the electrically resistive element was found to be R74, 990.95. Hence, the avoided electricity cost per annum stood at R57, 685.40. The overall capital cost of the swimming pool ASHP water heater was R56000. Furthermore, from the said table 4.2 it can be suggested that the maintenance of the swimming pool ASHP included the re-fill of the chlorine chemicals and the addition of sand to the filters that purified and reduced the debris from entering into the swimming pool. This made up to 90% of the maintenance cost. The purification of the pool by using salt, the maintenance of the heat pump system as well as the cleaning of the filter could be estimated to cost R2000.00.

Furthermore, from the table 4.3, the average month-day ambient temperature, temperature of water at the inlet and outlet of the swimming pool ASHP were 15.05^{o}C, 24.31^{o}C and 31.20^{o}C, respectively. The average month-day COP of the swimming pool ASHP water heater was 3.25.

The analysis focused on the average energy consumption for each of the three heating intervals of the swimming pool ASHP water heater on a daily basis and using the experimentally determined average COP of 3.25 (consider table 4.2). The average energy consumption of the swimming pool ASHP water heater per day in each heating interval was 23.06 kWh, 17.08 kWh and 11.38 kWh for the morning, afternoon and evening sessions, respectively. The average daily energy amounted to 52.3 kWh. Hence, the corresponding useful thermal energy produced to heat up the swimming pool using the derived average COP of 3.25 was 169.98 kWh. In a typical week, the total electrical energy consumed by the swimming pool ASHP system was 366.10 kWh, while the useful thermal energy gained by water in the swimming pool was 1189.90 kWh. In addition, over a year of operation of the swimming pool ASHP the accumulated electrical energy consumption was calculated to be 24626.90 kWh while the thermal energy generated was 82312.30 kWh. This thermal energy produced was equivalent to the electrical energy consumed by a traditional convection heating element.

It is important to note that by using a tariff structure of a megaflex (flat rates) whereby 1kWh equal to 1.30 Rand, the annual cost of the effective energy consumed by the swimming pool heat pump was 32, 015 Rand and the avoided electricity cost in totality was 74,990 Rand. The capital cost of the swimming pool ASHP system was 56,000 Rand. The maintenance cost of the swimming pool heat pump on an annual basis was well below 2,000 Rand and involved cleaning of the filter and adding of chlorine and bromine in order to purify and maintain the salt content of the water in the pool. The simple payback period for the swimming pool heat pump system was less than 13 months or 1.04 years. This payback period can even be lower since the coefficient of performance of a swimming pool ASHP water heater can be much higher than the derived coefficient of performance used in the analysis during the summer months where ambient temperatures are expected to be higher.

Table 4.3: Summary of average month-day achievable results for the key parameters in the determination of the simple payback period

Measure and calculated Quantity	Value obtained
Average ambient Temperature (^{o}C)	15.316
Average inlet of the swimming pool ASHP water Temperature (^{o}C)	29.067
Average outlet of the swimming pool ASHP water Temperature (^{o}C)	31.897
Average half hourly volume of water heated (L)	3263.124
Average daily electrical energy consumption (kWh)	67.471
Average daily thermal energy consumption (kWh)	225.513
Average daily COP	3.251

Table 4.3 shows the average month-day results for the key parameters in the determination of the simple payback period. It can be revealed from the table 4.3 that the average ambient temperature, temperature of water at the inlet and outlet of the swimming pool ASHP were

15.32 ^{o}C, 29.07 ^{o}C and 31.90 ^{o}C, respectively. Following, the three heating time intervals; morning, afternoon and evening, the analysis of the average power consumption was performed. The results showed that the average thermal energy of the swimming pool ASHP water heater was 225.51 kWh and the average electrical energy was 67.47 kWh, respectively. Lastly, the average daily COP was 3.25.

4.4 SUMMARY

In conclusion, the power consumption and COP of the swimming pool ASHP can be effectively determined experimentally with the aid of a suitable and reliable data acquisition system. An efficiently installed swimming pool ASHP in conjunction with optimal measures to prevent heat losses can achieve a payback period which is less than a year. Operating swimming pool with an ASHP can result in an avoided electricity cost of more than 50% owing to the higher coefficient of performance of this system. The coefficient of performance was higher compared to a residential ASHP water heater by the smaller temperature lift since the set point temperature of water in the swimming pool is much lower (swimming pool water set point range 30-35^{o}C and sanitary hot water set point temperature range 55-60^{o}C). The actual simple payback period can even be much lower by the utilization of Eskom's projecting tariff hikes into the economic cost analysis.

CHAPTER FIVE

DEVELOPMENT OF A MATHEMATICAL MODEL TO PREDICT PERFORMANCE

5.1 INTRODUCTION

A mathematical model is a computational model that uses a set of equations to forecast performance of a system. In this study, a multiple linear regression model was developed to predict the performance of swimming pool ASHP water heater whereby the predictors were power consumption of the water circulation pump, temperature of water at the inlet of the swimming pool ASHP unit and ambient temperature as well as the desired response was considered to be the power consumption of the swimming pool ASHP water heater.

5.2 MODEL DERIVATION

The equation of the mathematical model was developed and represented in the form found in equation 5.1.

$$P_{hp} = \alpha + \beta(P_{wp}) + \delta(T_i) + \lambda(T_{amb}) \qquad (5.1)$$

Where:

α = Forcing constant

λ, δ, β =Scaling constants for the respective predictors

T_i= Temperature of the water at the inlet of swimming pool ASHP in ^oC.

T_{amb} = Ambient temperature in ^{o}C.

P_{wp} = Average power consumption of water circulation pump in kWh

P_{hp} = Average power consumption of the swimming pool ASHP in kWh

More elaborately, all the parameters had their scaling values in the equation 5.1. The purpose of the scaling constants is to ensure that the derived model from the regression analysis is such that the input parameters accurately predicted the output parameter. From the observations, it can be shown that the scaling constants can be obtained from the use of the regression analysis performed with the predictors in the mathematical models and the desired output. The mathematical model was applied to determine the power consumption of the swimming pool ASHP water heater. The coefficient of determination and the mean bias error was calculated using the model and the actual data set. These parameters gave an indication of the strength of the relationship between the actual output results and the modelled output prediction values as well as the fitness of the data used in comparison to the developed model. When the value of the coefficient of determination was closer to 1, it depicts that there was a very strong linear correlation between the actual output data and the modelled predicted values. But if the determination coefficient was very close to 0, it revealed a very weak correlation between the actual output data sets and the modelled predicted values.

The sample data consisting of the input and output parameters used for the development of the mathematical model, and the scaling values are shown in table 5.1.

Table 5.1: Mathematical model of the power consumption of the swimming pool ASHP

I P	Scaling constant	Scaling constant	Output
P_{wp}	α	11.015	P_{ASHP}
T_i	β	0.074	
T_{amb}	δ	0.028	
FC	λ	-6.039	

It can be depicted from table 5.1, that all predictors scaling factors contributed positively to the power consumption of the swimming pool ASHP water heater. These could be affirmed by the positive constant values of each of the respective scaling constants (power consumption of the water circulation pump, temperature of water at the inlet of the swimming pool ASHP and the ambient temperature). The forcing constant (FC) is the derived constant in a multiple regression model that catered for the other plausible input parameters that could influence the desired output parameter; however, they were not considered in the derivation of the mathematical model. Clearly, the inclusion of the forcing constant in a multiple linear regression model is of significance as it compensates for the unaccounted input predictors that could also have an impact on the desired response. The determination coefficient and the mean bias error were 0.94 and 0.004, respectively.

Table 5.2 shows the sample data sets of the predictors, measured output and model values obtained from the experimental results.

Table 5.2: Sample of Measured data used in the model

inlet ASHP temperature (℃)	ambient temperature (℃)	Water pump power (kW)	Measured ASHP power (kW)	Modelled ASHP Power (kW)
28.285	11.002	0.821	5.439	5.439
28.291	10.948	0.827	5.495	5.496
28.295	10.927	0.830	5.532	5.531
29.376	20.828	0.807	5.595	5.644
29.399	20.610	0.805	5.632	5.613
29.424	20.796	0.808	5.642	5.65
29.429	20.750	0.807	5.656	5.646
29.425	20.777	0.808	5.633	5.656
29.407	20.351	0.809	5.646	5.657
29.222	17.236	0.827	5.824	5.748
29.174	16.460	0.837	5.857	5.829
29.127	15.799	0.826	5.837	5.695
29.088	15.107	0.831	5.667	5.726
29.069	14.408	0.825	5.590	5.635
29.056	13.368	0.828	5.616	5.641
29.058	12.812	0.830	5.576	5.649
29.061	12.525	0.826	5.539	5.586
29.056	12.181	0.820	5.510	5.519

From table 5.2, it can be shown that there was high average power consumption when the ambient temperature range was low between 17.23 ^{o}C and 15.10 ^{o}C. The average power consumption was 5.74 kW. When the ambient temperature range was between 20.8 ^{o}C and 20.7 ^{o}C, the average power consumption was 5.64 kW. This could be attributed to the fact that ambient conditions have an effect on the performance of the swimming pool ASHP. However, high ambient temperatures affected the temperature of the water at the inlet of the ASHP. Consequently, power consumption was increased at very low temperatures. But the unusual relationship manifested by the power consumption of the swimming pool ASHP and the ambient temperature was due to the fluctuation in temperature of water at the inlet of the swimming pool ASHP. The results of the measured output (calculated power consumption of the swimming pool ASHP) and the modelled power consumption for 22 observations are illustrated in figure 5.1.

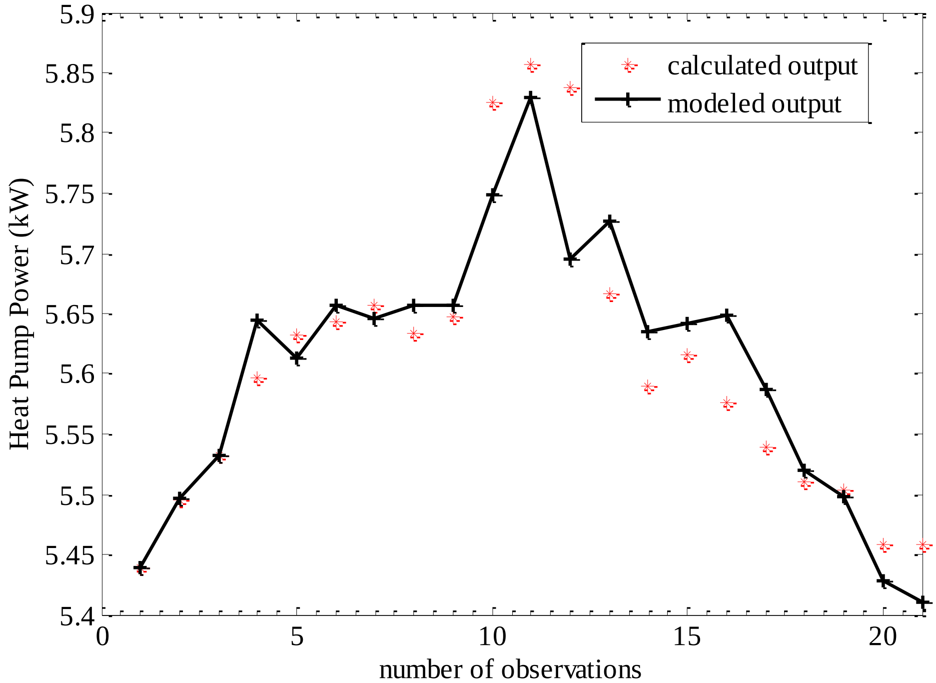

Figure 5.1: Calculated and modelled power consumption of swimming pool ASHP

From the observations, the determination coefficient was found to be 0.936 with a deviation of 5%; this showed the good fit of the model to the measured data. The deviation can be attributed to the fact that other predictors that influenced the desired response were excluded from the number of input parameters. Again, the deviation between the actual and modelled power consumption of the swimming pool ASHP was ascribed to modelled errors and data errors from the metering equipment or sensors. The modelled power showed that there was a correlation between the power consumption of the swimming pool ASHP and the input parameters including; power consumption of the water circulation pump, the temperature of the water at the inlet of the swimming pool ASHP and the ambient temperature. The findings from the developed mathematical model revealed that the model was accurate so it can be used to predict the performance of swimming pool ASHP water heater, although, some parameters such as relative humidity would also need to be considered.

5.3 RANKING OF PREDICTORS USING THE RELIEFF ALGORITHM

The three predictors namely, power consumption of the water circulation pump, the temperature of water at the inlet of the swimming pool ASHP and the ambient temperature (Pwp, Tin and Tamb) and the output (power consumption of the swimming pool ASHP, PASHP) from the processed data were used in the ReliefF algorithm to rank predictors according to their importance of weight contribution. The ReliefF test is a statistical tool that uses the regression method to rank predictors with respect to their importance of weight contribution to the output [Robnik-Sikonja and Kononenko, 2003]. The weight rank for a particular predictor can be between -1 and 1. A positive weight rank of a predictor shows that it is a primary factor while a negative weight rank depicts that it is a secondary factor. The figure 5.2 shows the reliefF bar plots for the predictors and the importance of weight contributions to the power consumption of the swimming pool ASHP system.

The weight ranking revealed that the power consumption of water circulation pump (Pwp), the temperature of water at the inlet of the swimming pool ASHP (Tin) and the ambient temperature (Tamb) were all primary factors. It can also be determined from the analysis that the predictors were primary predictors with the relative weight of contributions, including Tin = 0.505, Pwp = 0.278 and Tamb = 0.216 as shown in the bar plot of relative weight of predictors contribution against the considered predictors in figure 5.2. The impact exhibited by the temperature of the water at the inlet of the swimming pool ASHP was significant via the contribution by weight of importance to the desired output. The contribution by weight of the predictor (ambient temperature) exhibited the least influence to the desired response.

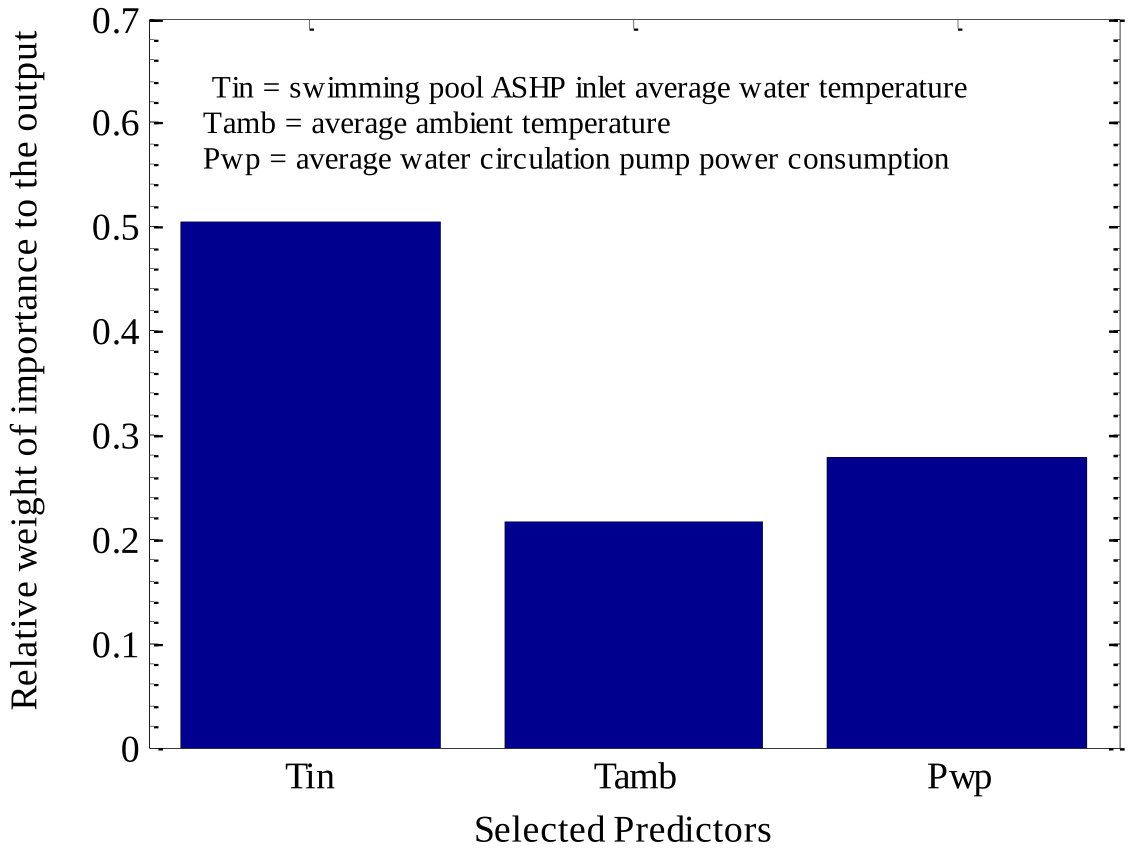

Figure 5.2: Bar plot of the relative contribution by weight for the selected predictors

5.4 SUMMARY

The derived multiple linear regression model can be used to predict the power consumption of the swimming pool ASHP with over 90% of confidence level. All the predictors scaling constants contributed positively to the desired response. The datasets of the output calculated power consumption of the swimming pool ASHP and the modelled predicted values exhibited excellent curve fitness with negligible deviation. The mathematical model is low cost but reliable and can predict the power consumption with a high degree of accuracy. Finally, based on the reliefF ranking, all predictors were primary factors with the average temperature of water at the inlet of the swimming pool ASHP contributing the greatest.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY OF FINDINGS

The heat pump water heater is an energy efficient technology that is used in residential, commercial and industrial sectors. The main advantage of ASHP is the utilization of a free, clean and renewable aero-thermal energy that will help in the reduction of power consumption and the use of fossil fuel energy which are not environmentally and economically friendly.

i. In this study, an investigation of the performance of the swimming pool ASHP water heater installed in Fort Beaufort was done by determining the COP of the system, and the development of mathematical models. The data collected during the performance monitoring period was used to develop a mathematical model which correlated with ambient temperature, relative humidity, and temperature at the inlet swimming pool ASHP for autumn season (August to October). Also, the power consumption analysis of the measured data was done that revealed the viability of the technology in terms of efficiency and simple payback period.

ii. Mathematical model describes behaviour of a real-life system using a set of equations. The aim of this study was fulfilled. From the results and observations, the performance of the swimming pool ASHP water heater (power consumption) can be predicted by the use of mathematical modelling. The mathematical model shows a very good correlation between the measured output dataset and the modelled predicted values. A low-cost data acquisition system (DAS) was designed and built which was used for the efficient and accurate monitoring of the daily performance of the swimming pool ASHP water heater.

6.2 SUMMARY OF CONTRIBUTIONS

Mathematical models are the powerful tools employed to predict the performance of the swimming pool ASHP water heater. The model has been used to forecast the behaviour of a residential swimming pool ASHP system and it used set of parameters known as predictors to predict the performance. The findings in this study will contribute in the development of an easily applicable and affordable mathematical model to predict power consumption of the swimming pool ASHP. This model can be useful in the prediction of the system performance by both manufacturers and homeowners of swimming pool ASHP. In addition, based on the analytical analysis of the experimental results and alongside the application of the economic life cycle of the technology, the simple payback period was determined.

6.3 CONCLUSIONS

i. From the results of the study and available, but limited literature, it is affirmed that the ASHP water heater is an energy efficiency technology for water heating in all the sectors (residential, commercial and even industrial). The growth of heat pump technology in the industries requires more accurate and fast methods to forecast performances. Thus, the development of the mathematical model is strictly essential.

ii. After completion of data analysis, it was evident that residential sectors can utilize renewable energy resources in an affordable manner rather than depend on non-renewable resources to heat swimming pools and for sanitary purposes.

iii. A very low cost and accurate data acquisition system was designed and built to monitor the performance of the swimming pool ASHP water heater.

iv. The installed swimming pool ASHP was covered with an isotherm blanket as an optimal measure to prevent heat losses and also to reduce the electrical energy consumption of the system. The implementation of swimming pool ASHP can save up to 70% of power consumed and improve on the performance of the system because the coefficient of performance will be higher.

v. The observations and literature of this study showed that the simple payback period was favourable. The simple payback period can be determined using the cost savings per year and an additional cost of the swimming pool ASHP in conjunction with the annual energy saving and the tariff per kWh.

6.4 RECOMMENDATIONS FOR FURTHER RESEARCH

i. In this research, evaluation of the performance of a swimming pool ASHP was done by the use of mathematical modelling. Factors affecting the performance of this technology were also evaluated. The results of the experimental studies indicated that the performance of a swimming pool ASHP was affected by some system parameters. Thus, in a bid to build up knowledge, it would be advisable for further studies to be conducted based on pre-design analysis to determine optimal system parameters that would ensure minimum energy consumption and favourable economy. With the aid of computerized energy simulation models and the model derived in this study (mathematical model) such analysis can be conducted with ease.

ii. It is recommended that the monitoring period for subsequent studies should be conducted in two different seasons, for example in winter and summer so that there can be a significant comparison base on performance and energy consumption of the swimming pool ASHP water heater. In addition, the comparison of the input parameters can be properly executed when the monitoring period is extended over two seasons of the year rather that very short monitoring period. This is to ensure that the results of the model can be very precise.

iii. It can be recommended that more predictors like relative humidity, wind speed should be included into the mathematical model to predict the power consumption of the swimming pool ASHP water heater.

iv. Also, a simulation application should be designed and used in simulating the performance of a swimming pool ASHP water heater on real time.

APPENDIX I

LIST OF PUBLICATION

Tangwe, S., Mqhayi, S, Simon, M. August. An experimental study to determine the performance and potential saving of swimming pool air source heat pump water heater. International conference on domestic used of energy-2017

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