A PROTOTYPE DESALINATION SYSTEM USING SOLAR ENERGY AND HEAT PIPE TECHNOLOGY

By

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DECLARATION

I, Ayad Almakhzum Mohamed Alwaer, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

The water desalination process needs large quantities of energy, either directly from fossil fuel or electricity from the national grid. However, these sources of energy significantly contribute to problems such as global warming in addition to creating a drain on the economy, due to their high cost.

This dissertation is a description of the research undertaken with the aim of producing a water desalination prototype; a novel approach that was designed using state-of-the-art solar water heating equipment, incorporating the technologies of evacuated tubes and heat pipes.

During the execution of the project, various modifications to the original commercially-available solar water heating system were attempted, each aimed at increasing the production of pure water. Finally, the system proved capable of producing a reasonable amount of pure water after twelve lengthy indoor experiments conducted in a laboratory in the department of Mechanical Engineering at the Cape Peninsula University of Technology, Bellville Campus, Cape Town, South Africa. Each experiment lasted five days on the basis of seven hours of exposure to an average amount of simulated solar radiation, followed by seventeen hours daily of inactivity and partial cooling down of the system.

The production of pure water was increased gradually during each day in each test according to improvements effected on the system.

The collector's area of 1.654 m^2 was the nominal value, comprising twelve evacuated tube heat pipes which were coupled to the geyser (150 l capacity) via the collector's manifold.

The results from the first/preliminary test with the basic system as acquired, indicated that the system’s output in terms of distillate was practically nil and had to be vastly improved through hardware modifications based on knowledge of classical thermodynamics and the science of heat transfer.

The various modifications were done on the plant, which enhanced and raised its performance to produce vapour during all the subsequent tests The productivity of distilled water increased from 2230 ml at the culmination of the second test to 12750 ml upon completion of the twelfth and final test; the water production efficiency (just in the last day for each test) improved from 11% to 38.2%.

Several tests were conducted using a test apparatus specifically made for the purpose of comparing the relevant attributes of heat pipes containing different working fluids.

The commercially available heat pipe, with its proprietary working fluid, was used as a reference in comparing the performance of other heat pipes containing distilled water, methanol, acetone and ethanol respectively as working fluids.

The results of the experiments that were carried out with the heat pipes containing pure water, methanol and acetone as a working fluid, achieved thermal efficiencies of 63.1%, 60.5%, 57.6%, respectively and therefore an improvement when compared to the commercially available heat pipe, which recorded an efficiency of 57.1%. The heat pipe containing ethanol yielded a thermal efficiency of 42.1%.

It is concluded that the existing solar water heating system based on evacuated heat pipe technology can become a viable potable water production system. It is also expected that such a system will improve its production of potable water with heat pipes containing pure water, methanol or acetone as working fluids.

ACKNOWLEDGEMENTS

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Special thanks to my colleagues in all scientific and technical departments for their valuable contribution throughout the project work.

For all the unconditional love and support and patience, for all the encouragement and sacrifices, I would like to thank my dearly departed Mother Salma, my wife Hana, my sister and brother for giving me, once again, the opportunity to study for this DTech degree and for their moral support all these years.

Also I would like to thank the staff of SolarJoy Company, especially its manager Mr. Mahmood Mia Chikte.

Special thanks to the Ministry of Higher Education in Libya and the Libyan Embassy in South Africa for their financial support which enabled this research.

Ayad
April 2016

DEDICATION

This thesis is dedicated to the Blessed spirit of my Mother Salma, my wife, my sister, my brother and my four angels Rudiena, Lujin, Rawan and Marya — may they see in this work the fruit of their love and support.

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GLOSSARY

TDS	Total Dissolved Solids
WHO	World Health Organization
EPA	Environmental Protection Agency
RO	Reverse Osmosis
MSF	Multi Stage Flash
BAP	Below Atmospheric Pressure
ETC	Evacuated Tube Collector
HP	Heat Pipe
WRC	World Radiation Centre
BESRI	Beijing Solar Energy Research Institute
G_{sc}	Solar Constant
$\mathrm{A_c}$	Collector Area (m^2)
C_p	Specific Heat Capacity of Solar Fluid (J/kg °C)
G_t	Total Global Solar Radiation on the Collector's Surface (W/m^2)
$\dot{\mathrm{m}}$	Solar Fluid Mass Flow Rate (kg/s)
Q	Quantity of Heat
Q_{aux}	Auxiliary Heating Requirement (MJ)
Q_c	Useful Heat Collected (J)
Q_d	Useful Heat Delivered (J)
Q_l	Supply Pipe Heat Loss (J)
Q_s	Solar Yield (MJ)
S_f	Solar Fraction (%)
η_c	Collector Efficiency (%)
η_s	System Efficiency (%)
η_{hp}	Heat Pipe Efficiency (%)
α	Absorptance
ε	Emittance
H	Monthly Average of daily global solar radiation
H_c	Monthly Average Clear Sky Daily Global Radiation
n	Monthly Average of the Actual Sunshine Hours per Day
N	Length of Day
a, b	Empirical Constants
ϕ	Latitude of the Site
δ	Sun Declination
ω_s	Sunset Hour Angle
d	Day of the Year
dia	Diameter

CHAPTER ONE

INTRODUCTION

1.1 Water resources on Earth

Studies and reports indicate that only around three percent of the world's water resources contain sufficiently low levels of dissolved salt and other solids to guarantee their safe consumption. Referring to the statistics of the World Health Organisation, the rate of total dissolved solids (TDS) in drinking water should be lower than 1000 mg/l, (WHO, 1984). As a secondary standard, TDS in drinking water, as determined by the United States Environmental Protection Agency (EPA), should be lower than 500 mg/l (EPA, 2002), orders of magnitude lower than seawater, which contains an average TDS of about 35,000 mg/l. The same is true when compared with other sources of water (see Table 1.1). Thus, most of the earth's available water contains a lot of salt, making it unsuitable for use as drinkable water. Most of the clean water around the world exists in the polar ice caps "or is located underground. (It is estimated that less than one-half percent of the world's water is easily accessible and has acceptable levels" of salinity) (NRC, 2004).

Table 1.1: Source and water classification, according to quantity of dissolved solids.

Source	Total dissolved solids (milligrams per litter)
Potable water	<1,000
Mildly brackish waters	1,000 to 5,000
Moderately brackish waters	5,000 to 15,000
Heavily brackish waters	15,000 to 35,000
Average seawater	35,000

Note: Some seas and lakes have showed a wide variability in TDS; e.g., the Arabian Gulf has an average TDS of 48,000 mg/l and Mono Lake, CA has a TDS of 100,000 mg/l. SOURCE: USBR, 2003a; NRC, 1987; Pankratz and Tonner, 2003.

Studies on potable water caution that sources of fresh water have become very scarce, and most countries are suffering from acid rain due to global warming. These issues have become a source of concern for interested bodies and researchers, thus motivating them to try and find environmentally-friendly sources and means of obtaining additional potable water (Ali et al., 2011). It's no exaggeration to say that clean water is the primary resource in the creation and development of human habitats. It is very disturbing to contemplate the future of our world when less than half a percent of the Earth's total water resources is available as pure water for direct human use or for agricultural and industrial consumption (Watson et al., 2003).

Currently there is a steady increase of consumption of the available freshwater resources as a result of, according to Xiao et al., (2013) and Watson et al., (2003):

A. “Excessive growth in global population
B. Need for general irrigation and agricultural use
C. Rise of global living standards of humans
D. Increase of industrial processes
E. Environmental needs that require clean water
F. Decrease of water quality (pollution) of existing resources”

It is imperative that alternatives to conventional desalination plants based on fossil fuels be developed to provide additional water, alleviating the drain on the natural sources. These alternatives should also ideally involve minimal or no use of fossil fuels, to avoid harmful environmental impact (Lindblom, 2010).

Solar energy can be directly used for the desalination of water, such as is the case with a solar still, or indirectly utilised by converting solar energy into heat or electricity and using that to drive a conventional desalination system (Belessiotis & Delyannis, 2000).

The use of solar energy as a heat source for seawater desalination is one of the sustainable energies which is environmentally friendly, as well as being an alternative to the use of fossil fuels, which are currently being used in seawater desalination plants (El-Agouz et al., 2014) and (Garcia-Rodriguez, 2002).

1.2 Historical data on water desalination

One of the main types of water desalination is the process of water distillation, which involves heating it to the point of boiling, thus producing vapour. The boiling point, in terms of temperature, at which water undergoes a change in state from liquid state to gaseous, depends on the pressure which surrounds it. Water vapour is condensed into pure water by passing it onto a cooling surface, where it can be collected free of impurities, such as salt and heavy metals, which will remain in the boiler or distiller basin). See schematic of the distillation process in Figure 1.1.

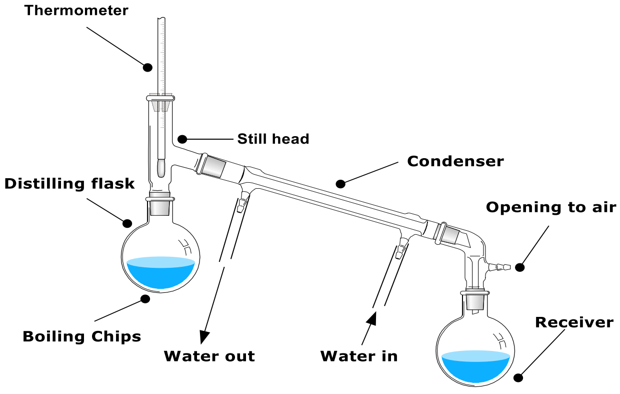

Figure 1.1: General principle of distillation (Saidur et al., 2011)

The history of solar desalination technology possibly begins in the fourth-century BC, when Aristotle outlined methods of evaporating seawater and then condensing it to produce drinkable water.

Solar distillation technology was used as early as the fifteenth century by Arab alchemists supply mineworkers with drinkable water while they worked. Prototypes similar to these old distillers still exist today (Al-Hayek & Badran, 2004) .

In the sixteenth century, Arab alchemists utilised wide earthen pots containing water which, when exposed to the Sun’s heat, would evaporate the water in them, and through a condensation process on the inverted pots placed over them, water would be collected into similar vases placed underneath, as shown in Figure 1.2. This is commonly known as the Della Porta solar distillation unit (Tiwari et al., 2003) and (Salem, 2013).

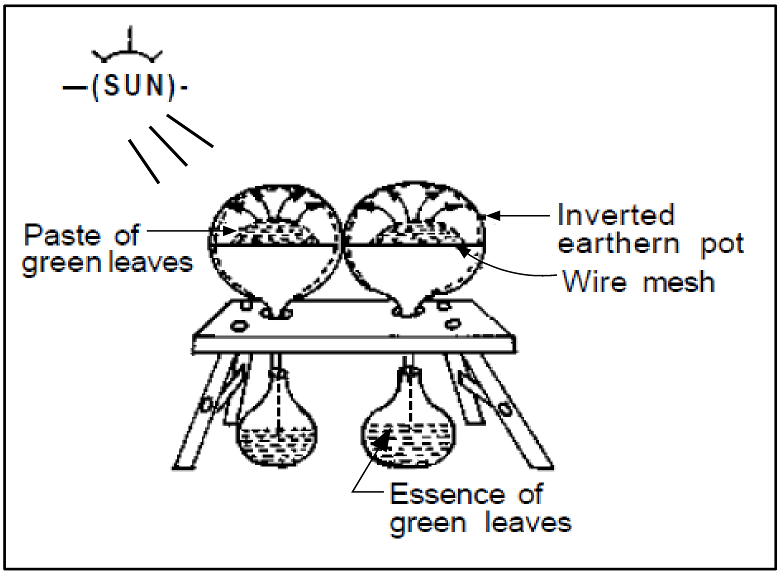

Figure 1.2: Della Porta solar distillation apparatus (Delyannis, 2003)

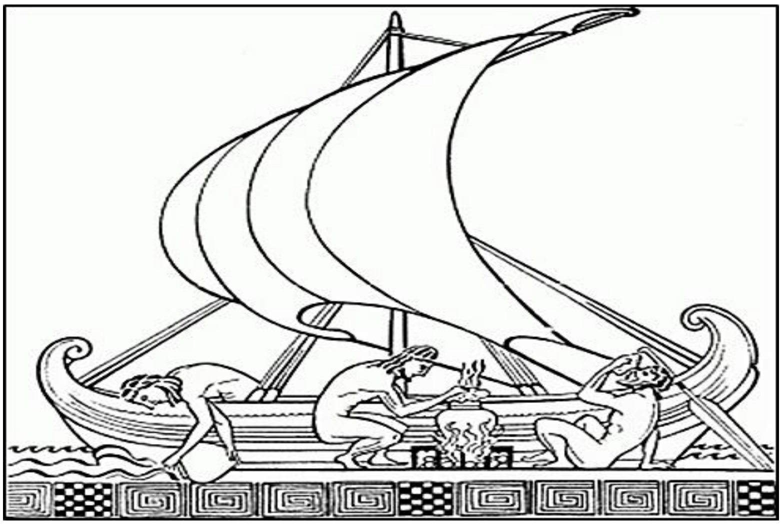

Figure 1.3: Producing pure water with seawater distillation (Kalogirou, 2005)

Probably the first application of seawater desalination using distillation was the above method of producing freshwater for sailors' needs. Figure 1.3 depicts a 200 A.D. historical account by Alexander of Aphrodisias, who described vapour from seawater, having been boiled by sailors at sea, being captured by large suspended sponges (Kalogirou, 2009).

The nineteenth century witnessed major applications of the method of solar distillation for desalination. The first patent for distillation of water by solar energy was issued in 1870 in Las Salinas, Chile (Harding, 1883). In 1872, a station was built to produce pure water for workers of nearby saltpetre and silver mines. The station's framework was built of wood and timber and covered with glass sheets of a surface area of 4450 m^2, laid onto a surface area on land of 7896 m^2. The productivity of the station was 22.70 m^3 of pure water per day (about 4.9 l/m^2) (Delyannis, 2003).

Solar-energy desalination projects in the 20th century concentrated on the development of relatively small solar stills, which are appropriate for use in remote areas around the world during a water-supply shortage or emergencies (Kalbasi & Esfahani, 2010). In 1952, the Office of Saline Water, in the US government, many experiments were conducted and concerned with different aspects of solar stills, including multiple-effect basins and condenser applications (Delyannis, 2003). This trend ended in the early 1970's, with the emergence of desalination techniques which were more lucrative, such as reverse osmosis (RO) and multi-stage flash (MSF), a technique of sequential stages where evaporation processes depend on low pressure, which allows for the lowering of the boiling point at each stage or "flashing" of the water (Dessouky et al., 1999) and (Fath, 1998).

Solar desalination using the Sun (indirect or solar-driven) developed after the 1980's, when concentrating collectors as well as flat plate collectors became commercialised.

Shahmohamadi et al., (2015) presented a paper titled "Solar water distillation by using water in the inner glass evacuated tubes," In this study; the system consisted of only two evacuated tubes, which were installed at an angle of 60 degrees with the horizon. The length of the tubes was 1820 mm; the inner and outer radius was 47 and 57 mm respectively, coupled to a condensation box. The total production of distilled water was 1000 ml.

Karuppusamy (2012) proved that coupling an evacuated tube collector with a solar still increased the productivity from 1965 to 3910 ml/m^2.

Sharif et al. (2013) in a study titled "A novel integrated solar desalination system with a pulsating heat pipe" demonstrated a remarkable increase in the yield of pure water productivity; from 500 to 875 $ml/(m^2.h)$. Panchal (2015), in a study titled "Enhancement of distillate output of double basin solar still with vacuum tubes" conducted in Mehsana, Gujarat, showed that, by adding vacuum tubes to a double basin solar still, the distilled water yield was also in the vicinity of 56%.

Blanco et al. (2004) published their work “Advanced Solar Desalination: a Feasible Technology to the Mediterranean Area”, as an alternate feasibility study of the use of solar thermal seawater desalination, by coupling a parabolic trough solar collector field with a conventional multi-effect distillation unit. However, this technology is unable to compete economically with other desalting technologies without further enhancements.

Flat-plate solar energy collectors are used typically for heating water with temperature requirements up to 75 ℃ and are therefore not directly suitable for solar desalination, unless higher temperatures could be obtained from collectors, where the working fluid (normally water) is substituted with another heat-transfer liquid (Jesko, 2008). In the twentieth century it was recognised that the creation of vacuum between the absorber and the cover of a solar collector resulted in an improvement in efficiency due to minimising the heat losses by conduction and convection (El-nashar, 1981). As a result, various evacuated-tube models were developed in order to harvest solar energy, with a number of them still being sold commercially. Using selective absorption surfaces in the evacuated collectors also significantly reduced the radiated heat losses and upgraded the solar collector efficiency (Emmet, 1911). Evacuated tube solar collectors are more effective than the flat plate solar collectors, as they utilise a vacuum envelope (see Figure 1.4), which ameliorates the loss of heat in the absorber while increasing the potential to obtain higher temperatures (Sabiha et al., 2015). Evacuated heat collectors are made up of vacuum-sealed glass tubes with absorbent surfaces of different shapes located in the inner section of each individual glass tube. A larger glass tube surrounds each tube, with annular evacuated space between the tubes in order to decrease the loss of generated heat. The heat transfer liquid is heated constantly as it circulates within the tubes (Ayompe & Duffy, 2013), (Morrison et al., 2004) and (Zambolin & Del Col, 2010).

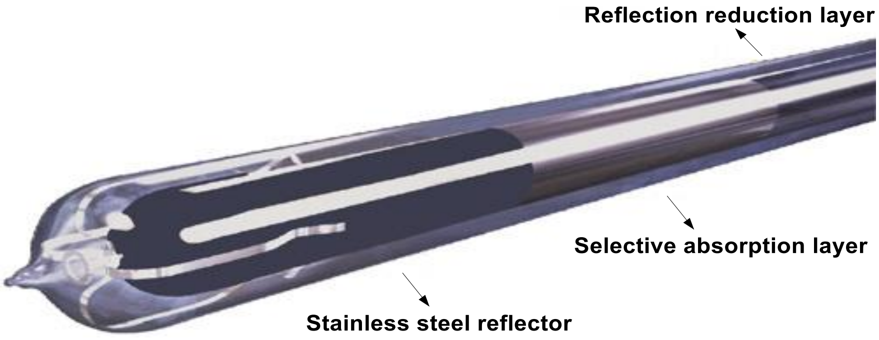

Figure 1.4: Glass tube (vacuum envelope), covered with selective coating (www.jinyi-solar.com)

The technology of the evacuated tube (not to be confused with the latest development of containing a copper heat pipe in the inner section) initially developed by researchers at the University of Qing Hua in Beijing in the early eighties, and piloted for industrial application in 1985, (www.navitron.org.uk).

The Beijing Solar Energy Research Institute (BESRI) is the largest and most important specialised research institution in the solar field in China. Since the 1990s, with the cooperation of Daimler-Benz Aerospace of Germany, BESRI have successfully developed several advanced types of evacuated tube collectors incorporating heat pipe technology. ETCs with heat pipes consist of a glass tube covered with a selective coating "black Co" ($\boldsymbol{\alpha}$ = 0.92-0.94, $\boldsymbol{\varepsilon}$ = 0.07-0.08) for heat absorption, a copper heat pipe with fins attached to it and a flexible joint seal, as shown in Figure 1.5 (He et al., 2003) & (Tongze et al., 1989).

A heat pipe (HP) is often manufactured from a sealed envelope of copper pipe, of different lengths and diameters, which contains a small quantity of working fluid. The HP has a high level of thermal conductivity, which transfers the energy of latent heat by evaporating the working fluid in a heating section. This vapour condenses in another section, called a cooling/condenser section. This circulation is completed with the condensate flowing back to the heating section via the gravity or the capillary structure, into the container's inner wall (Dunn & Reay, 1982) and (Faghri, 1995). The use of evacuated tube collectors with heat pipe (ETCs-HP) in modern domestic solar water heating systems has increased worldwide, due to their high thermal efficiencies and the high operating temperatures which are provided by this technology when compared with flat plate solar collectors. The thermal performance of solar water heating systems using evacuated tube solar collectors has not yet been properly evaluated and is consequently not familiar to future potential users (Ayompe & Duffy, 2013) and (Chow et al., 2011).

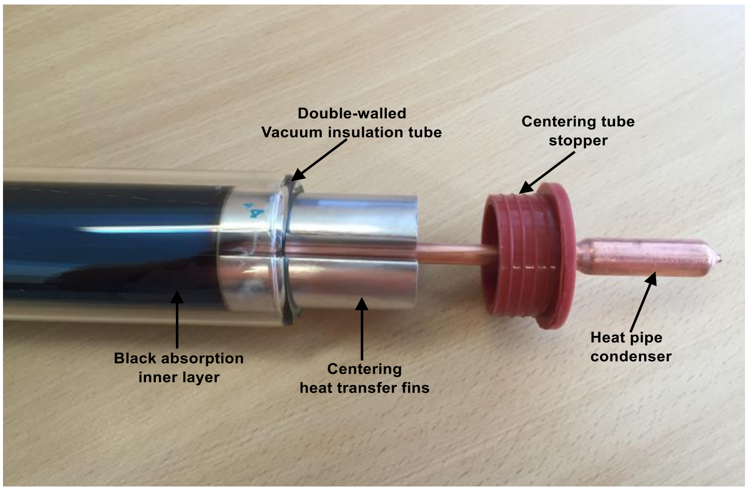

Figure 1.5: Vacuum tube heat pipe construction

1.3 The motivation for this work

The motivation for the present work is that humanity's suffering from shortage of pure water from natural resources increases exponentially. Water desalination is a solution; but it currently carries a heavy price as a direct consequence of steadily rising energy prices, lack of adequate supply of energy, lack of clean energy and an increase of environmental pollution caused by fossil-fuel use to produce heat energy.

Availability of technological equipment that can be employed in the field of desalination of water, such as solar collectors employing evacuated tube heat pipe technology, may become a viable solution to the above-described problems.

1.4 Statement of the research's objectives

This project will consist of the design of a desalination plant using the commercially-available, current state-of-the-art evacuated tube heat pipe solar collector, for the capture of solar radiation. This will be a novel approach in the process of water purification/desalination since currently evacuated tubes (some with heat pipes) are being used, only for the purpose of domestic water heating. The temperature of the water in such systems does not exceed the 75 $°C$ level, which is too low for sufficient vapour production to harvest potable water. Using auxiliary equipment such as pumps, geyser, condenser, etc., a prototype plant will be erected. Using classical thermodynamics and the science of heat transfer, the performance of the prototype plant on the basis of pure water produced, will be evaluated by carefully collected data on the basis of heat balance and energy transfer on each component of the plant.

The performance of the desalination plant, as measured experimentally, will be compared as various parameters of the system are modified/altered or hopefully enhanced. The project will culminate with an experimental parametric study which attempts to improve the functionality or performance of the heat pipes that are used in the commercially available solar collector. Data delivered from this part of the study will provide much-needed information to users of heat pipe technology and will also reflect on the performance of the project's prototype solar distillation plant.

1.5 Outputs

The prototype solar desalination system should be evaluated on the basis or usefulness of being able to produce a reasonable amount of pure water for domestic use on a daily basis.

The results of the parametric study of the heat pipe's performance, based on the various working fluids tested, would be used to categorize the device in terms of its efficiency of capturing solar energy for the purpose of heating water. Such data would be useful to designers and users of heat pipe technology.

1.6 Research design and methodology

The work will involve designing, constructing and the testing of a prototype for seawater desalination, using solar energy as source of heat for generating steam, and a subsequent condensation process. A heat transfer balance will inform on the thermal behaviour of the system, using experimentally-obtained data associated with the amount of potable water harvested.

The quantity of distilled water produced by the prototype depends on the size of the solar collector and the quantity of sun radiation available. Outdoor experimental performance under different weather conditions is temperamental, and thus time-consuming; therefore, all experiments will be conducted indoors. A sun simulation model designed and manufactured, will be a reliable tool in the evaluation of the system's performance.

In addition, the parametric study involving the type of the liquid contained in a typical Heat Pipe, associated with the solar-energy collector of the system, will be experimentally performed, with the view to possibly enhancing its performance.

1.7 Scope of the Thesis

The research involved theoretical and experimental studies, as reported in different chapters of this dissertation. The thesis report is comprised of six chapters, briefly outlined below:

Chapter One gives a general introduction and background information about water resources on Earth, and introduces the history of solar desalination technologies. It also describes the motivation for this work, as well as objectives of the research. The chapter concludes with similar published works and an outline of this document.

Chapter Two gives an overview of fundamental knowledge and theoretical background concerning solar energy and estimation of terrestrial solar radiation. The chapter presents some formulae which estimate the average of daily global radiation at any specific location. The chapter includes the theory of heat pipe technology.

It also includes an energy performance analysis, such as the equation that calculates energy collected in the manifold, energy delivered to the geyser, solar collector's efficiency, as well as the system's efficiency in terms of heating the water, the enthalpy of a substance's phase change and efficiency of the system with regard to the production of distilled water.

Chapter Three describes the design of the prototype of solar water desalination, the progressive modifications that were imposed on it and the apparatus used for the testing of the heat pipe's performance with different working fluids.

The chapter concludes by describing the techniques and measuring equipment used.

The fourth chapter covers the experimental protocol while testing the water desalination prototype during the various stages of modifications from its originally acquired commercial solar water heating configuration. It also describes the experimental protocol that was adopted in order to assess the performance of the evacuated tube heat pipes with different working fluids and the manner of data collection and analysis.

Chapter Five presents in addition to the summary of the results from the various tests that were performed with the desalination prototype plant, the detailed results from each individual experiment. As a separate issue, also inferring or linked to the plant's performance, the results of the investigation into the performance of the heat pipes which form a salient feature of the prototype plant, are presented and discussed.

Chapter Six is the final chapter, where conclusions of this work and recommendations for future work are presented.

The dissertation document also includes five appendices:

Appendix A: Technical data for the evacuated tubes and heat pipes of the collector

Appendix B: The detailed description of measuring instruments and auxiliary equipment.

Appendix C: Raw data collected during the desalination prototype experiments.

Appendix D: Raw data collected during the heat pipe tests for various working fluids.

Appendix E: sample calculations of how different results were obtained.

1.8 Publications

The following are the author's contributions to the body of literature in the field of water desalination using solar energy, as outcomes from the work entailed in this research.

<u>Peer reviewed Conference proceedings:</u>

1. A. Alwaer and J. Gryzagoridis, "Water Desalination by Evacuated Tube Heat Pipe Solar Collector" 11th Industrial and Commercial Use of Energy Conference (ICUE2014), pp. 361-365. 18–20 August 2014 in Cape Town, South Africa.

2. A. Alwaer and J. Gryzagoridis, "Experimental study of solar water desalination system utilising evacuated tube heat pipe collector" 2015 Proceeding of the 23nd Domestic Use of Energy, pp. 155–162. 31 March–1 April 2015 in Cape Town, South Africa

CPUT Conferences:

3. A. Alwaer and J. Gryzagoridis, “a prototype desalination system using solar energy and heat pipe technology”, Engineering Postgraduate Seminars 2014, 19 June 2014, Bellville campus, (power point presentation).

4. Alwaer, A, “Water Desalination by Evacuated Tube Heat Pipe Solar Collector”, CPUT Research Day 2014, 27 November 2014, Mowbray Campus, (Poster presentation).

CHAPTER TWO

FUNDAMENTALS AND THEORETICAL BACKGROUND

Assessment of the performance of a solar energy application or project is dependent upon measured data, which is analysed using basic principles of engineering and physics. “The success of a solar energy project relies on measured data obtained and accurately evaluated during its development process” (Myers, 2005).

2.1 Solar energy

The Sun’s light is known as solar energy or radiant energy, and is harnessed by means of constantly-evolving technologies such as solar water heating, solar photovoltaic panels etc. It is one of the most vital sources of renewable energy available to us (IEA, 2011).

Solar radiation is accessible practically everywhere on Earth, but due to its low density and the fact that the energy reaching us varies by geographical location and time, it poses significant challenges for optimal harvesting and use (Howe, 1974) and (WEC, 2004).

The energy provided by the Sun to the planet Earth is known to be associated with the fact that the sun accounts for 99.98% of the total mass of our solar system, so is largely responsible for all the extra-terrestrial energy arriving on earth and the existence of life on this planet. The mean distance between Sun and Earth, known as AU (Astronomical Unit) is 150 million kilometres, where the solar radiation flux reaching the earth’s atmosphere is 1367 W/m^2 (SAYIGH 1997) and (SAYIGH 1984). This quantity is named the Solar Constant (G_{sc}) which has been the subject of substantial research, as outlined below.

Measurements of solar radiation for most of Earth’s atmosphere were conducted via high-altitude aircraft, balloons and spacecraft. These measurements have been taken with a variety of instruments and expressed separately in nine experimental stages. The results concluded in the calculation of the value of the solar constant G_{sc} of 1353 W/m^2, with an estimated error of ± 1.5%. For more information about these experiments, see Thekaekara & Drummond, (1971) or Thekaekara, (1976).

In 1971, this standard value was approved by NASA and by the (ASTM) American Society of Testing and Materials (2006), (Duffie & Beckman, 2013).

Frohlich, (1977) re-examined the value of 1353 W/m^2 in previous research, based on comparisons of instruments with absolute radiometer, reducing it to a new pyro-hellion-metric scale. Frohlich therefore recommended in 1978 a new value for the solar constant of 1373 $/m^2$, with estimated error margin of 1-2%. In addition, other spacecraft readings were conducted by Hickey et al., (1982) and Willson et al., (1981) reporting $G_{sc}$of 1373 W/m^2 and G_{sc} of 1368 W/m^2 respectively. Moreover, other measurements were conducted from three rocket flights: 1367, 1372 and 1374 W/m^2, reported by Duncan et al., (1982).

A value of 1367 W/m^2 was adopted by the world Radiation Centre (WRC) with uncertainty of the order of 1% (Duffie & Beckman, 2013).

Figure 2.1 illustrates the entire annual sunlight which penetrates and passes through our atmosphere and the solar radiation by atmospheric and surface processes for the whole Earth over a 12-month period of which 51% is exploited by the Earth's surface. The employment of this energy is to be used to generate heat for the Earth's surface, warmth to the air, melting of ice, performance of photosynthesis in plants and the evaporation of water. The remaining 49% of the solar energy, is spread as follows: 4% is reflected back to space via the Earth's surface; 20% and 6% are scattered or reflected respectively to space by clouds and atmospheric particles, 16% is absorbed by atmospheric gases, and 3% by particles and clouds (Falayi & Rabiu, 2012).

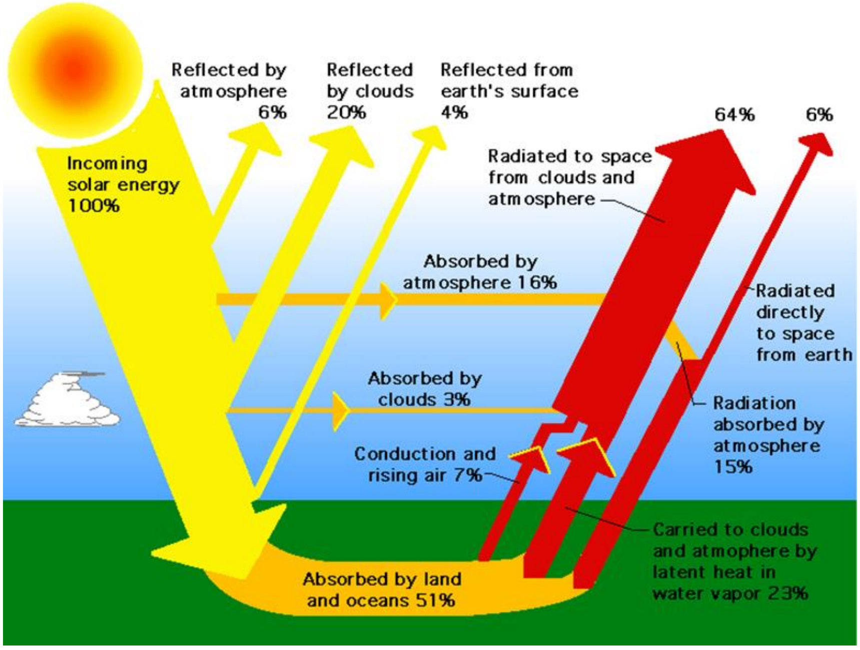

Figure 2.1: Schematic representation of the Earth's radiation or energy balance (Atmospheric Science Data Center, 2011) and (Falayi & Rabiu, 2012)

Figure 2.2 explains the spectrum distribution of solar radiation emitted from the Sun and distributed continuously over a wide spectrum, ranging from ultraviolet to infrared rays. The solar radiation in this spectrum is in short wavelengths, ranging between 0.29 to 0.3 μm, constituting about 97% of the total energy emitted.

2.1.1 Estimation of terrestrial solar radiation

As is schematically described in Figure 2.1, when extra-terrestrial solar radiation penetrates the atmosphere, a portion of it is reflected into space, some will be absorbed by air and water vapour, and some is scattered by molecules of air, water vapour, aerosols and dust particles. The part of the solar radiation which reaches the surface of the Earth with no significant change in direction is called direct or beam radiation. The scattered radiation reaching the surface from the sky is called diffuse radiation.

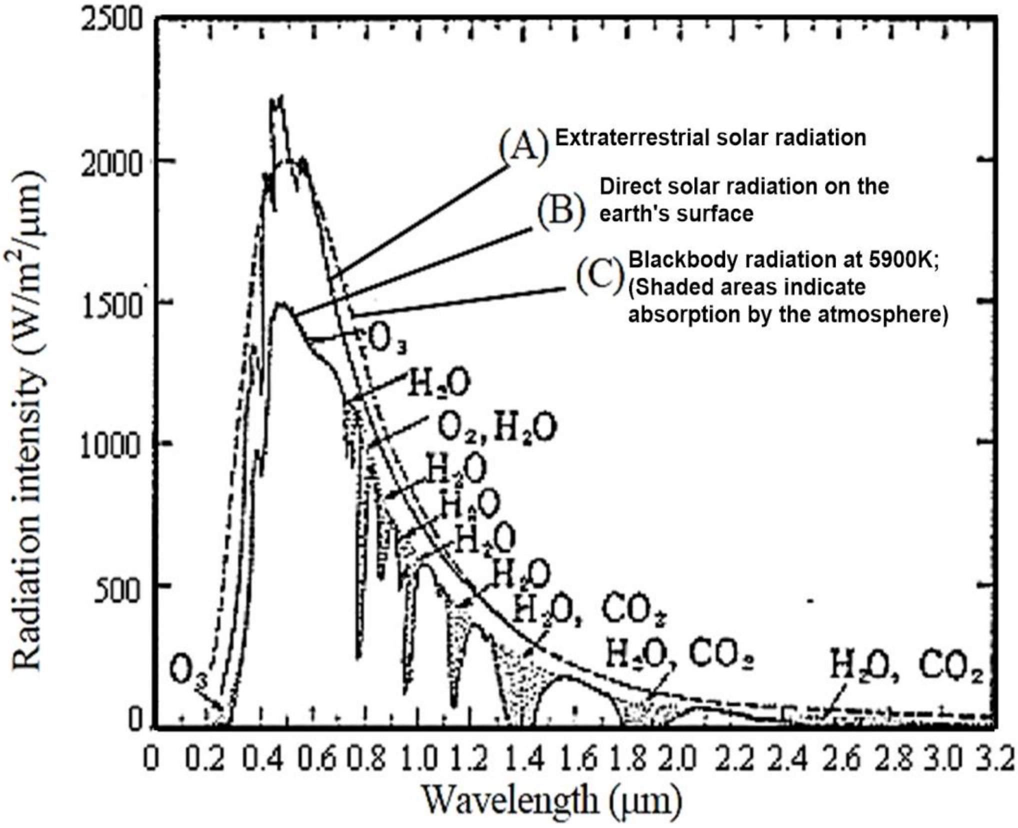

Figure 2.2: Spectrum distribution of solar radiation, adapted from Duffie et al., (1994) and Goswami et al., (2000)

Even though extra-terrestrial radiation can be described with utmost certainty, levels which actually reach the surface of the Earth can vary according to local climatic interactions. Therefore, longer collections periods using a variety of locations produce better results (for example, 30 years or more in different locations).

The average global radiation in any specific location is estimated by the actual sunshine hours and the maximum possible sunshine hours per day at the specified site. The data was a simple linear relation, given by Angstrom (1924) and corrected by Prescott (1924) (Falayi & Rabiu, 2012).

Equations for predicting the availability of solar radiation were developed and implemented, such as equation 2.1 by Sarsah & Uba (2013):

$$\frac{H}{H_c} = a + b(n/N) \qquad (2.1)$$

Where H is the monthly average of the daily global solar radiation on a horizontal surface $(KJ/m^2.day)$, H_c is the monthly average clear sky daily global radiation $(KJ/m^2.day)$, n is the monthly average of the actual sunshine hours per day, N is the length of day, a and b are empirical constants. Accurate calculation of the clear sky radiation for equation 2.1 was difficult, and therefore clear sky radiation was replaced with extra-terrestrial radiation, H_0 and this model was modified to a more convenient form by Prescott(Prescott, 1940):

$$\frac{H}{H_0} = a + b(n/N) \tag{2.2}$$

$H_{0,}$ is calculated from the following equation (Duffie & Beckman, 2013):

$$H_0 = \frac{24\times 3600}{\pi} \times G_{sc}\left(1 + 0.033\ \cos\frac{360n}{365}\right)$$

$$\times\left(\cos\emptyset\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\emptyset\sin\delta\right) \tag{2.3}$$

Where G_{sc} is the solar constant (1367 W/m^2), ϕ is the latitude of the site, δ is the sun declination and ω_s is the sunset hour angle.

Declination, sunset hour angle and length of day can be computed by the following equations (Prescott, 1940) , (Duffie et al., 1994) and (Falayi & Rabiu, 2012):

$$\delta = 23.45\sin\left(\ 360 \times \frac{284+d}{365}\right) \tag{2.4}$$

Where, d is the day of the year, $1 \leq\ d\ \leq\ 365$

$$\omega_s = \cos^{-1}(-tan\emptyset\ tan\delta\ ) \tag{2.5}$$

$$N = \frac{2}{15}\cos^{-1}(-tan\emptyset\ tan\delta\ ) = \frac{2}{15}\omega_s \tag{2.6}$$

Table 2.1 is a summary of models (regression models) that have been proposed for estimating the monthly average daily global solar radiation H , based on the Angstrom-Prescott model (Sarsah & Uba, 2013).

Table 2.1: Regression models for estimating the monthly average daily global solar radiation H

Model No.	Regression Equation	Model type
1	$H/H_0 = a + b(n/N)$	Linear
2	$H/H_0 = a + b(n/N) + c(n/N)^2$	Quadratic
3	$H/H_0 = a + b(n/N) + c(n/N)^2 + d(n/N)^3$	Cubic
4	$H/H_0 = a + b(n/N) + c\log(n/N)$	Linear logarithmic
5	$H/H_0 = a + b\log(n/N)$	Logarithmic
6	$H/H_0 = a + b(n/N) + c\exp(n/N)$	Linear exponential
7	$H/H_0 = a + b\exp(n/N)$	Exponential
8	$H/H_0 = a(n/N)^b$	Exponent

Adopted from (Emmanuel A. Sarsah, Felix A. Uba, 2013)

Data available in the literature concentrates on beam and diffuse solar radiation on the horizontal surface, which can be very useful for solar process simulation. On the other hand, a limited number of inclined surface readings are available. Hourly solar radiation can be estimated from the daily data, while total monthly solar radiation on the horizontal surface can be obtained by various methods and processes (Duffie et al., 1994).

When researching solar energy applications, measurements of parameters such as sunshine duration, diffuse radiation and beam radiation are essential. For this a number of different kinds of measuring equipment is available (Kalogirou, 2009) and (Zerlaut, 1989).

2.2 Evacuated tube heat pipe solar collector technology

The evacuated tube consists of an outer and inner glass tube with a vacuum trapped between these glass sections. This allows for radiation to penetrate into a centrally located heat pipe, but prevents heat loss via dissipation. The heat pipe is located centrally inside the inner tube. The heat pipe normally consists of a long copper tube containing a very small quantity of the working fluid (e.g., water, acetone, methanol, ethanol, etc.) which forms the vehicle for moving heat to the cooler section of the copper tube. Each collector is made up of a frame, a manifold and a set of tubes – either 8, 12, 18 or 24 tubes, depending upon the geyser size.

There are various forms of heat pipes which are commercially used in the solar collector panels. As shown in Figure 2.3, the structure is basically very similar with variations in the shape and size of the (upper portion) condenser (Jack & Rockendorf, 2013) and (Barua et al., 2013).

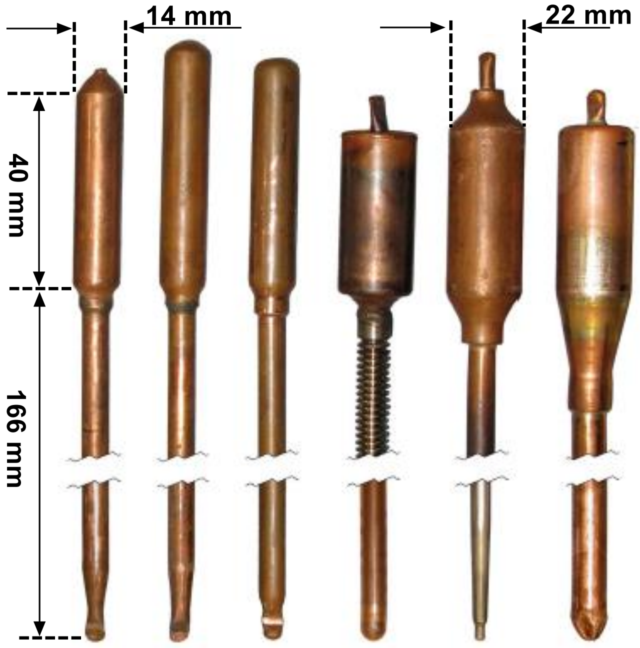

Figure 2.3: Various geometrical forms of heat pipes(Jack & Rockendorf, 2013)

2.2.1 Structure and operation of heat pipe

The design of the heat pipe includes a long copper pipe with a larger diameter condenser at the top and welded at the other end. A small amount of working fluid with additives is added into the heat pipe and then heated to high temperature, or a vacuum pump is used to remove the air from within the space. The result of either method is a vacuum in the copper pipe (Ashok & Mali, 2015).

The vacuum inside the heat pipe alters the behaviour of the fluid inside it. This allows the phase change of the fluid to a gas to occur at a lower temperature. The reason for this is to expedite the heat transfer process and create the continuous heat transfer cycle (Gaugler, 1944), (Grover, 1966) and (Grover et al., 1964).

The evacuated tube heat pipes typically found in solar collectors containing a small amount of working fluid have a boiling point of around 25 $^{\circ} C$ as a result of the induced vacuum, so when heating the heat pipe above this temperature the working fluid begins to evaporate. The vapour rises to the condenser at the top of the heat pipe, where it condenses (giving off heat to the desired spot) and returns to the evaporation section at the bottom of the heat pipe. This process is repeated as a cycle (Gaugler, 1944), (Grover, 1966) and (Grover et al., 1964).

2.2.2 The working fluid

As stated before, the heat pipes can utilise various liquids as a working medium. Table 2.2 refers to the characteristics of typical fluids that could be used for this application.

Table 2.2: Heat pipe working fluids

Medium	Melting point (°C)	Boiling point at Atmosphere pressure(°C)	Useful range (°C)
Helium	-271	-261	-271 to -269
Nitrogen	-210	-196	-203 to -160
Ammonia	-78	-33	-60 to 100
Pentane	-130	28	-20 to 120
Acetone	-95	57	0 to 120
Methanol	-98	64	10 to 130
Flutec PP2[1]	-50	76	10 to 160
Ethanol	-112	78	0 to 130
Heptane	-90	98	0 to 150
Water	0	100	30 to 200
Toluene	-95	110	50 to 200
Flutec PP9[1]	-70	160	0 to 225
Thermex[2]	12	257	150 to 350
Mercury	-39	361	250 to 650
Caesium	29	670	450 to 900
Potassium	62	774	600 to 1000
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

Note: (The useful operating temperature range is indicative only.)

[1] Included for cases where electrical insulation is a requirement.

[2] Also known as Dowtherm A, an eutectic mixture of dipheny1 ether and dipheny1.

Some working fluids need a compatible vessel material to prevent and avoid chemical reactions or corrosion between the fluid used and the vessel. Chemical effects such as corrosion reduce the efficiency of the vessel, as a non-condensable gas can be produced by chemical reactions.

For example, using ammonia as a working fluid in the heat pipe provides a temperature range from –70 to +60 ℃ and is compatible with several vessel materials such as aluminium, nickel and stainless steel, but not copper. Typical Operating Characteristics of Heat Pipes are shown in Table 2.3 (Holman, 2010).

Table 2.3: Typical operating characteristics of heat pipes

Temperature Range (°C)	Working Fluid	Vessel Material	Measured axial[8] heat flux (kW/cm^2)	Measured surface[8] Heat flux (W/ cm^2)
-200 to -80	Liquid Nitrogen	Stainless steel	0.067 at -163°C	1.01 at -163°C
-70 to +60	Liquid Ammonia	Nickel, Aluminium, Stainless Steel	0.295	2.95
-45 to +120	Methanol	Copper, Nickel, Stainless Steel	0.45 at100°C[X]	75.5 at 100°C
+190 to +550	Mercury*+0.02% Magnesium +0.001%	Stainless Steel	25.1 at 360°C*	181 at 750°C
+400 to +800	Potassium*	Nickel, Stainless Steel	5.6 at 750°C	181 at 750°C
+500 to +900	Sodium*	Nickel, Stainless Steel	9.3 at 850°C	224 at 760°C
+900 to +1,500	Lithium*	Niobium +1% Zirconium	2.0 at 1250°C	207 at 1250°C
1,500 + 2,000	Silver*	Tantalum +5% Tungsten	4.1	413

[8] Varies with temperature

[X] Using threaded artery wick

[*] Tested at Los Alamos Scientific Laboratory

[*] Measured value based on reaching the sonic limit of mercury in the heat pipe

Reference of “Heat Transfer”, 10th Edition, JP Holman, McGraw-Hill

In selecting a working fluid for use in a heat pipe application, the prime requirements are as follows, (Wallin, 2012).

A. Good thermal stability.
B. Vapour pressures not too high or low over the operating temperature range.
C. High latent heat.
D. High thermal conductivity.
E. Low liquid and vapour viscosities.
F. Acceptable freezing or pour point.

The viscosity, sonic, capillary, entrainment and nucleate boiling limitations play important roles when selecting the working fluid (Gaugler, 1944), (Grover, 1966) and (Grover et al., 1964).

However, in the context of this research, the choice of the working fluid in the heat pipe will rest solely on the level of temperature achieved in the condenser part of the heat pipe. The reason adopted here is that this factor will govern the amount of heat that the heat pipe could transfer. In other words, the higher temperatures at the condenser will inherently be able to transfer more heat (comparatively speaking among heat pipes containing different working fluids) to the bulk of the fluid that is being desalinated. Therefore, internal heat pipe criteria such as the viscous limit (Wallin, 2012), the sonic limit (Manimaran et al., 2012), the entrainment limit affecting the maximum heat flux (Wallin, 2012) & (Reay & Kew, 2006): the capillary limit, etc., will be ignored and, the recommendation of which working fluid will best enhance the performance of the commercial evacuated heat pipe used in the solar desalination prototype will depend entirely on calorific results.

2.3 Energy analysis in the desalination unit

The energy performance indices which were evaluated in this study are: energy collection at the manifold, energy acquisition by the water inside the geyser, efficiency of the collector and geyser (the system) and the relevant enthalpy associated with the efficiency of producing the distillate.

2.3.1 The rate by which Energy is collected in the manifold

Some of the energy taken up by the solar energy collector is transferred to the fluid flowing in the manifold and can be accounted for by (Kalogirou, 2009):

$$Q_1 = \dot{m}\, C_p\, (T_{c,o} - T_{c,i}) \qquad (2.7)$$

Where Q_1 is the heat transferred in watts, $\dot{m}$ is the flow rate in litres (i.e. kg) per second, C_p is the constant pressure specific heat of water (4186) Joules/$kg°C$ (avg. value used) $T_{c,o}$ and $T_{c,i}$ are the outlet and inlet temperatures (in degrees centigrade), of the collector's manifold.

2.3.2 The rate of energy delivered to the geyser

The energy rate delivered by the fluid flowing in the collector's manifold to the geyser's water can be calculated by (Ayompe & Duffy, 2013):

$$Q_2 = m\, C_p\, (T_{avg1} - T_{avg0})/\Delta t \qquad (2.8)$$

Where Q_2 in watts is the average hourly heat rate that went into the increase of the geyser's bulk water temperature, having a mass m in kg, T_{avg0} and T_{avg1} represent the average bulk water temperature in the geyser recorded at (Δt) time intervals.

2.3.3 Solar collector's efficiency

The solar collector's efficiency depends upon its ability to absorb the Sun's irradiance and turn it into a useful heat or electrical energy. (Trier, 2012).

The collector efficiency can be calculated using the expression (Sukhatme, 1998) and (Duffie & Beckman, 2006):

$$\eta_c = \frac{\dot{m}\, C_p\, (T_{c,o} - T_{c,i})}{A_c G_t} \qquad (2.9)$$

Where η_c, is the collector's efficiency (%), A_c, is the collector's area (m^2), G_{ct}, is global solar radiation on the collector's surface (W/m^2). All other quantities as described in equation 2.7

2.3.4 The system's efficiency in terms of heating the water

The system's average hourly efficiency can be calculated using the expression below: (Sukhatme, 1998) and (Duffie & Beckman, 2006):

$$\eta_s = \frac{m\, C_p\, (T_{avg2} - T_{avg1})}{A_c G_t} / \Delta t \qquad (2.10)$$

Where η_s, is the system's efficiency (%) and all other quantities as defined previously in equations 2.8 and 2.9

2.3.5 The enthalpy of a substance's phase change

The release or absorption of heat energy during the process of a fluid's phase transition for example, water vaporising or condensing at specific temperature and pressure, is named latent heat of vaporisation or enthalpy of condensation respectively. The latent heat is the difference in enthalpy between the final vapour, and the initial saturated liquid phases at the same temperature and pressure, i.e.

$$h_{fg} = T v_{fg} \left(\frac{dP}{dT} \right) \qquad (2.11)$$

It can be shown that equation 2.11, known as the Clausius-Clapeyron equation, represents the relationship between the changes in the specific volume of a substance at liquid and vapour states, the slope of the saturation line dp/dT and the enthalpy associated with the phase change at a fixed pressure and temperature.

2.3.6 The system's efficiency in terms of producing distilled water

The efficiency with regard to the production of distilled water of the solar desalination plant is calculated by means of formula 2.12 (Rahim, 2001 and Franceschetti & Gonella, 2012) which involves the enthalpy of the change of phase from saturated liquid to saturated vapour, as indicated in equation 2.11

$$\eta_{sd} = \frac{Q_v\, \emptyset_p}{I} \times 100\% \qquad (2.12)$$

Where η_{sd}, is the system's desalination efficiency (%) in terms of producing distilled water:

Q_v kJ/kg, is the energy associated with the enthalpy necessary to evaporate 1 kg of brackish water at the system's temperature ℃ ; $\emptyset_p$ is the productivity of pure water by the plant $l/m^2/day$; (where litres can be converted to kg) and I is the radiation energy that irradiates the system's collector in $kJ/m^2/day$ (Rahim and Taqi, 1990).

2.4 Energy performance analysis in the heat pipe testing apparatus

The energy performance indices to be obtained using a specially designed and constructed apparatus in this part of the study, will entail the energy collected from the sun simulator via the heat pipe (using different working fluids) to equal the energy transferred by the heat pipe to the water in the apparatus's tank. In other words the efficiency of the heat pipe can be calculated in terms of heat transfer associated with the change of the internal energy of the water in the system.

The heat input will be controlled using a solar simulator and the ambient temperature is not expected to change appreciably since the testing will be done in a laboratory.

2.4.1 Efficiency of heat pipe in terms of heat transfer to tank's water

$$\eta_{hp} = \frac{(\Delta Q_u)/t}{I} m \times 100\% \qquad (2.13)$$

Where η_{hp} is the heat pipe's efficiency (%) in terms of heat transfer to the tank's water.

ΔQ_u (kJ/kg), is the change in the internal energy which is dependent on the temperature T and pressure P of the system.

$t(s)$, is the solar irradiance time; $m(kg)$, is the mass of water in the tank and $I(kW)$, is the actual total solar radiation on the surface of the evacuated tube heat pipe, which is the irradiance kW/m^2 from the solar simulator multiplied by the heat pipe's actual receiving area of (0.08084 m^2).

CHAPTER THREE

THE DESIGN OF THE PROTOTYPE, TESTING EQUIPMENT AND INSTRUMENTATION

This chapter describes the prototype's design, construction and modifications of the solar water desalination plant using the basic heat pipe solar collector technology as well as a ”prototype” testing equipment in order to study the heat pipe's performance with several working fluids. All materials and components used in the construction of the two prototypes (the desalination unit and heat pipe testing apparatus) were sought/acquired as they were readily available from commercial outlets. The process adopted in the procurement of all parts and the construction of the equipment, employing experienced qualified industry personnel, ensured acquisition of state of the art equipment and components; thus proven functionality, reliability and relatively low cost, were integrated in the production of the two systems.

3.1 Description of the solar water desalination prototype

A new system of seawater desalination has been developed, as shown in its final form during this research work in the following schematic diagram (Figure 3.1).

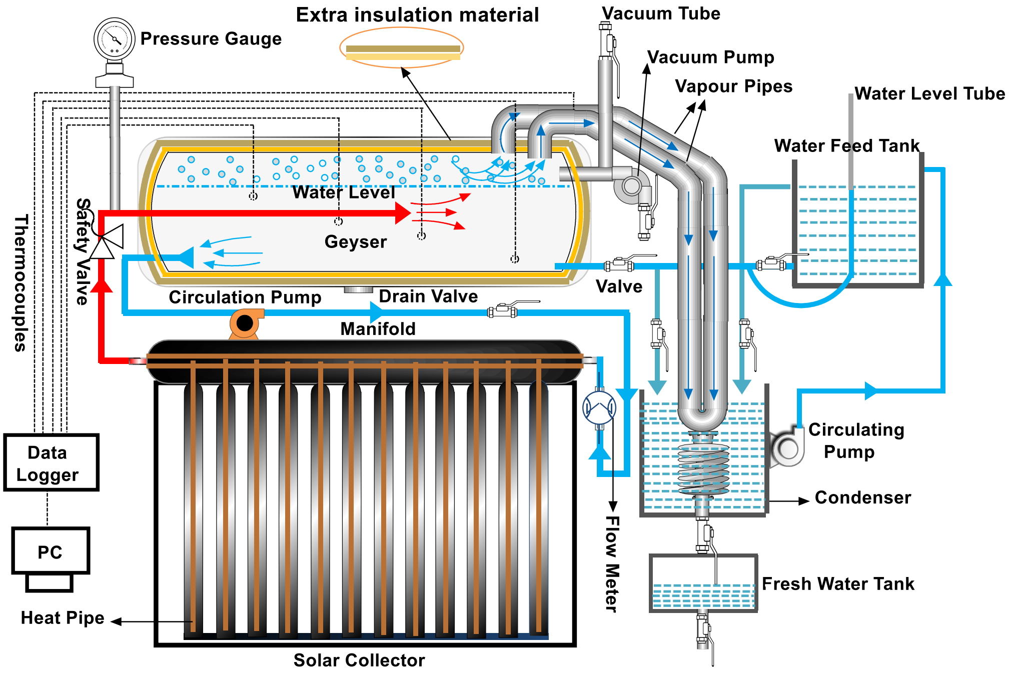

Figure 3.1: Schematic diagram of the prototype solar water desalination plant

In the prototype's ‘geyser' containing saline water, vapour is created by the heat harvested from the available solar energy, using an evacuated tube heat pipe solar collector. The vapour is passed through the condenser to produce fresh water (distillate). As a result of continuous evaporation, the concentration of minerals dissolved in the water (including salt), will increase and eventually saturate the contents of the geyser. In order to refresh the water, the mineral-saturated water will be discharged out via a drain created at the bottom of the geyser. The basic system of the water desalination prototype, as shown in Figure 3.2, is comprised of the following components:

1- The feed tank
2- The condenser
3- The geyser
4- Variable voltage transformer - Variac
5- The 12 vacuum tube heat pipe solar collector
6- The sun simulator comprised of 12 halogen lamps
7- Fresh water tank
8- Circulating pump
9- Rotary vane vacuum pump
10- Pressure gauge
11- Steam pipes
12- The thermocouples
13- Thermocouples to data logger
14- Tube to determine and control the water level inside the geyser
15- Flow meter
16- Circulating pump
17- Drain valve

Figure 3.2 Photograph of the solar water desalination prototype

3.1.1 The geyser

The geyser, with a capacity of 150 litres, is one of the main units in the prototype; originally intended for heating water for domestic use. The internal cylinder is manufactured from 1.6 *mm* mild steel sheet, with a galvanised external casing and internally lined with enamelled thermo-fused porcelain for cylinder longevity and hygiene. Polyurethane insulation between the cylinder and external galvanised sheet casement reduces heat loss. Short pipes of the water's inlet and outlet were located in one of the geyser's sides. A coiled copper tube attached to the inlet and outlet pipes within the geyser's envelope was intended for the heat exchange between the geyser's contents and the circulating fluid through the collector's manifold. Four thermocouples were installed in different positions within the geyser for measuring the water's temperature. A pressure gauge was provided.

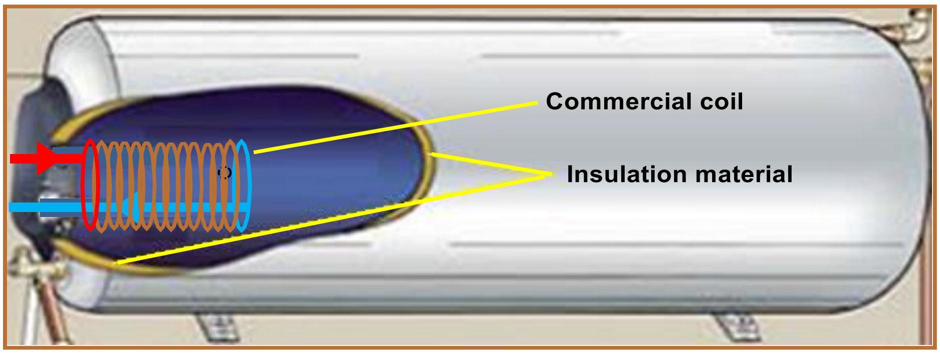

Figure 3.3: Sector of the geyser illustrating commercial design

3.1.2 Specifications and dimensions of the geyser

Table 3.1 and Figure 3.4 below list the specifications and dimensions of the geyser.

Table 3.1 Geyser specifications

Capacity	Operating Pressure	Mass Empty	Dimension A	Dimension B	Dimension C	Dimension D
150 l	Up to 600 KPa	39 kg	1320 mm	480 mm	895 mm	355 mm

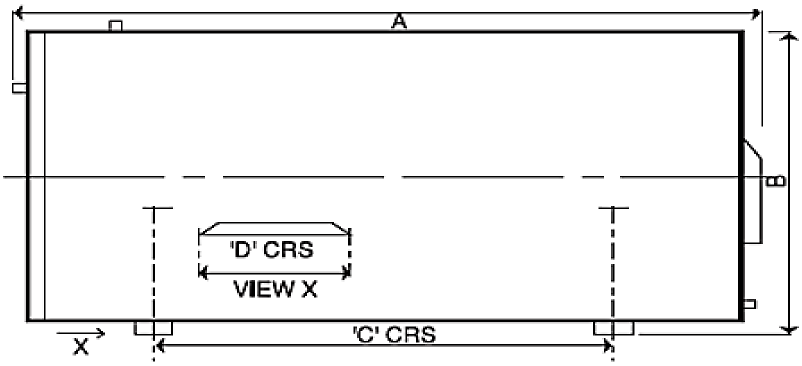

Figure: 3.4: Geyser Dimensions

3.1.3 Modifications to the geyser

Many of the modifications to the geyser were implemented as a result of testing the system's performance in terms of distillate harvest and are summarised below:

The commercial geyser consisted of a steel tank fitted with a 3 KW thermostatically-controlled electrical element, as well as a drain valve and a temperature and pressure relief (TP) valve. There were standard inlet and outlet ports of 22 mm at opposite ends of the tank. The actual outlet was only 16 mm inside the bush, and it was located on the upper side of the geyser. The schematic diagram Figure 3.5 shows the commercial design of the geyser with the electrical heating element removed the positioning of the four water temperature thermocouples and the modified outlet steam pipe with suitable geometry to avoid liquid carryover.

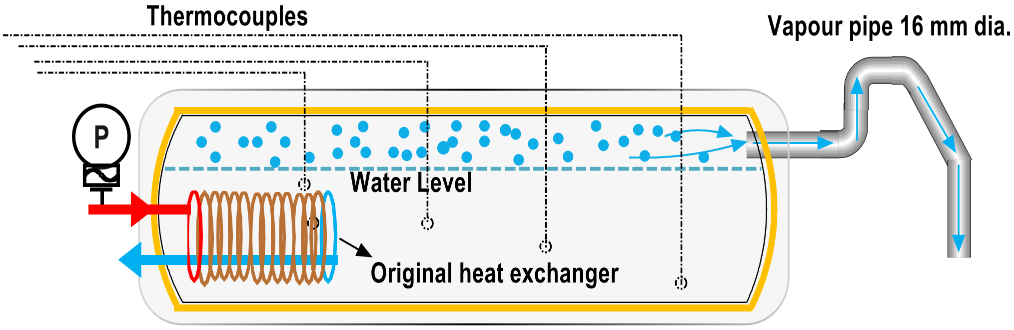

Figure: 3.5: Schematic diagram of geyser after removal of the electric element, temperature probes insertion and modification of the 'vapour' pipe

3.1.4 Custom built heat exchanger to improve the transfer of heat from the manifold to the geyser's contents.

Using the existing standard heat exchanger flange, the original copper coil heat exchanger was replaced with a new heat exchanger consisting of six 22 mm dia. copper pipe sections, approximately 900 mm long each and shaped to fit into the geyser, as shown in Figure 3.6

The new heat exchanger increased the heat transfer surface area from the original value of 0.15 m^2 to 0.373 m^2 (2.5 times larger). The schematic diagram, Figure 3.7 shows the geyser with the new heat exchanger in position.

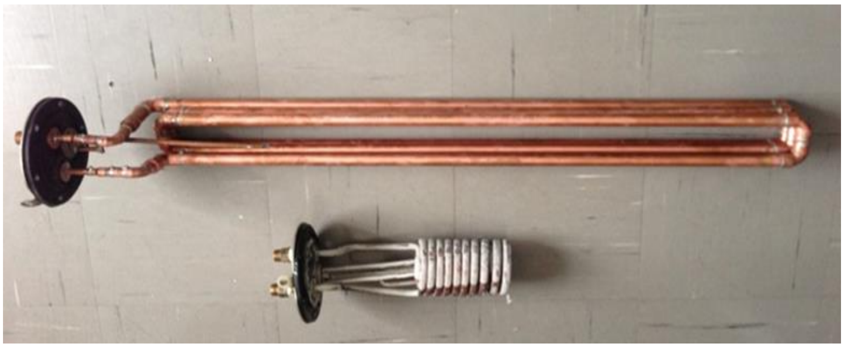

Figure 3.6: Comparison between the commercial heat exchanger with its replacement

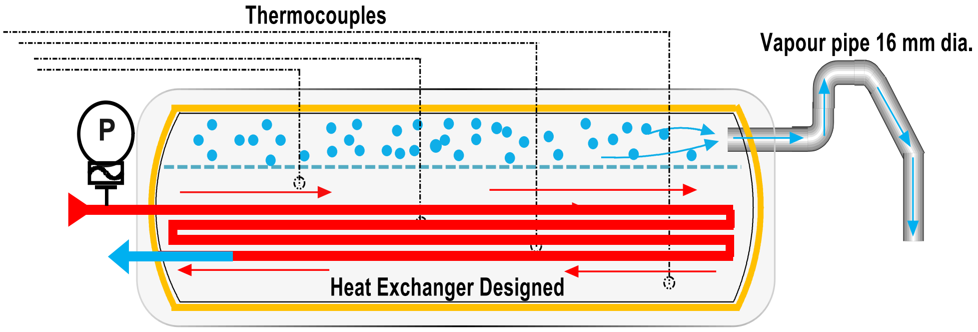

Figure: 3.7: Schematic diagram of geyser after replacing the original heat exchanger

3.1.5 Restriction of vapour outflow by the standard/original geyser outlet

Since more heat was required for the yield of distillate to be increased, the heat exchanger was removed (keeping the same 16 mm dia. outlet), and replaced with a long inlet pipe to ensure the hot water created in the collector's manifold was deposited as far as possible into the geyser and not near the "cold" water return inlet as shown in Figure 3.8.

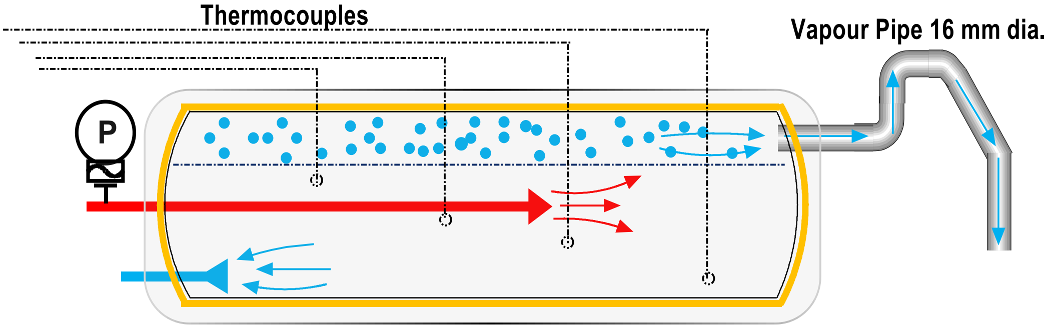

Figure 3.8: Schematic diagram of the geyser with the 16 mm dia. outlet pipe and the heat exchanger removed

Due to the nature of the standard geyser construction, it was realised that the relatively small vapour outlet of 16 mm dia. and its original position were possible reasons causing restriction of the flow of steam being generated.

In order to facilitate the vapour flow into the condensing section, the outlet of the steam was changed from the side exit to a top exit and increased to a 76 mm dia. by cutting a 76 mm dia. hole into the top of the geyser and welding a steam socket (see Figures 3.9 and 3.10). The inside diameter of the pipe was 74 mm, and this represents an increase in flow area of 21.4 times compared to the original outlet of the commercial unit. The first section of the vapour carrying pipe exiting the geyser was insulated to avoid premature condensation, which would cause water/distillate to run back into the geyser.

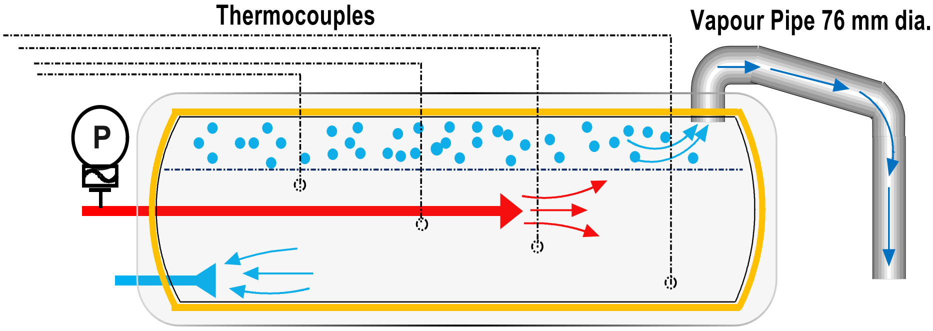

Figure 3.9: Schematic diagram of the geyser with the 76 mm dia. Single outlet pipe And the heat exchanger removed

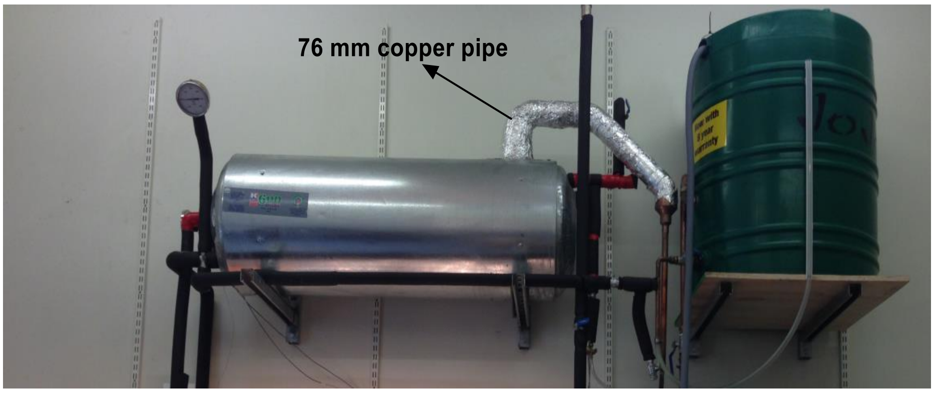

Figure: 3.10: photograph of the geyser with 76 mm dia. outlet pipe

3.1.6 Improving the insulation of the geyser

The standard geyser as designed for domestic hot water use loses heat of approximately 3 kWh over 24 hours, which is unacceptable. During the testing of the prototype, it was observed that considerable heat was lost from the system during periods of inactivity (i.e. during the night when the sun simulator was turned off). For the purpose of reducing these ‘overnight’ heat losses from the system, a standard geyser blanket was wrapped around the geyser and the test results indicated a fair improvement over the previous yield. Geyser blankets are available in 50 or 75 mm thicknesses made of various insulation materials, the most common being fiberglass. A reflective aluminium foil encases the insulation layers. The insulation material used is shown in Figure 3.11.

Figure 3.11: Extra insulation material (Geyser blanket).

3.1.7 Doubling of the outlet vapour carrying pipe

Based on the previous increase of distillate harvest after the modifications to the geyser's vapour outlet, the process was repeated by adding another 76 mm dia. copper pipe outlet. The two outlets were joined together at a point below the water level in Tank 2. The vapour outlet was now 42.8 times larger than the original. The schematic diagram in figure 3.12 illustrates the geyser with the final vapour outlet pipes.

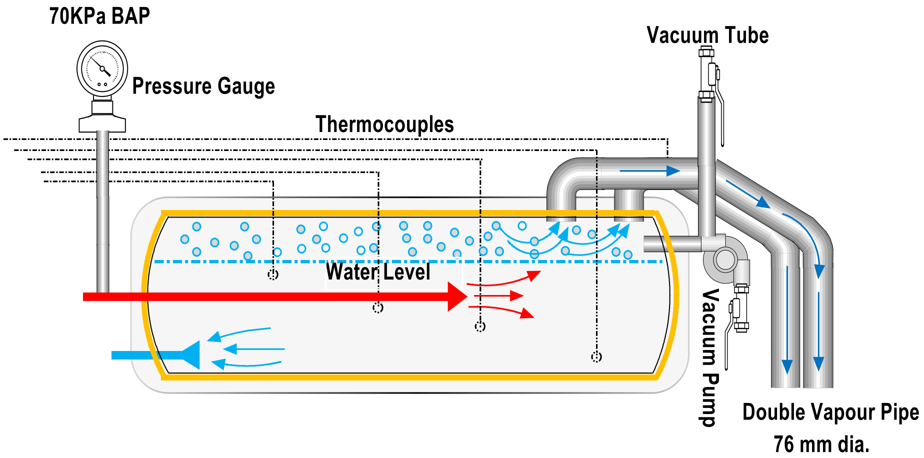

Figure 3.12: Schematic diagram of the geyser with two 76 mm dia. vapour outlet pipes

3.2 Evacuated tube heat pipe solar collector

The actual unit of the evacuated tube heat pipe solar collector used in this project consisted of a frame, a manifold and a set of 12 glass evacuated tubes, each equipped with a heat pipe, as shown in Figure 3.13. Technical data for the evacuated tubes and heat pipes of the collector used in this project can be found in Appendix (A).

Figure 3.13: Solar collector actual unit employed

3.2.1 The manifold and heat pipe connection

The joint between the manifold and heat pipe has great importance in ensuring optimal heat flow. The heat pipe was inserted into the special sheath provided for it in the manifold; a silicone heat transfer compound was applied to the heat pipe's bulb/condenser to ensure efficient thermal contact between heat pipe and manifold (see Figure 3.14). The dry connection between the manifold and the heat pipe is of significant advantage in that it makes the collector suitable for applications where the geyser in the system can operate at any desirable pressure (see Figure 3.15).

Figure 3.14: Applying silicone heat transfer compound on the bulb of the heat pipe

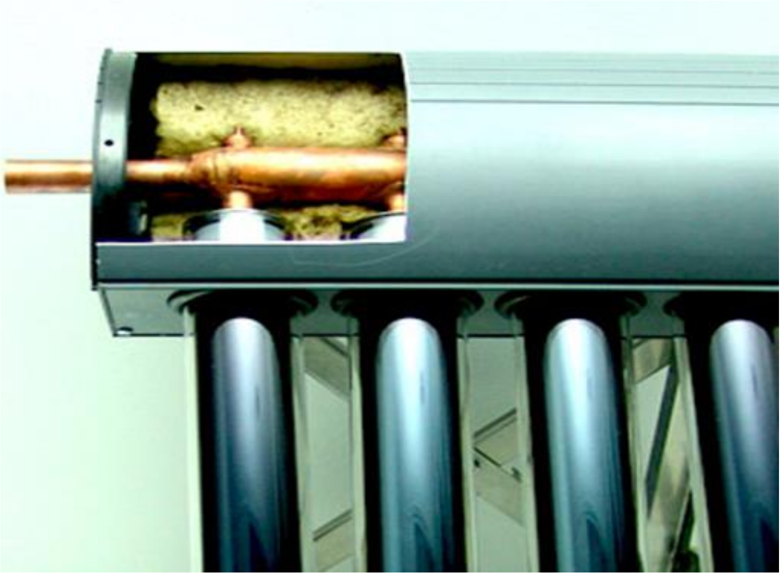

Figure 3.15: Detail of the heat pipes inserted into the manifold
http://www.hanania.me/heat-pipes

3.3 The condenser

3.3.1 Fabrication of the condenser

The main function of the condensing system was to convert the vapour that was generated in the geyser to pure water in addition to being the supply of saline water to the geyser.

The condenser is a relatively simple device, consisting of copper coil tubing, which is covered by the saline water supply inside a plastic tank. Figure 3.16 shows the condenser components.

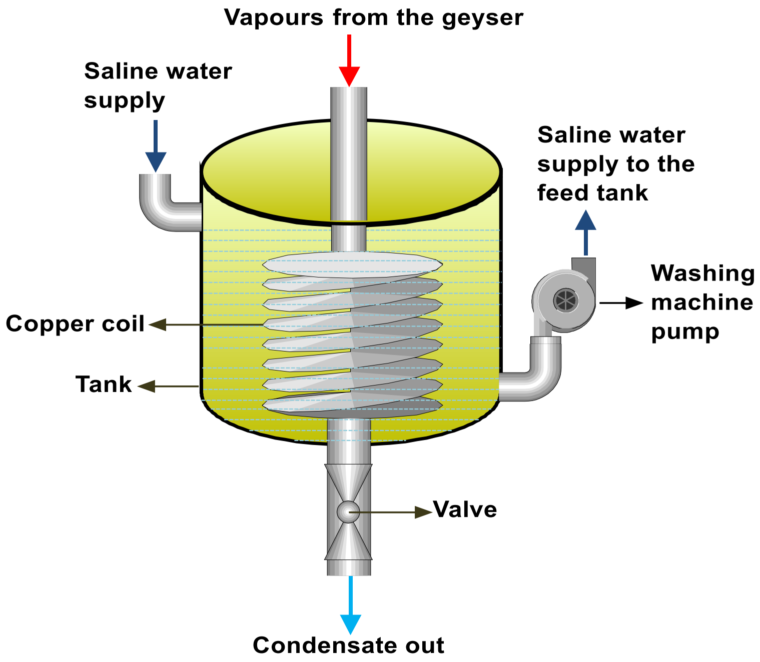

Figure 3.16: Condenser components

3.4 Fresh water tank

A small water tank was installed at the bottom of the condenser to collect the purified water, which was measured using a graduated glass jar with a resolution of 100 ml/division.

3.5 The sun simulator for the main system

A sunlight simulator, as shown in Figure 3.17, comprised of an array of twelve halogen floodlights, with the maximum electrical power consumed by each floodlight of 1000 W, covering an area of 1.6 m^2.

An electric lights array was used, consisting of three distinct groups of lights connected to the grid via variable voltage, using a variac transformer, facilitated constant regulation of the level of radiation flux.

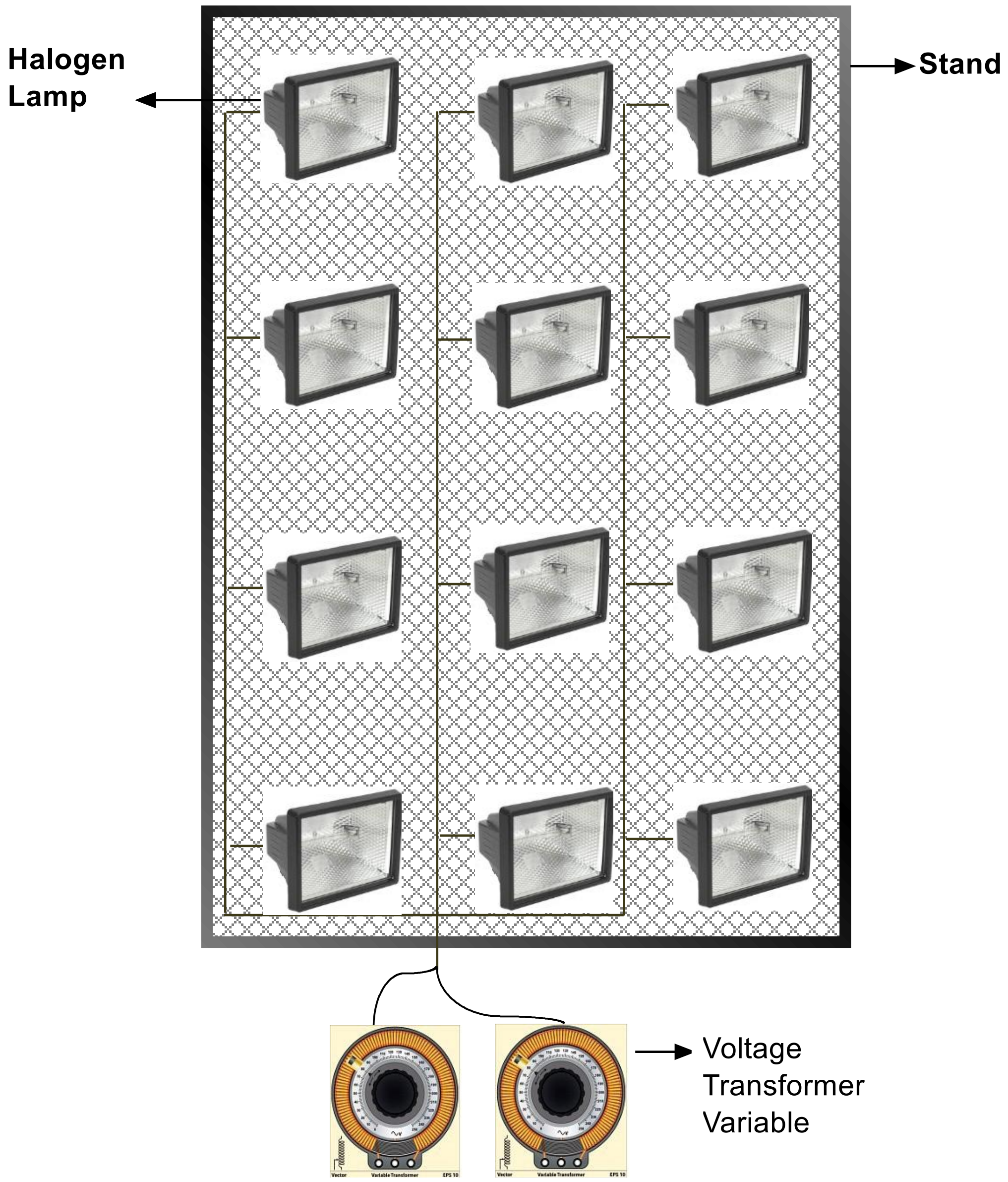

Figure 3.17: Solar simulator for the desalination plant

3.6 A rig for testing the performance of the heat pipe with various working fluids

In order to test the performance of the heat pipe with various working fluids, an apparatus was designed and constructed consisting of a small geyser tank mounted on a frame. A heat pipe with its evacuated glass tube could easily be inserted and removed in a short turnaround time (see Figures 3.18 and 3.19).

A single evacuated heat pipe assembly could be inserted in a dry bay attached to a tank which could accommodate four litres of water. Halogen floodlights mounted on a frame over the heat pipe assembly provided the heat source.

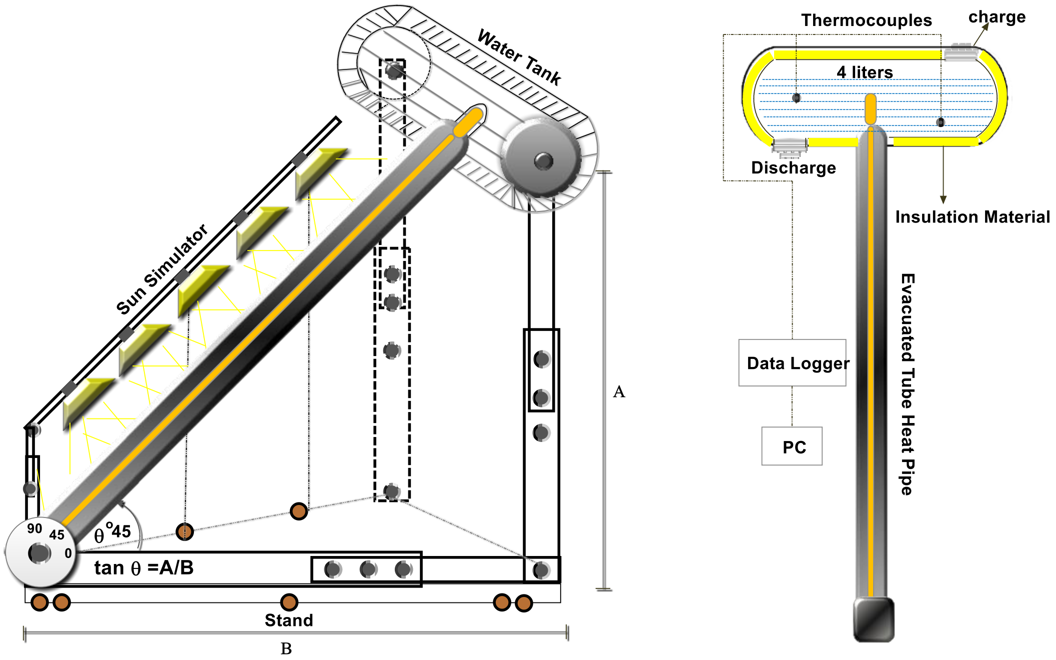

Figure 3.18: Schematic diagram of the heat pipe apparatus

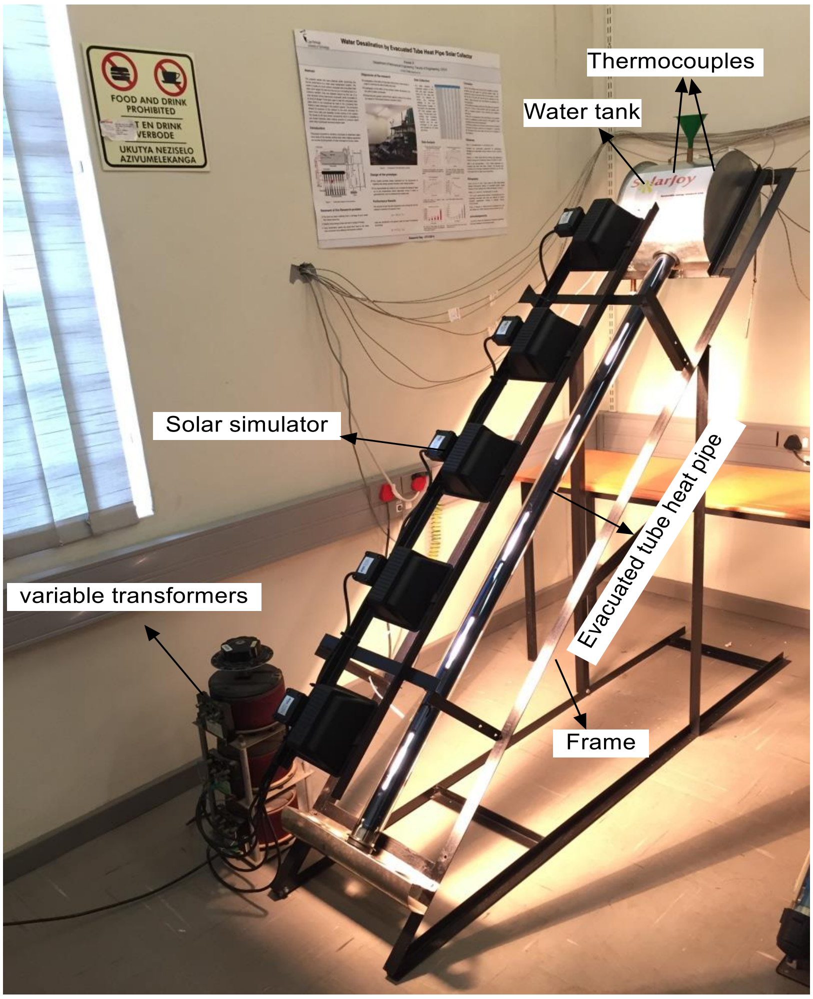

Figure 3.19: The heat pipe apparatus

3.6.1 Tank description

The cylindrical tank was made of 1.2 *mm* thick stainless steel sheet; with dimensions of 200 ***mm*** dia. and 150 ***mm*** long (see Figure 3.20). An outer casing was built around the tank to cover the polyurethane insulation as shown in Figure 3.21.

A brass heat pipe sleeve (14 *mm* internal diameter) was welded into the tank at a 45 degree angle to line up with the mounting frame of the heat pipe, tank and simulator.

In addition, two wells were built into the top of the tank to place thermo-couple sensors in order to record the temperature of the top and bottom fluid levels in the tank respectively. On the side of the tank a valve drain pipe was fitted with a 15 *mm* filling pipe fitted at the top.

The halogen lights were controlled via a variable transformer thus regulating the simulated radiation on the heat pipe.

Figure 3.20: The tank for testing the heat pipe’s performance

Figure 3.21: The tank being insulated during its construction.

3.6.2 The sun simulator for the heat pipe tester

The second and smaller solar radiation simulator was used to heat the evacuated heat pipe (see Figure 3.22). It consisted of an array of five halogen floodlights of 500 W each. The halogen lamps were distributed evenly over the length of the evacuated tube heat pipe, at a distance of 225 mm above it. The solar simulator’s irradiance level was set to a level consistent with an average 800 watts per square metre, as measured over the evacuated heat pipe surface. The output of the sun simulator could be controlled by means of a Variac (variable transformer) which controlled voltage supplied to the array of halogen lamps.

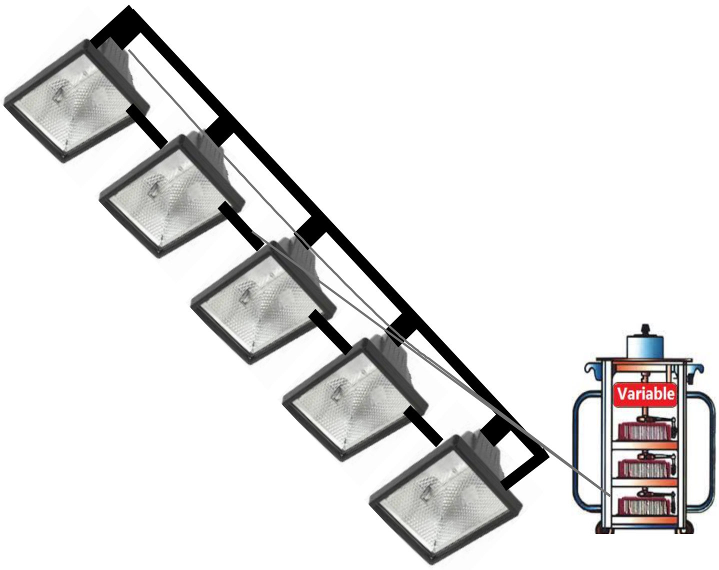

Figure 3.22: The Solar simulator for the evacuated heat pipe tester

3.6.3 Frame

The frame was built using mild carbon steel sections set for testing at a fixed angle of 45 degree.

3.7 Instrumentation

3.7.1 Instrumentation on the desalination plant

Experiments were conducted indoors and over a period of five days for each test, between 9:30 AM and 4:30 PM. The sun simulator for the main system was set to provide on average 682 watts per square metre, as measured by a solar power meter (TES-1333) over the surface of the evacuated heat pipe collector. Temperatures were measured at the inlet and exit of the solar collector’s manifold with the use of J-type (iron-constantan) thermocouples connected to a data recorder (Agilent-34972A). A Vacuum Pump-2f-3 was used to reduce the pressure inside the geyser. Pressure gauges were installed for the purpose of monitoring pressure levels. The amount of desalinated water produced every day was measured by a graduated glass jar with a resolution of 100 $\boldsymbol{ml}$/division. The detailed description of measuring instruments and auxiliary equipment used is provided in Appendix (B).

3.7.2 Instrumentation for the heat pipe tests

Two J-type thermocouples, one of them at the bottom and another at the top of the “geyser”, were fitted to measure the water temperature in the storage tank, and, together with the ambient temperature, were recorded during the test period. A digital display data logger (Agilent-34972A; see no. 5 in Appendix B) was used to record the temperature scale. All experiments were carried out for seven hours.

CHAPTER FOUR

EXPERIMENTAL PROTOCOL

This chapter covers the experimental protocol for the testing of the water desalination prototype that was basically repeated during the various stages of modification of the system from its originally acquired commercial solar water heating configuration. It also describes the experimental protocol that was adopted to test the performance of the evacuated tube heat pipes with different working fluids.

The research protocol as outlined below was conducted upholding the norms of Research Ethical requirements at Cape Peninsula University of Technology, relating to research involving humans, animals or research that poses risk to society. Since none of these apply to this research, attention and good conduct was adhered to, on topics including “conflicts of interest, data management, and research misconduct (e.g., fabrication or falsification of results)”.

4.1 Prototype of seawater desalination experimental setup and data acquisition

The working prototype of the solar-powered desalination plant, illustrated in Figure 4.1 and 3.2, was assembled inside a small laboratory at the Bellville campus of the Cape Peninsula University of Technology’s Mechanical Engineering Department.

Figure 4.1: Photograph of the desalination prototype

Indoor experiments were carried out with the aim of facilitating collection of data for evaluating performance of the prototype. The experiment was located indoors and a solar simulator was utilised in order to minimize environmental disturbances and maintained a steady/constant energy input when experiments were performed.

In order to accurately gauge the effect of an imposed change, it was necessary to maintain the utmost consistency in observing and recording the values of the various parameters influencing the performance of the plant. Random climatic changes, like ambient temperature, hours of sunshine etc. could only interfere time-wise and lead to the data collected for comparison purposes being inadequate.

To represent field operations conservatively, a period of seven hours of irradiance a day was chosen.

Likewise, the average irradiance of the solar simulator was set to 682 watts per square meter, a fair approximation of the Cape Town area's conditions.

The solar simulator's irradiance of 682 watts resulted when setting arbitrarily a 180 voltage for the lamps through the two (variacs) voltage transformers. The resulting irradiance since it was within the range of regional solar irradiance was adopted for the experiments.

- At start, the system was charged by inserting 110 litres of water into the geyser.
- All valves were appropriately set so as to facilitate the flow of condensate, vapour and working fluid.
- Water temperatures (circulating working fluid) on the collector's manifold's the inlet and outlet positions were recorded.
- The temperatures of the water in different positions in the geyser were similarly recorded.
- The solar simulator was turned on.
- The system's circulating pump (collector's manifold to geyser) was set to maximum capacity.
- The flow rate of the working fluid (water) was recorded using the flow meter.
- After a period of one hour, all temperatures were recorded.
- For seven hours, the various temperatures were recorded in 60-minute intervals.
- The system was shut down (both pump and lamps were switched off).
- The system was checked for levels of condensate collected during the test period.

- The following day, all temperatures were recorded before initiating the solar simulator and the circulating pump, i.e. just before the next seven hours period of testing.

The data collection is displayed in Appendix C, where: T_{m1} and T_{m2} represent temperatures (in degrees centigrade) at inlet and outlet respectively, of the water flowing through the collector's manifold, $T_{\mathrm{g}1}, T_{\mathrm{g}2}, T_{\mathrm{g}3}$ and $T_{\mathrm{g}4}$ (water temperature readings) were recorded hourly via four thermocouples located at different levels in the geyser; these temperature readings are represented with their average value $T_{g\ avg.}$.

Experiments were done and results were obtained testing both the original system and later systems afterwards, as the original was subjected to modifications that are summarised in table 4.1.

Table 4.1: Modifications to the desalination plant prototype

	Description of the test	**Date of test**
1	Commercial/original design of geyser with its original Heat Exchanger.	07/05/2014 - 11/05/2014
2	The geyser after replacing the original Heat Exchanger with a larger one.	04/06/2014 - 08/06/2014
3	Removal of the Heat Exchanger (System's performance test at normal pressure).	02/09/2014 - 06/09/2014
4	System's performance test at low pressure of 50 kPa, BAP.	18/09/2014 - 22/09/2014
5	Change the size of the vapour pipe outlet to (760mm). System's performance test at normal pressure.	17/11/2014 – 21/11/2014
6	System's performance test at low pressure of 50 kPa, BAP.	06/04/2015 – 10/04/2015
7	System's performance test at low pressure of 70 kPa, BAP.	08/12/2014 – 12/12/2014
8	Enhancement of the geyser's insulation (extra layer of insulation material) at normal pressure.	26/01/2015 – 30/01/2015
9	At low pressure of 50 kPa, BAP. after step 8	16/03/2015 – 20/03/2015
10	At low pressure of 70 kPa, BAP. after step 8	09/02/2015 – 13/02/2015
11	Doubling the vapour pipe outlet (760 mm x2), at normal pressure, (original insulation).	03/05/2015 – 07/05/2015
12	Under pressure of 70 kPa, BAP with extra layer of insulation material.	11/05/2015 – 15/05/2015

4.1.1 Testing the commercial design of the geyser with its original heat exchanger

In the basic system as commercially available, a 150 litre Kwikot electric geyser was incorporated. The standard 3kW spiral heating element in this geyser was replaced with a Retrosol indirect heating coil, normally used in an indirect solar water heating retrofit installation. The heating coil was connected to a 12 tube ITS evacuated (EVT) (incorporating heat pipes) solar water heating collector through an FES GPD20/6Bz 3 speed 100 W water circulating pump on the hot side of the loop. An in-line flow meter was fitted to regulate and generally monitor the water flow rate through the manifold (see figure 4.1)

To extract the steam from the system, using the geyser's original/normal hot water outlet a 16 mm dia. copper pipe was connected and submerged in ambient temperature water in (tank2) at a level about 1000mm below the bottom of the geyser. This coil was then led off to a small receptacle (receiver) fitted with isolating valves to allow condensed vapour to be trapped and drawn off.

A Circulating pump (pump #2) was fitted to tank2 and connected to tank1 continuously circulating water between the two tanks.

Test 1 results

Several tests were performed and it was deduced that too little heat was being transferred by the heat exchanger placed inside the geyser and that the shape and size of the standard heat exchanger might be a factor in the poor performance of the geyser. In this first test, no water distillate was produced after several attempts.

It was decided that the heat exchanger would have to be replaced with a custom-built heat exchanger.

4.1.2 Geyser modified with custom-built heat exchanger

The heat exchanger was replaced with a new heat exchanger consisting of six 22 mm dia. copper pipe sections approximately 900 mm long each and shaped to fit as far down as possible into the geyser. The new heat exchanger was connected back into the circulation loop and new tests were carried out. Other minor alterations were carried out to optimise operation of the system, such as adding pressure control measures to allow excess pressure from the geyser to be vented off in case of overheating etc.

Figure 4.2 shows the geyser after replacing the original heat exchanger with a newly designed larger one.

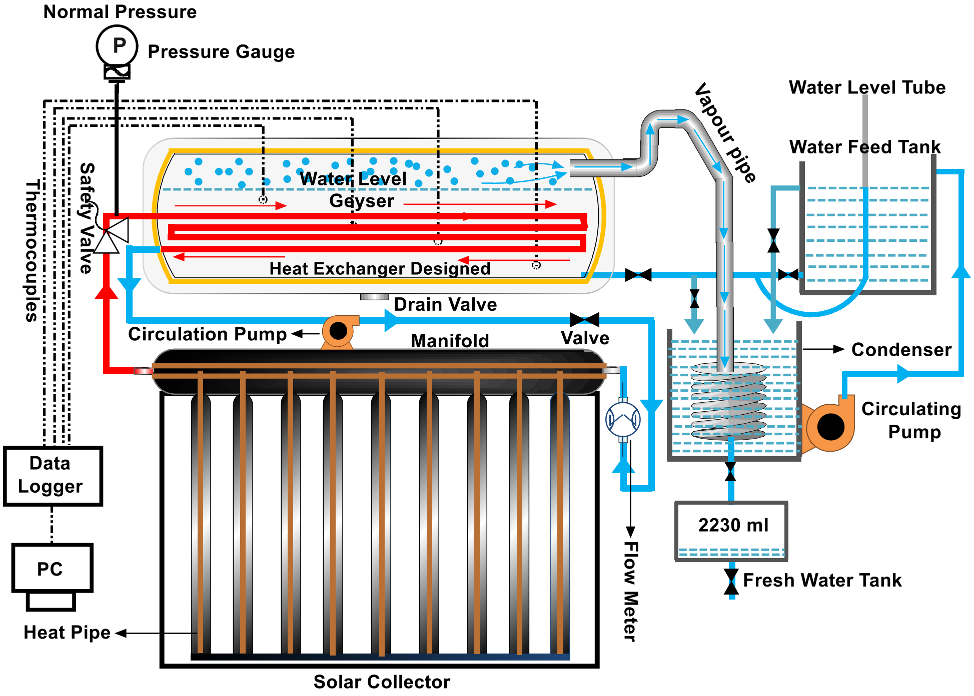

Figure 4.2: The geyser after replacing the original heat exchanger with a larger one

Test 2 results

The testing protocol was repeated and the results were noteworthy in that water vapour was produced and drawn off as liquid/distillate in the receiver. A water volume of 2230 ml was extracted at normal atmospheric pressures of approximately 101 kPa.

4.1.3 Removal of the heat exchanger

Since more heat was required to increase the yield of distillate, the heat exchanger was removed, as shown in Figure 4.3.

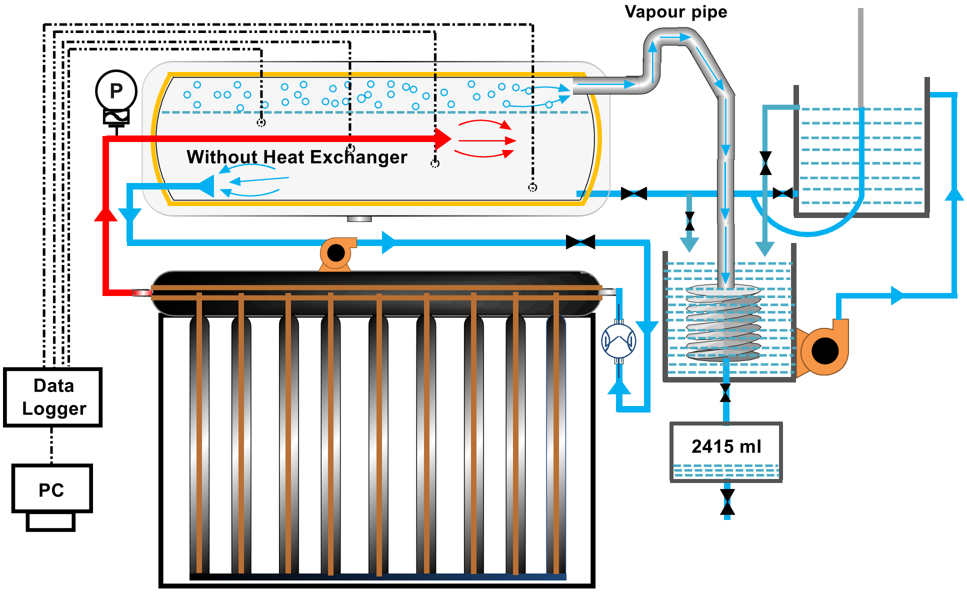

Figure 4.3: The system without a heat exchanger in the geyser tested at normal atmospheric pressure

Test 3 results

The change in the system, as described above, resulted in a slight improvement to the distillate harvest (2415ml) at standard atmospheric pressure.

4.1.4 Lowering the geyser pressure to 50 kPa below atmospheric pressure

A small alteration was made to the plumbing to fit a standard refrigeration system vacuum pump to create a vacuum in the geyser under operating conditions. A pressure of 50 kPa below atmospheric was established in the geyser and testing was resumed.

Test 4 results

This change in the protocol resulted in a further improvement to (3080ml) of distillate extracted.

4.1.5 Restriction of flow by standard geyser outlet

Due to the nature of the standard geyser construction, it was realised that the relatively small vapour outlet (16 mm dia.) was restricting the vapour flow from the geyser, as shown in Figure 4.4.

To increase the flow of vapour into the condensing section, the outlet from the geyser's side exit was moved to the top and increased to a 76 mm dia. copper outlet The geyser's vapour outlet was increased to 76 mm using a sought large diameter, commercially available, copper pipe which was appropriately shaped to facilitate the passage of the water vapour (described as well in 3.1.5) and shown schematically in figure 4.4 below.

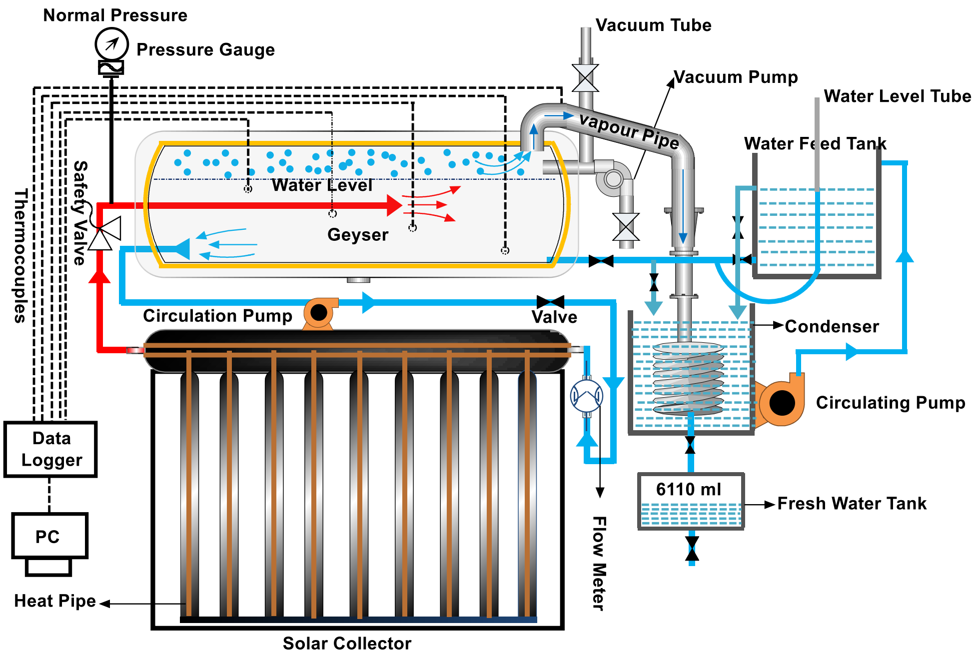

Figure 4.4: The system tested at normal atmospheric pressure after fitted with a 76 mm dia. vapour outlet pipe

Test 5 results

The physical change in the prototype, as described above, resulted in a considerable change in the yield of distillate (6110ml), which is almost double the previous yield.

4.1.6 Lowering the geyser pressure to 50 kPa below atmospheric pressure

After increasing the geyser's vapour outlet diameter to 76 mm dia. and testing at normal pressure, a test was performed with the pressure in the geyser reduced by 50 kPa below atmospheric pressure (see Figure 4.5).

Test 6 results

The lowering of the geyser pressure to 50 kPa below atmospheric pressure increased the yield to a total of 6300ml of distilled water.

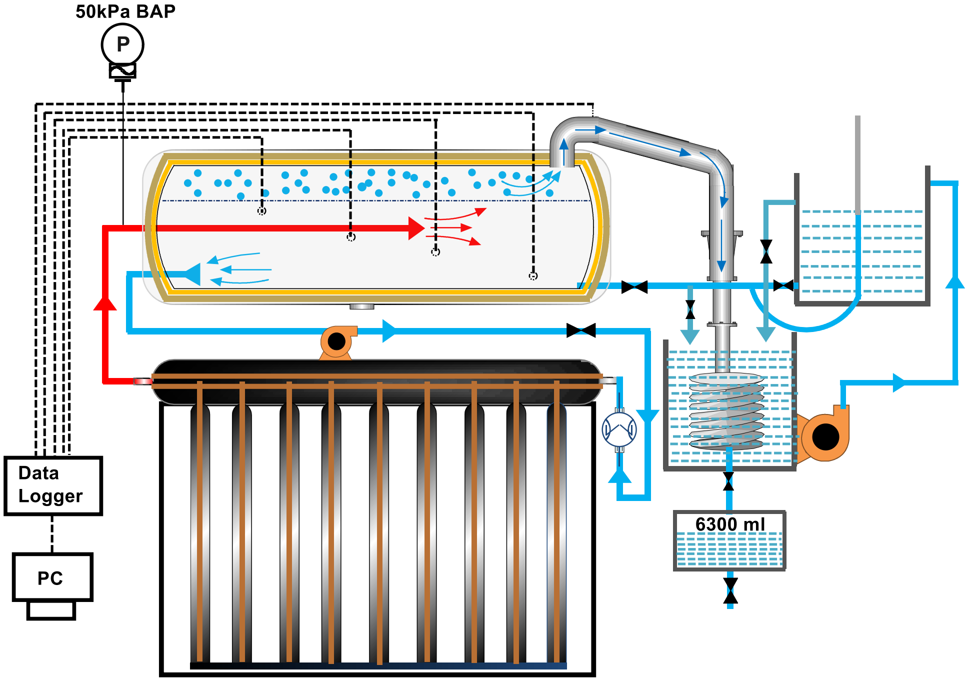

Figure 4.5: The prototype tested with a 76 mm dia. vapour outlet pipe under partial vacuum (50 Kpa below atmospheric pressure)

4.1.7 Lowering the geyser pressure to 70 kPa below atmospheric pressure

A further change in testing protocol (i.e. reducing the geyser pressure to 70 kPa below atmospheric pressure) resulted in a significant increase in the yield of distilled water.

Test 7 results

This latest change in protocol yielded a total of 7500 ml of distilled water.

4.1.8 Improved insulation

In an attempt to reduce or lower the level of the heat losses from the geyser, a standard geyser blanket was wrapped around the geyser (as described in 3.1.6), and a test was performed at normal pressure with the system as shown in Figure 4.6.

Test 8 results

The added insulation to the geyser improved the yield of distilled water by a further significant margin, raising it to 9130 ml.

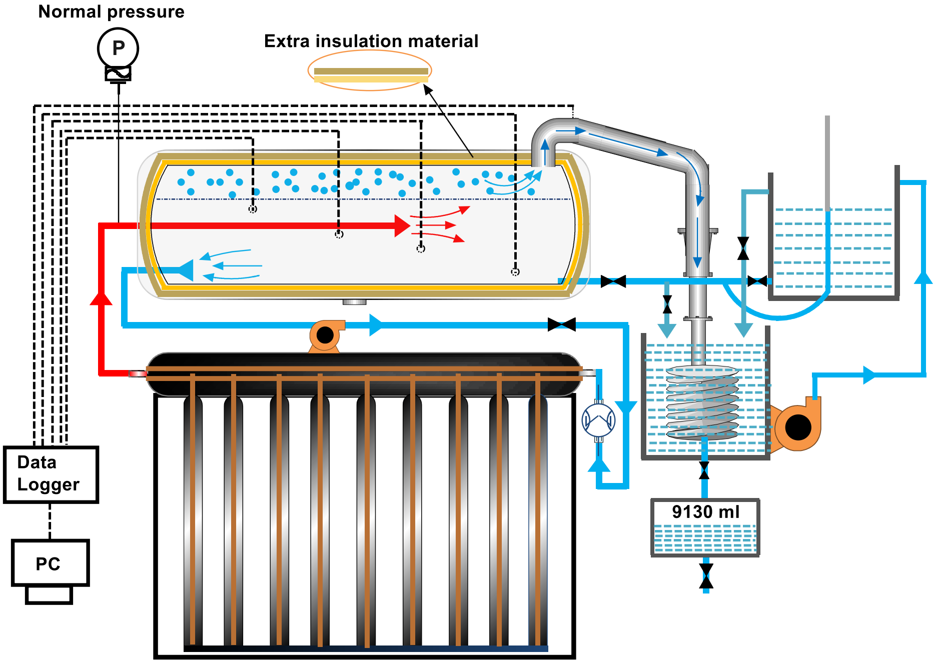

Figure 4.6: The system tested at normal atmospheric pressure after the addition of the extra insulation on the geyser

4.1.9 Testing at lower pressure with added insulation

A test was performed at a pressure of 50 kPa below atmospheric pressure after the addition of the extra insulation on the geyser (as shown in Figure 4.7). As anticipated, there was an improvement on the yield of the distillate water once more.

Test 9 results

This test resulted in a yield of 9550 ml of distilled water.

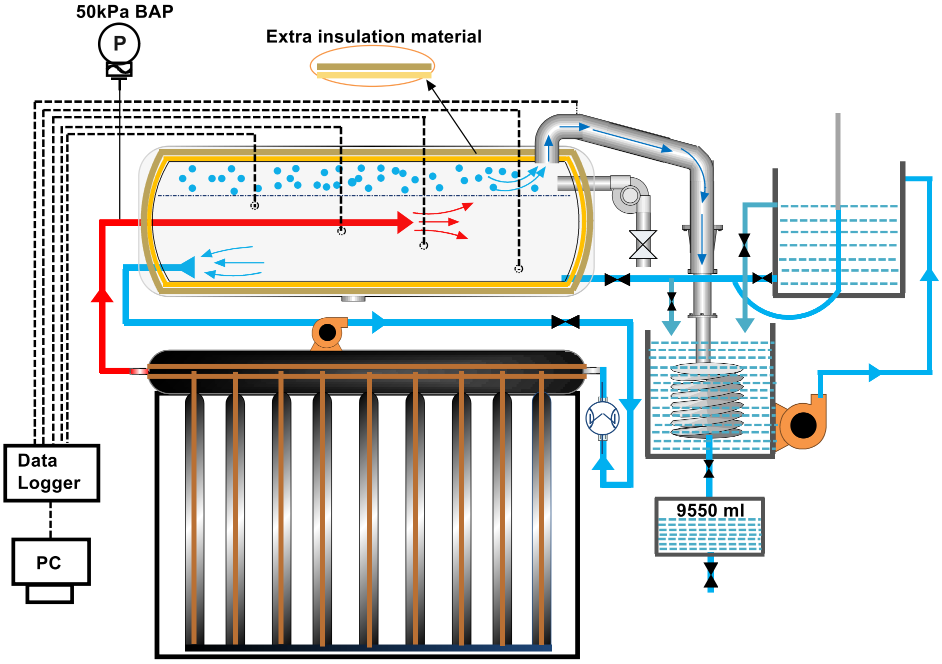

Figure 4.7: The system tested under vacuum (50 Kpa below atmosperic pressure) with the 76mm dia. vapour outlet pipe after the addition of the extra insulation

4.1.10 Further lowering of the geyser pressure

Lowering the geyser pressure to 70 kPa below atmospheric pressure, resulted in a significant improvement in the distillate yield.

Test results 10

The further lowering of the geyser pressure to 70 kPa below atmospheric pressure yielded (10560 ml) of distilled water.

4.1.11 Doubling of the outlet pipe

Based on the previous improvement on the yield of distilled water following the increase of the diameter of the geyser's vapour outlet, another 76 mm dia. copper pipe vapour outlet was provided (as described previously in 3.1.7). Performance testing of the prototype with the double vapour outlet, without additional insulation and at normal atmospheric pressure was carried out for the prototype, as shown in Figure 4.8.

Test 11 results

The results of this test yielded 8300 ml of distilled water and should be compared with the results obtained from the previous test 5, with similar conditions but with the single geyser vapour outlet (6110ml).

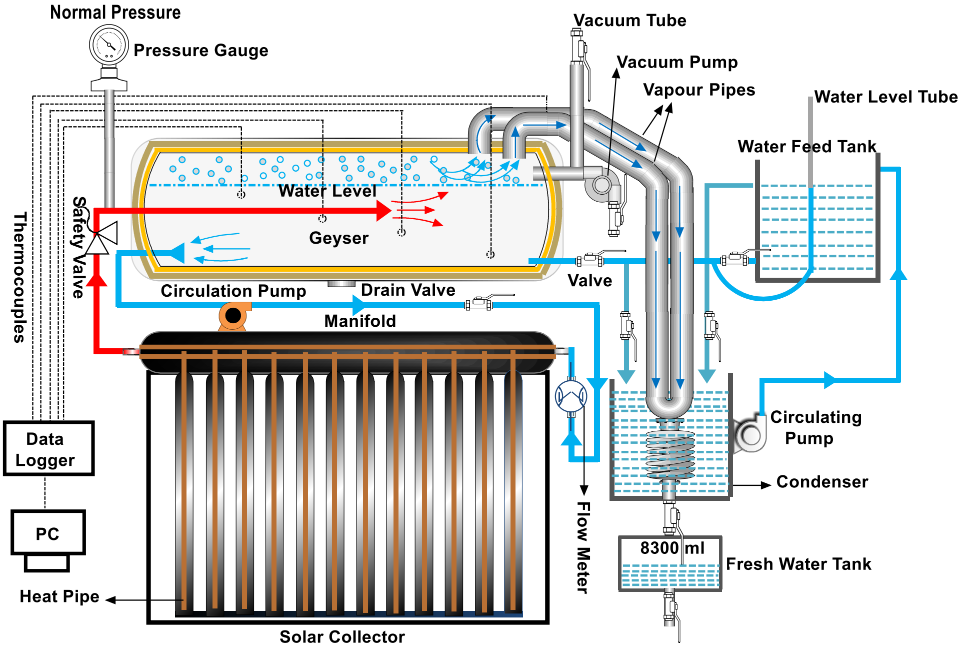

Figure 4.8: The system tested at normal atmospheric pressure after doubling the 76 mm dia. vapour outlet

4.1.12 Adding back the extra layer of insulation

The addition (re-introduction) of the extra insulation and the testing of the system with the geyser pressure at 70kPa below atmospheric pressure marks the end of the research work on the solar water desalination prototype (see Figure 4.9) .

Test 12 results

In this 12th and last test the system yielded its highest level of distilled water when it reached the level of 12750 ml.

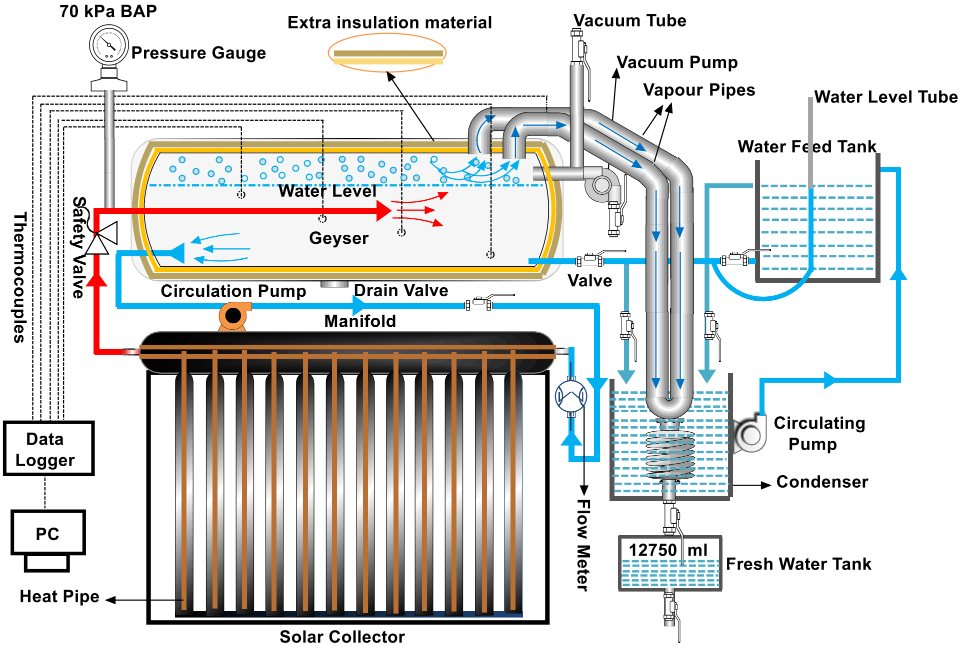

Figure 4.9: The final configuration of the prototype tested at 70 Kpa below atmospheric pressure with double 76 mm dia. copper pipe vapour outlet

4.2 Testing the heat pipe performance with different working fluids.

The relatively elevated temperatures which are obtainable when using evacuated tube heat pipes in the field of water heating is the reason for the attempt to use them in the desalination of seawater.

The method followed in testing a set of working fluids in the heat pipe is described below:

Testing of the heat pipe's performance with various working fluids required a benchmark. This benchmark was obtained by first testing the commercial heat pipe (as it came from the manufacturer) with the original working fluid. Attempts to obtain information about the constitution of the working fluid, from the manufacturer in China, were unsuccessful. It was assumed that the liquid was water, but it had an orange/yellowish colour possibly because of some kind of additive. The fluid was drained and the heat pipe was charged with new fluid, after which the performance test was undertaken over the standard seven-hour period. The test procedure was very similar to the one previously adopted for the testing of the water desalination prototype. It is worth mentioning here that the quantity of working fluid encountered in three commercial heat pipes varied considerably in the range of 3, 5 and $7ml$; however this did not seem to affect their performance.

The raw data that was collected during each heat pipe experiment with the four working fluids required recording the temperatures of the water at two locations in the tank's water, the irradiance from the solar simulator and the ambient temperature T_a. The duration of the individual tests was seven consecutive hours daily. The data are displayed in Appendix D, where:

T_1 and T_2 are the tank's water temperatures (in degrees centigrade) which was recorded every 15 minutes via two thermocouples located at the top and bottom levels in the tank's water, using a data-logger. T_{a1}, T_{a2} and T_{a3} (Ambient temperature readings): these temperature readings, represented with their average value $T_{a\,avg.}$, were also recorded each 15 minutes via three thermocouples located around the heat pipe testing apparatus.

CHAPTER FIVE

RESULTS AND DISCUSSION

This chapter presents a summary of the results from the various tests that were performed with the desalination prototype plant. The tests were a consequence of modifications to the plant in order to enhance its performance. As a separate issue, also inferred or linked to the plant's performance, the results of the investigation into the performance of the heat pipes, which form a salient feature of the prototype plant, are also presented in this chapter.

5.1 Results from the experiments with the prototype of the solar desalination plant

In this research, twelve experiments were conducted to test the prototype, which was designed, the amount of water produced in the last test is the highest yield can be obtained according to the modifications which were applied on the prototype.

The results obtained during twelve tests that were performed are presented separately and in detail in this chapter.

Table 5.1 presents a description of the tests that were performed subsequent to various modifications made to the solar desalination plant prototype, coupled to the quantity of water harvested and efficiency of its production.

Table 5.1: Total water harvested (ml) and best daily efficiency of water production with each modification of the system

TEST No.	Description of the test	Total water harvested ml	Water production efficiency% (test's last day)
1	Commercial/original design of geyser with its original heat exchanger.	0.00	0.00
2	The geyser after replacing the original heat exchanger with a larger one.	2230	11
3	Removal of the heat exchanger (System's performance test at normal (Atm.) pressure).	2415	14
4	System's performance test at pressure of (Atm. 50kPa below Atm.)	3080	16.34
5	Change the size of the vapour pipe outlet to (760mm) System's performance test at normal (Atm.) pressure	6110	27.13
6	System's performance test at pressure of (50 kPa below Atm.), with the new vapour outlet pipe (760mm).	6300	26.96
7	System's performance test at pressure of (70kPa below Atm.).	7500	31.44
8	Enhancement of the geyser's insulation (extra layer of insulation material), at normal pressure.	9130	32.99
9	At pressure of (50kPa below Atm.), after step 8.	9550	30.55
10	At pressure of (70kPa below Atm.) after step 8.	10560	34.12
11	Doubling the vapour pipe outlet (760 mm x2), at normal pressure, commercial insulation material.	8300	29.58
12	Under pressure of (70kPa below Atm.), with extra layer of insulation material.	12750	38.21

5.1.1 Results from the first test (geyser with its original heat exchanger)

The results from the first test of the plant, featuring the minor modification of replacing the electrical heating element in the geyser with a small commercial heat exchanger and creating a space for the steam aggregation, did not yield any distillate. Figure 5.1 shows the temperature range of the geyser's water, as achieved during the heating of the seven hour period for the 5 days of testing and the respective temperature drops during the overnight cooling.

With an initial temperature of geyser's water around 21 ℃, a 67.3 ℃ rise in temperature was observed, reaching 88.3 ℃. The system's energy acquisition during the five day duration of the test, as shown in Figure 5.2, was approximately 54.8 MJ, but did not produce any distillate.

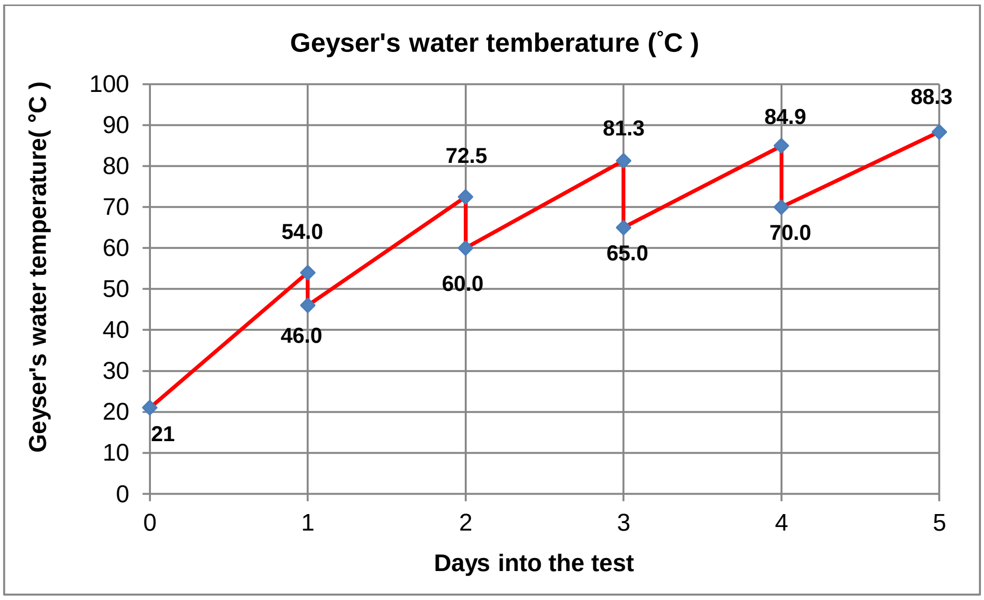

Figure 5.1: Heating and cooling of the geyser’s water temperature during Test No.1

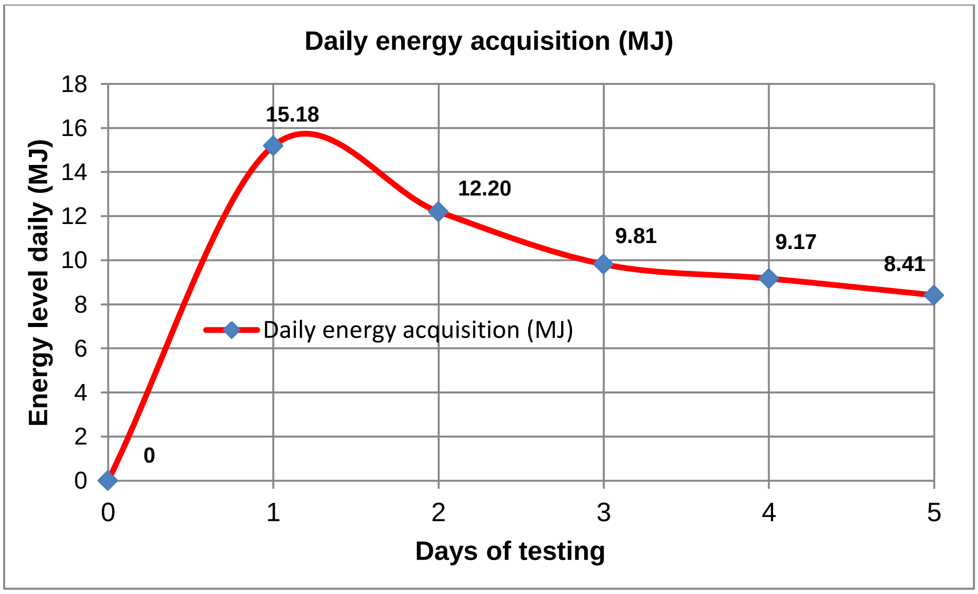

Figure 5.2: Level of system’s daily energy acquisition (Test No.1)

5.1.2 Results from the second test (after replacing the original heat exchanger)

Figure 5.3 demonstrates the performance of the system's geyser during the full duration of the five days of testing.

During the seven hour heating period on the first day, the highest bulk temperature increase was observed for the water inside the geyser. During the inactive period following this, a drop in the geyser's bulk water temperature was observed, resulting from heat loss to the surroundings. Subsequent heating and cooling of the geyser's water occurs in a pattern consistent with this observation: smaller increases in average water temperature and a larger temperature drop due to heat loss during the cooling period.

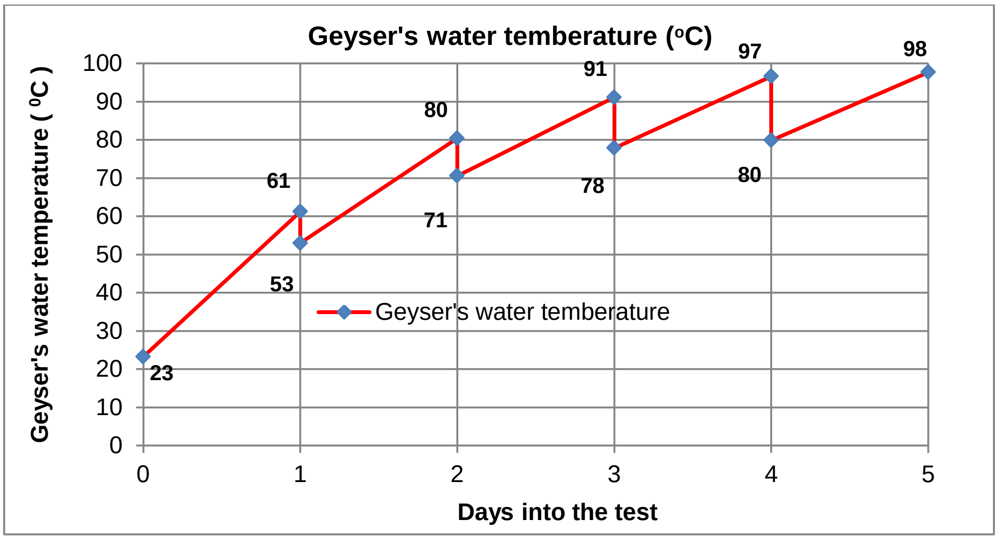

Figure 5.3: Heating and cooling of geyser's water temperature during Test No.2

Figure 5.4 illustrates the daily acquisition of energy during the test, amounting to about 65.46 MJ in total.

Similarly, during the 17 inactive daily hours, the geyser lost energy to the air, amounting to a total of more than 28.22 MJ, as illustrated in Figure 5.5.

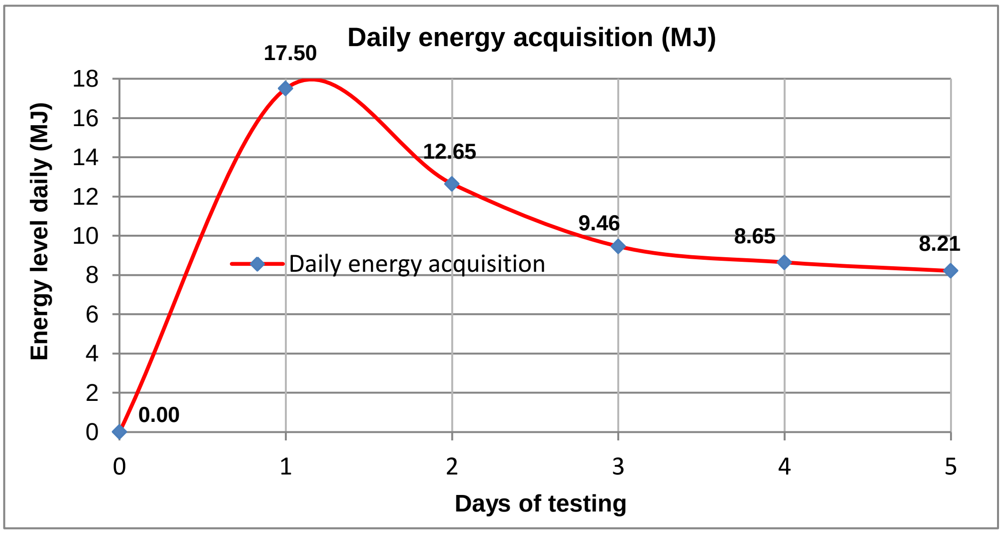

Figure 5.4: Level of daily system's energy acquisition (Test No. 2)

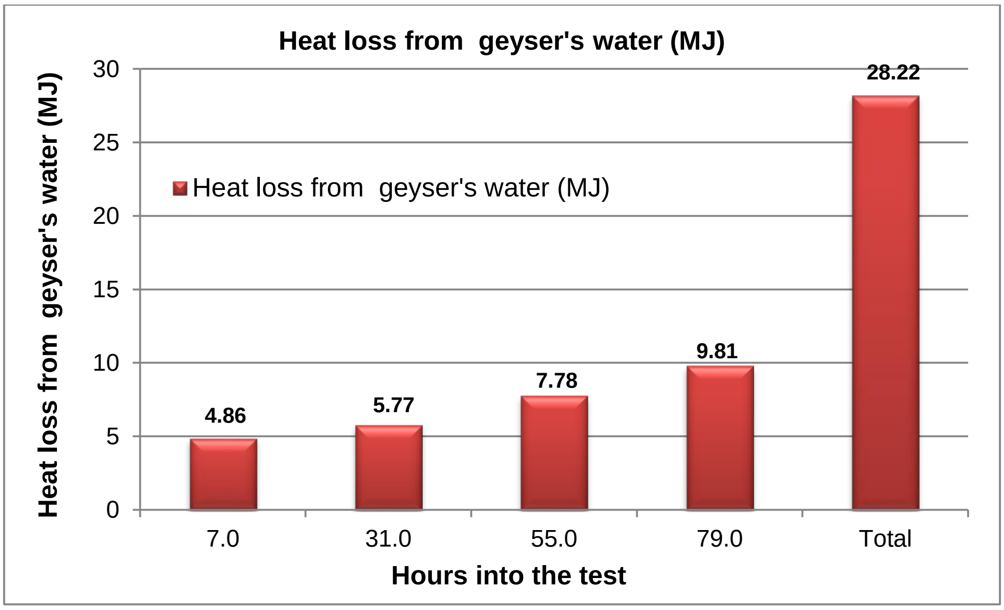

Figure 5.5: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No. 2

The amount of water that was desalinated under normal/atmospheric pressure was 2230 ml, as shown in Figure 5.6

The system's efficiency in terms of heating the water was calculated using equation 2.10. Figure 5.7 shows the efficiency for each day, which ranged between the highest on the first day (68.7%) and lowest in the last day (3.1%).

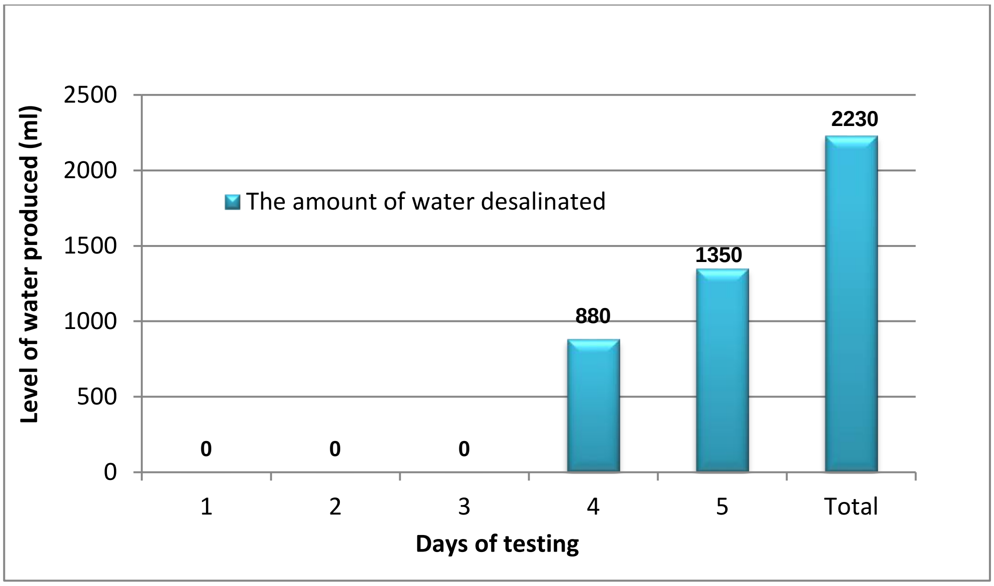

Figure 5.6: The amount of desalinated water harvested (daily and total) during Test No. 2

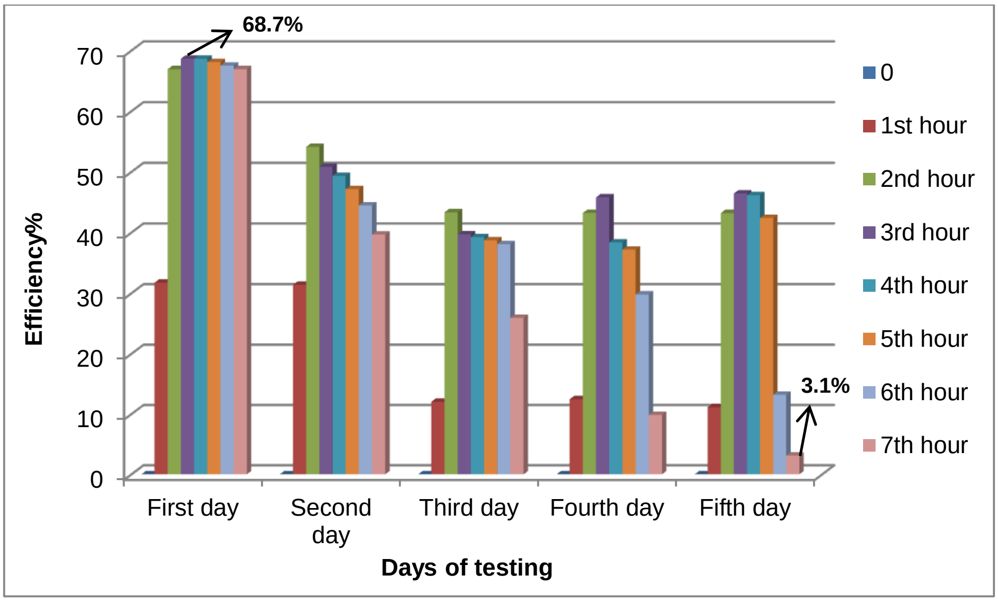

Figure 5.7: The system's daily and hourly efficiencies in terms of heating the water during Test No.2

The system's efficiency in terms of producing distilled water, using equation 2.12, was 7% and 11% during the 4th and 5th day respectively, as shown in Figure 5.8.

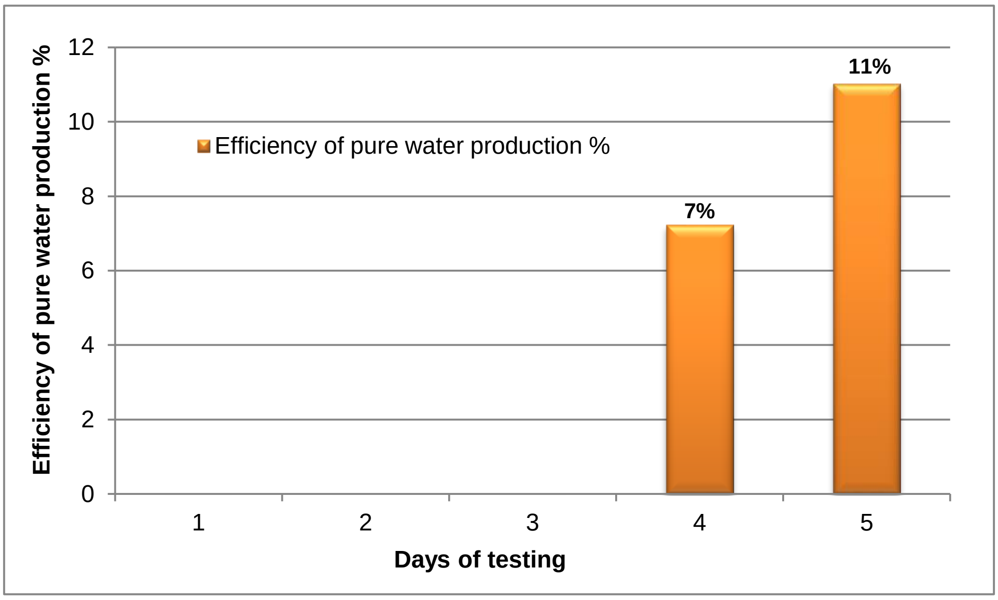

Figure 5.8: The daily efficiency of pure water production (Test No.2)

5.1.3 Results from the third test (geyser without heat exchanger)

The removal of the heat exchanger resulted in improved heat transfer from the manifold to the water of the geyser, where the cumulative yield of distillate increased to 2415 ml. Figure 5.9 shows the temperature range of the geyser's water, as achieved during the heating of the seven hour period for the 5 days of testing and the respective temperature drop during the overnight cooling. The system's energy acquisition was increased, as shown in Figure 5.10. During the period of the test the system acquired approximately 62.75 MJ.

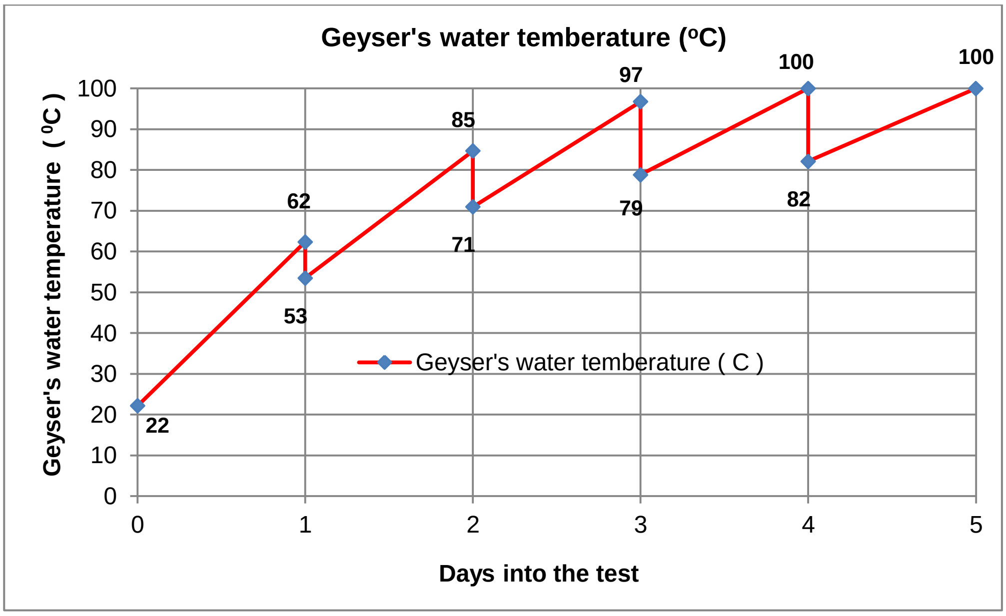

Figure 5.9: Heating and cooling of geyser’s water temperature during Test No. 3

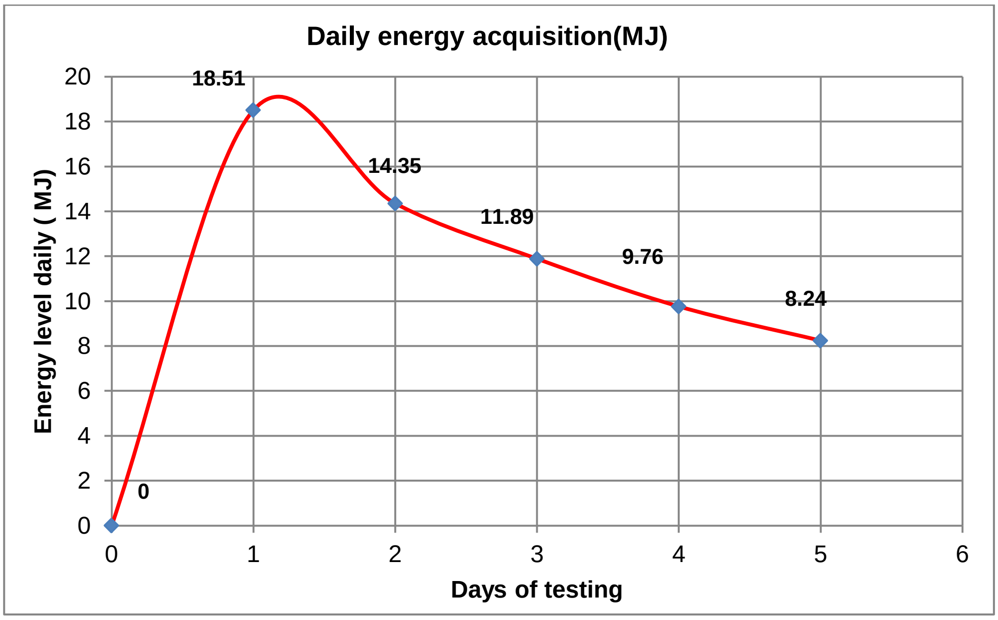

Figure 5.10: Level of daily system’s energy acquisition (Test No.3)

Clearly, the improvement in heat acquisition was accompanied by an increase in heat loss; during the 17-hours daily inactivity period, the total energy loss from the geyser's water was approximately 34.23 MJ, as illustrated in Figure 5.11.

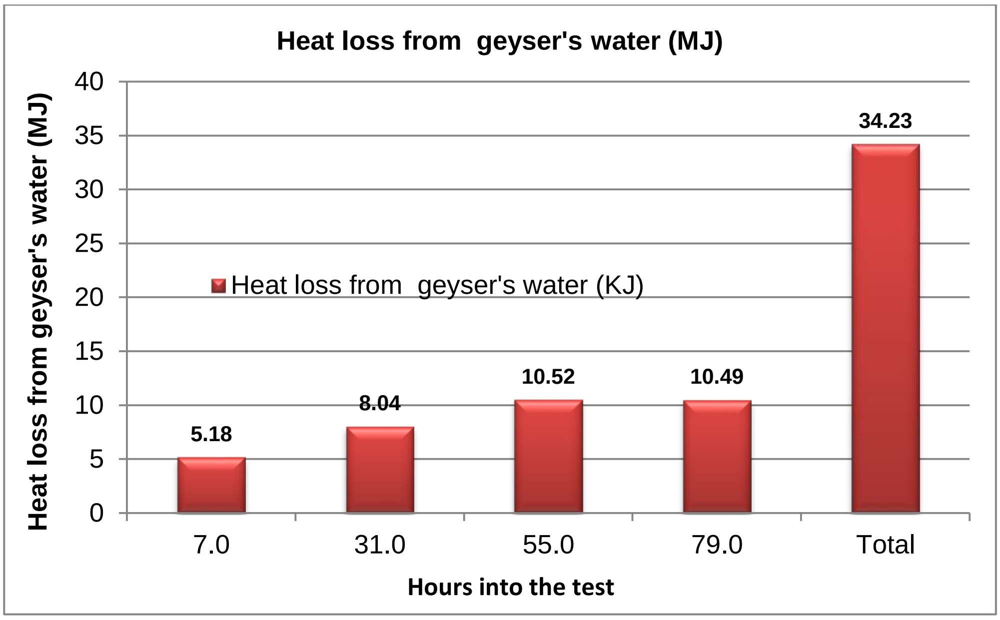

Figure 5.11: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.3

As a result of the improvement in heat transfer from the solar collector’s manifold to the geyser, the amount of pure water yielded reached 2415 ml total, as shown in Figure 5.12. The heating efficiency ranged between 71.5% and 2.4%, as shown in Figure 5.13.

The system’s efficiency in terms of producing distilled water was increased to 6% and 14% during the 4th and 5th day respectively, as shown in Figure 5.14.

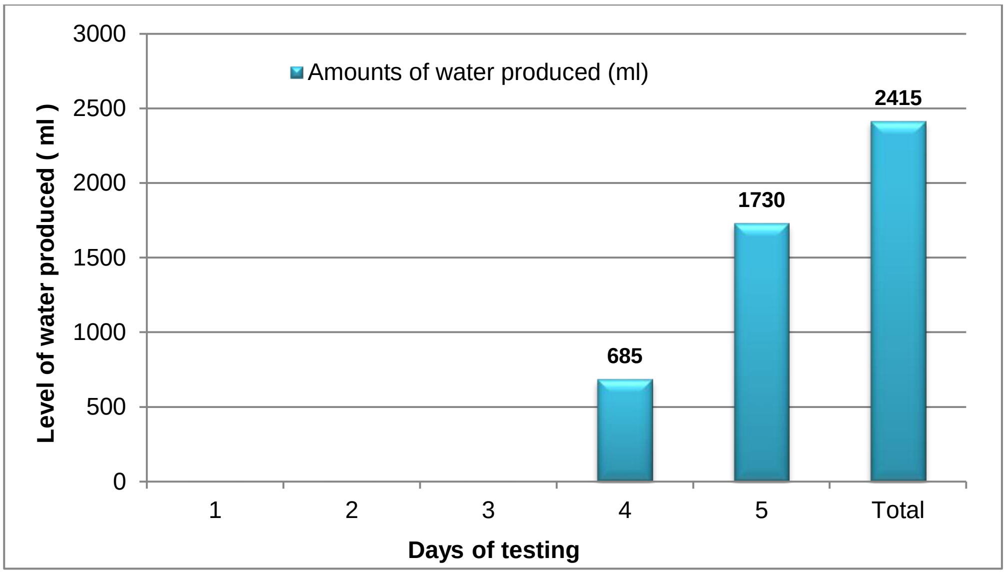

Figure 5.12: The amount of desalinated water harvested (daily and total) during Test No.3

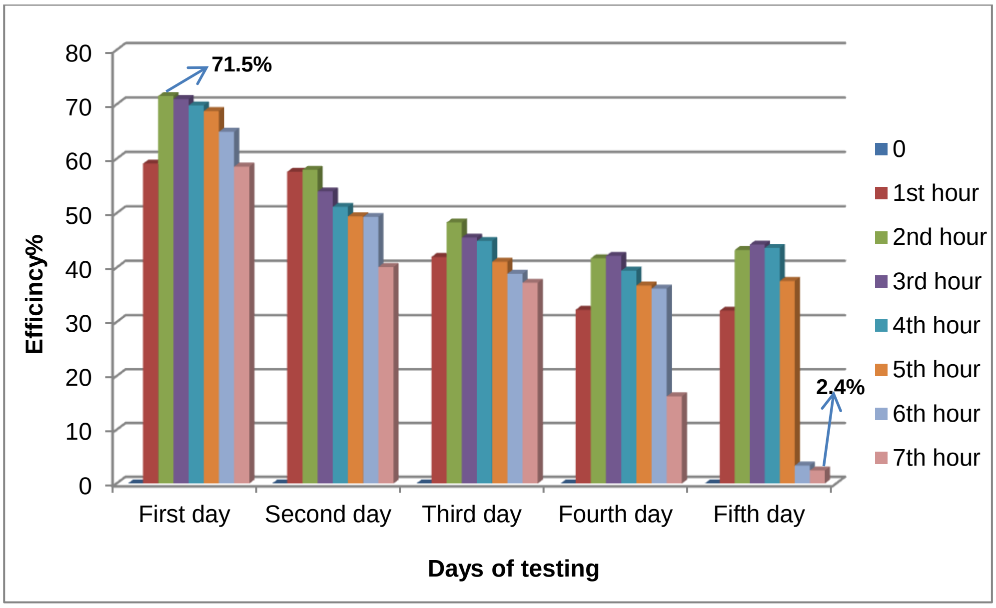

Figure 5.13: The system’s daily and hourly efficiencies in terms of heating the water during Test No.3

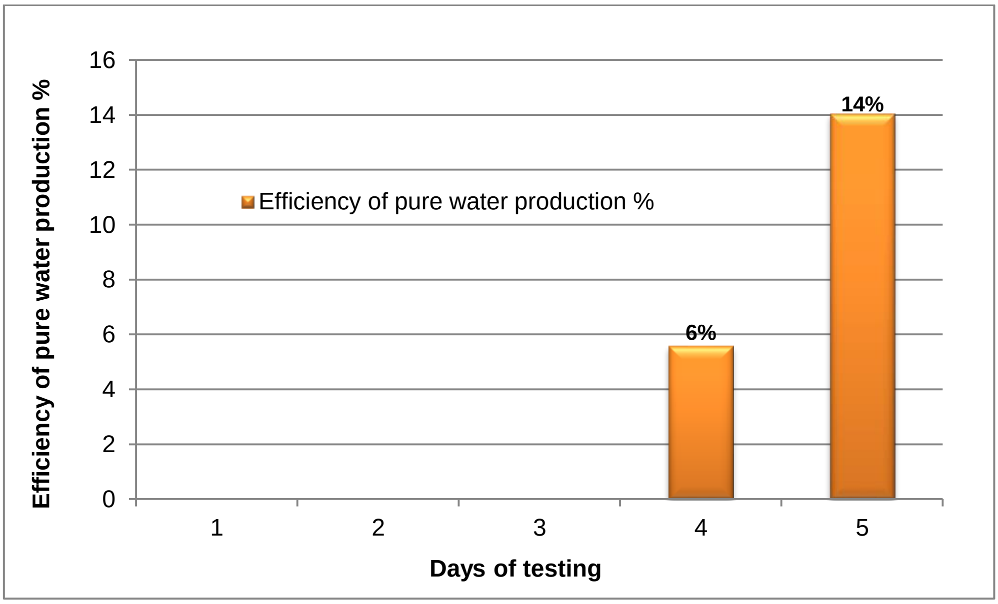

Figure 5.14: The daily efficiency of pure water production (Test No.3)

5.1.4 Results from the fourth test (System’s performance at pressure of 50 kPa below atmospheric)

Results of the plant’s performance for this test were obtained at a reduced pressure of 50 kPa below atmospheric level (using a vacuum pump). Figure 5.15 demonstrates the system’s geyser performance.

The system's energy acquisition during this period, as shown in Figure 5.16, was approximately 62.31 MJ.

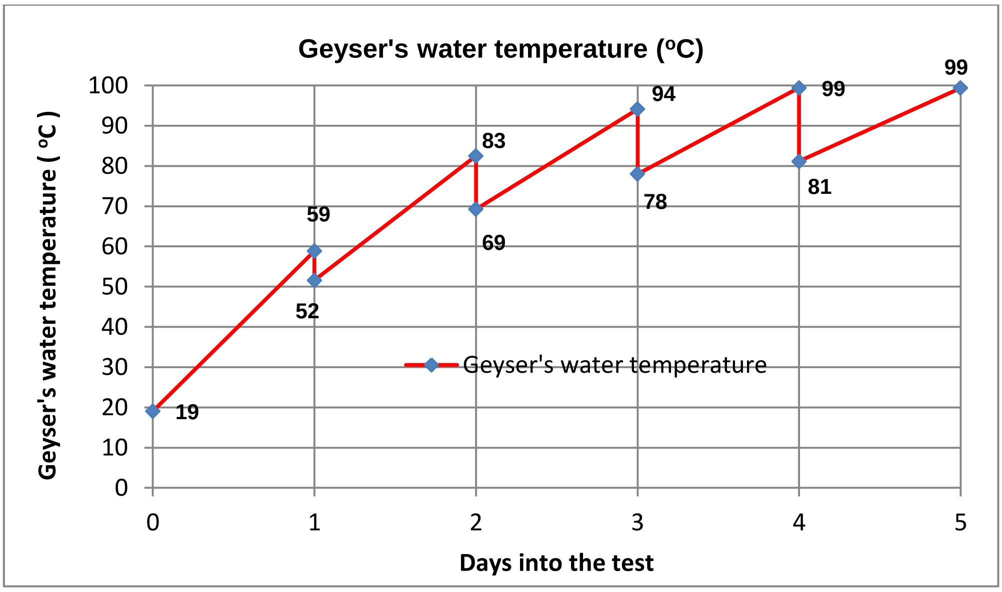

Figure 5.15: Heating and cooling of geyser's water temperature during Test No. 4

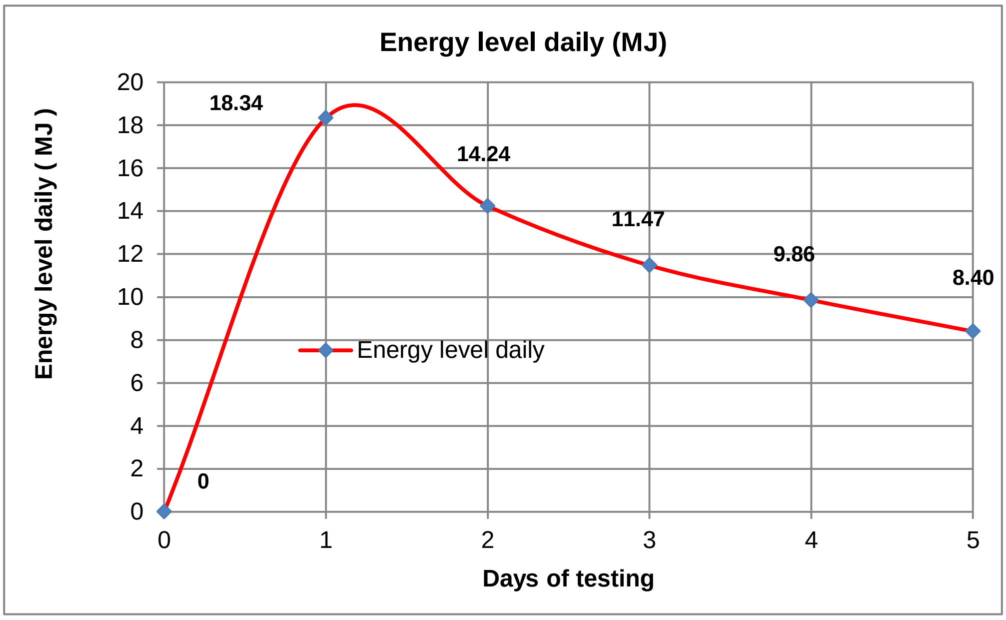

Figure 5.16: Level of daily system's energy acquisition (Test No.4)

The total energy loss from the geyser's water was approximately 32.19 MJ, as illustrated in Figure 5.17.

The yield of pure water was increased to 3080 ml total, as shown in Figure 5.18, as well as the heating water efficiency, which ranged between 67.78% and 23.85%, as shown in Figure 5.19.

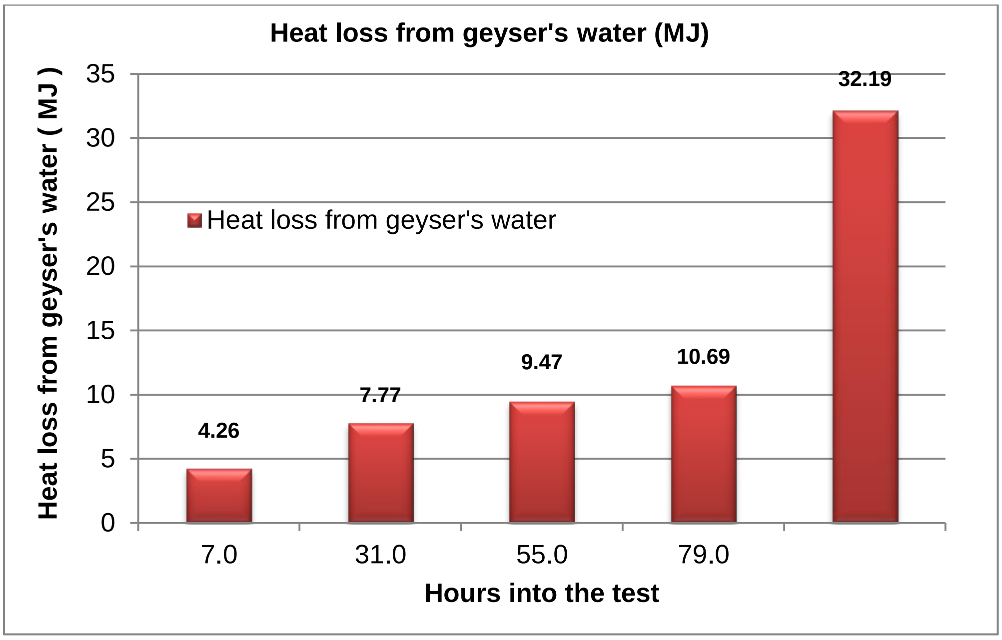

Figure 5.17: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.4

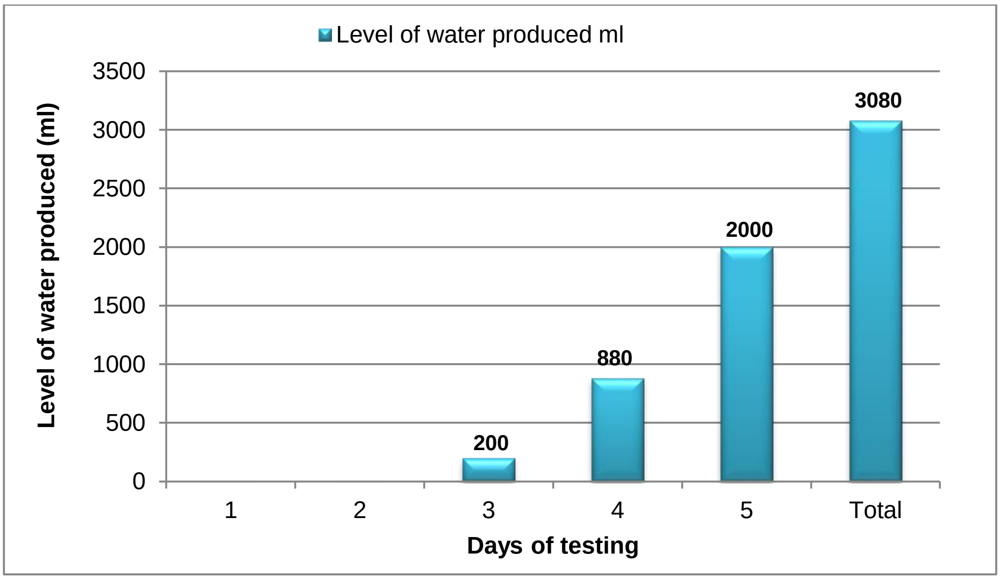

Figure 5.18: The amount of desalinated water harvested (daily and total) during Test No.4

The system’s efficiency in terms of producing distilled water, with a reduced pressure of (50 kPa) below atmospheric level, was increased to 16.34% on the last day and distillate harvesting began on the third day of the test, as shown in Figure 5.20

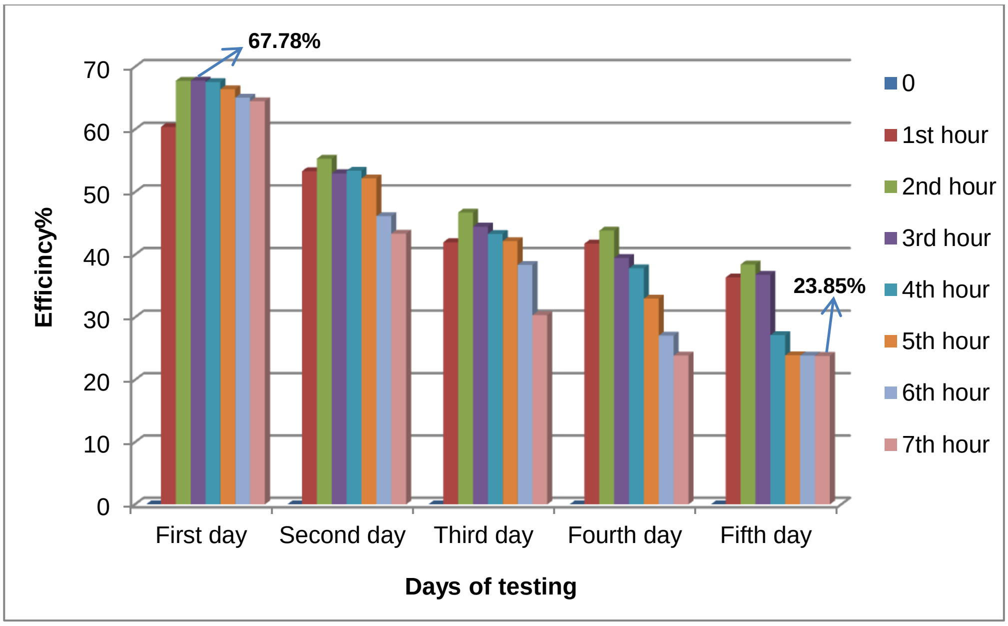

Figure 5.19: The system’s daily and hourly efficiencies in terms of heating the water during Test No.4

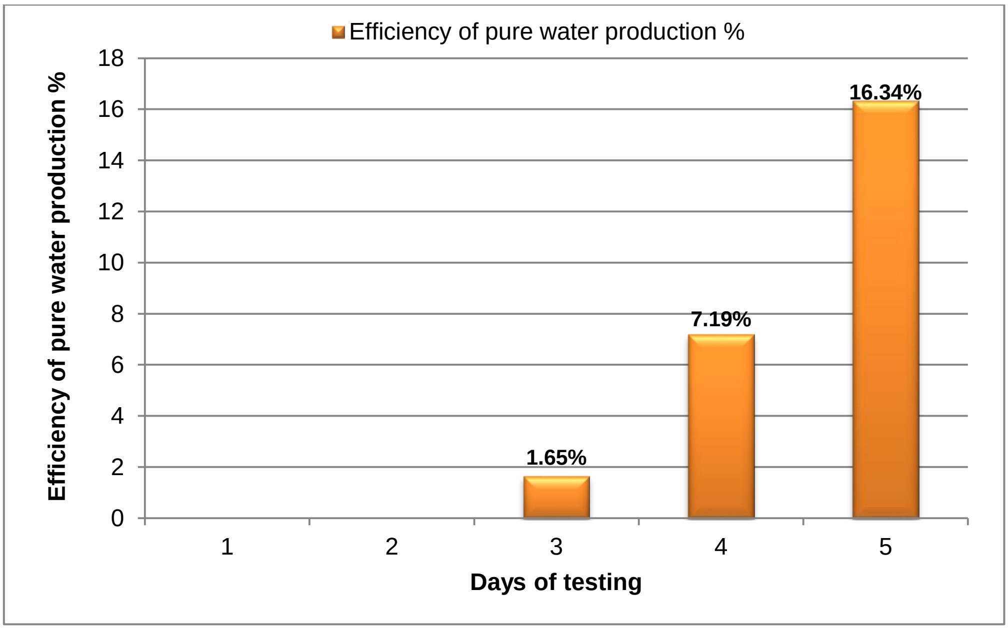

Figure 5.20: The daily efficiency of pure water production (Test No.4)

5.1.5 Results from the fifth test (after changing the size of the vapour pipe outlet to 76 mm dia.)

Figure 5.21 demonstrates the performance of the system’s geyser, the system's energy acquisition, as shown in Figure 5.22, was approximately 62.19 MJ during this period.

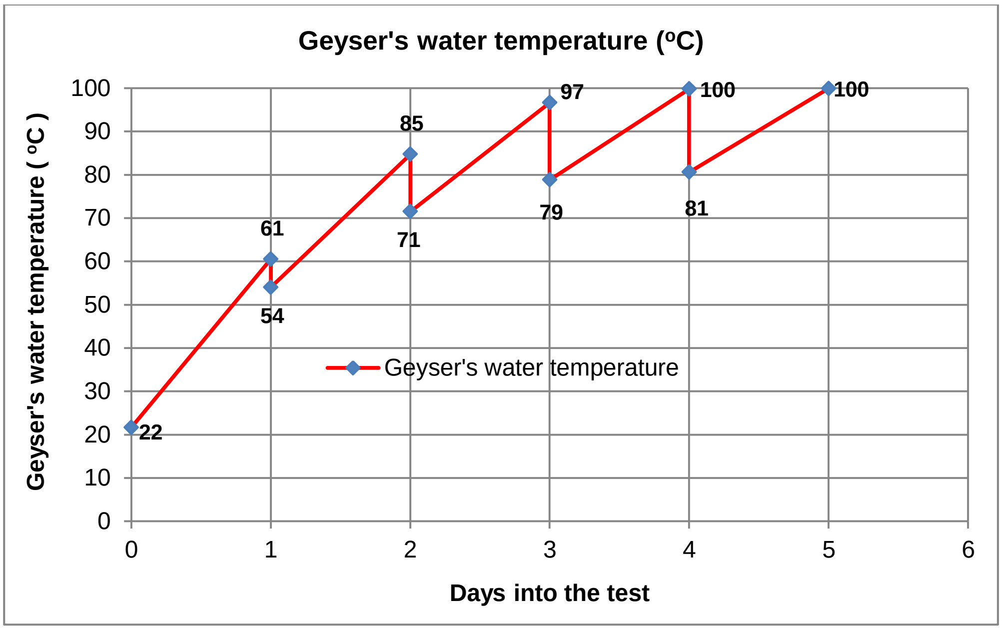

Figure 5.21: Heating and cooling of geyser’s water temperature during Test No.5

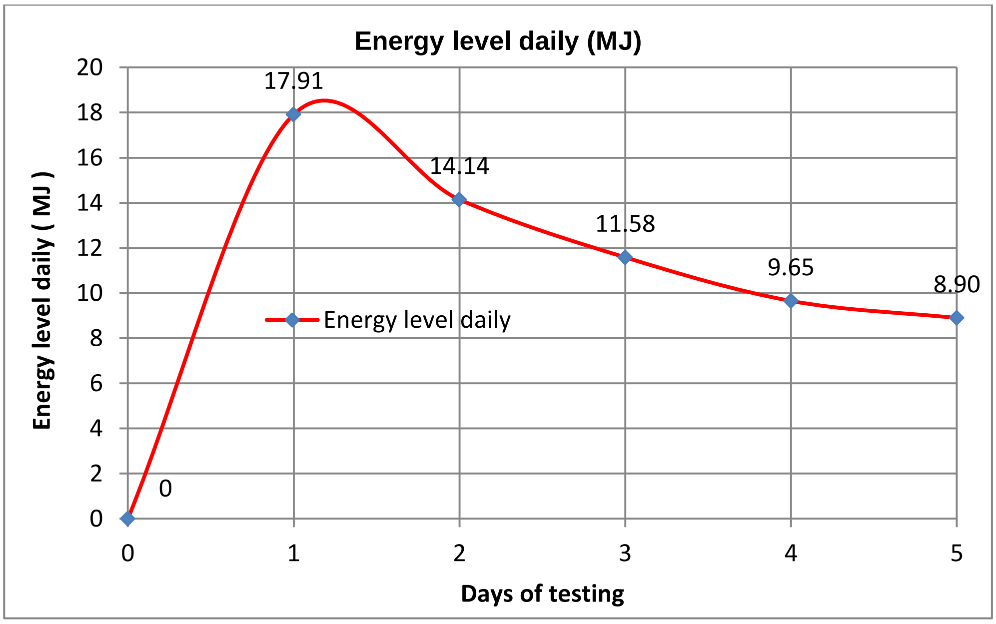

Figure 5.22: Level of daily system’s energy acquisition during Test No.5

The total of energy losses during overnight cooling of the geyser water was approximately 26.14 MJ, as shown in Figure 5.23

The yield of pure water was increased to a total of 6110 ml, as shown in Figure 5.24

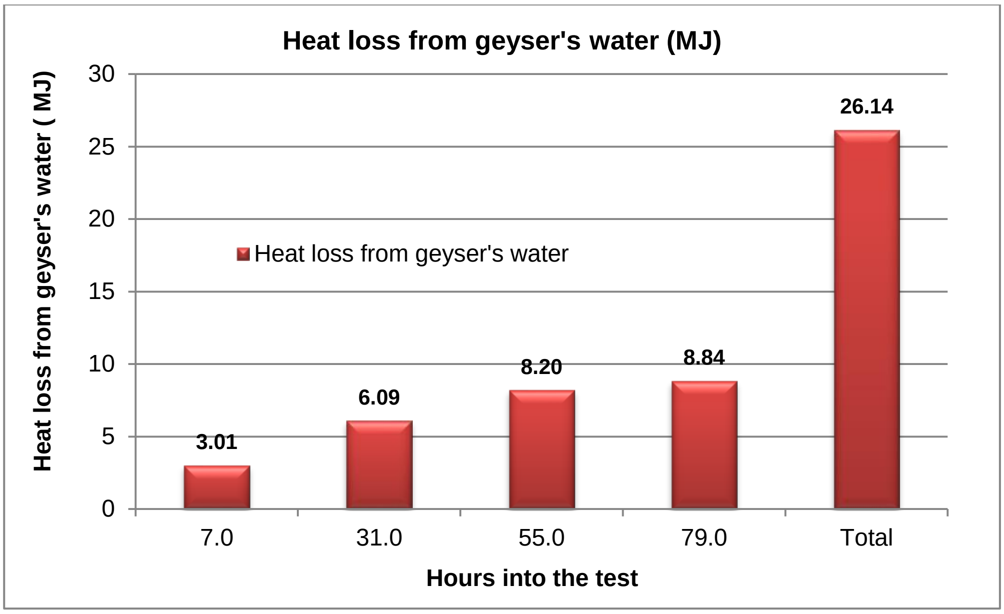

Figure 5.23: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.5

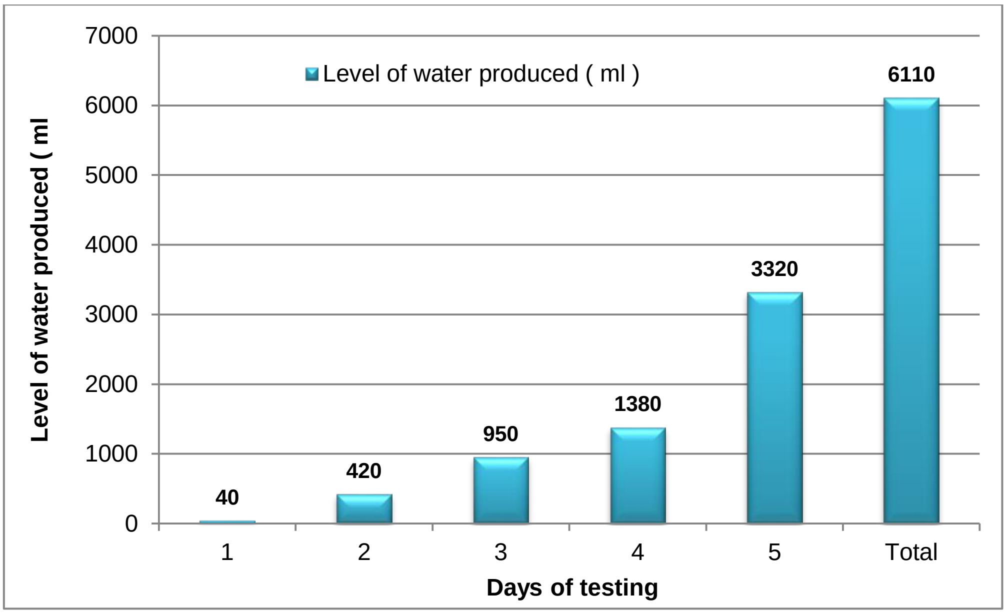

Figure 5.24: The amount of desalinated water harvested (daily and total) during Test No.5

The heating water efficiency was recorded as being between 70.6% and 1.4%, as shown in Figure 5.25

The system's efficiency in terms of producing distilled water was increased to 27.13% on the last day of the test, and distillate harvesting began on the first day of the test, as shown in Figure 5.26

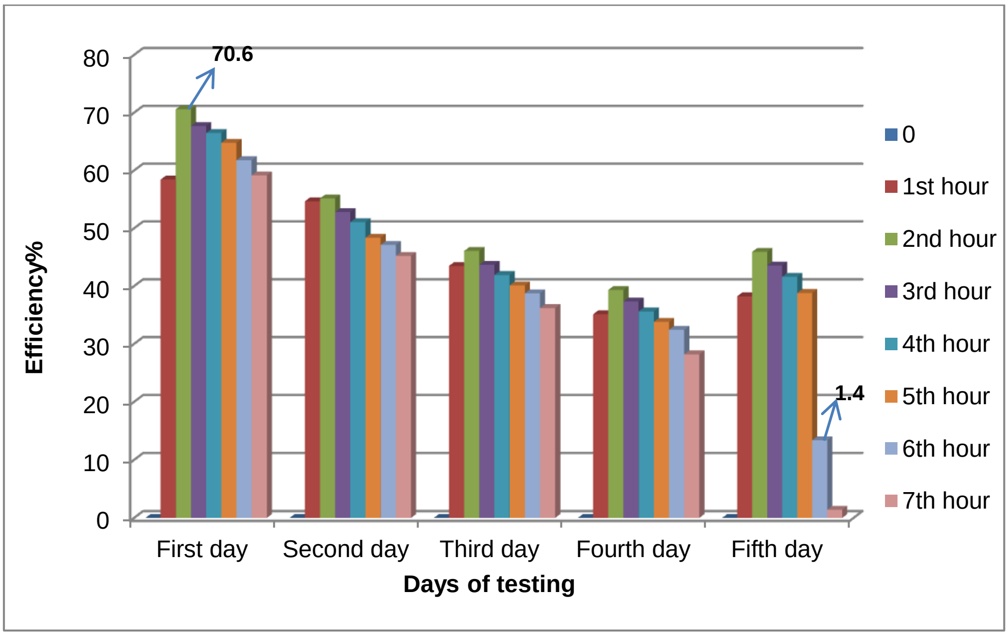

Figure 5.25: The system's daily and hourly efficiencies in terms of heating the water during Test No.5

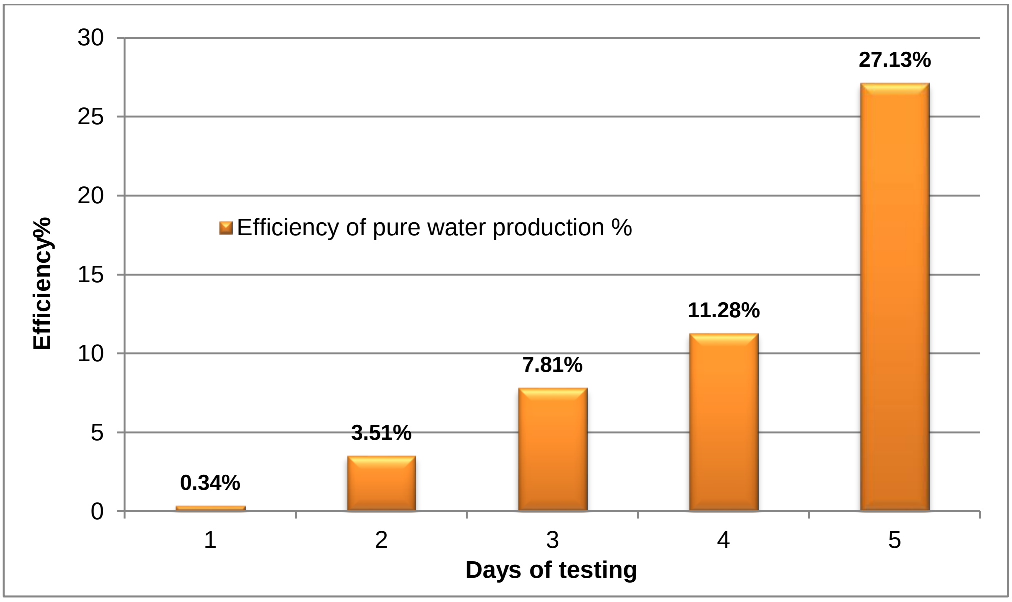

Figure 5.26: The daily efficiency of pure water production (Test No.5)

5.1.6 Results from the sixth test (system's performance test at pressure of 50 kPa and increased vapour pipe's outlet dia.)

Figure 5.27 shows the temperature range of the geyser's water, as achieved after the modification described above.

The system's energy acquisition, as shown in Figure 5.28, was approximately 65.12 MJ.

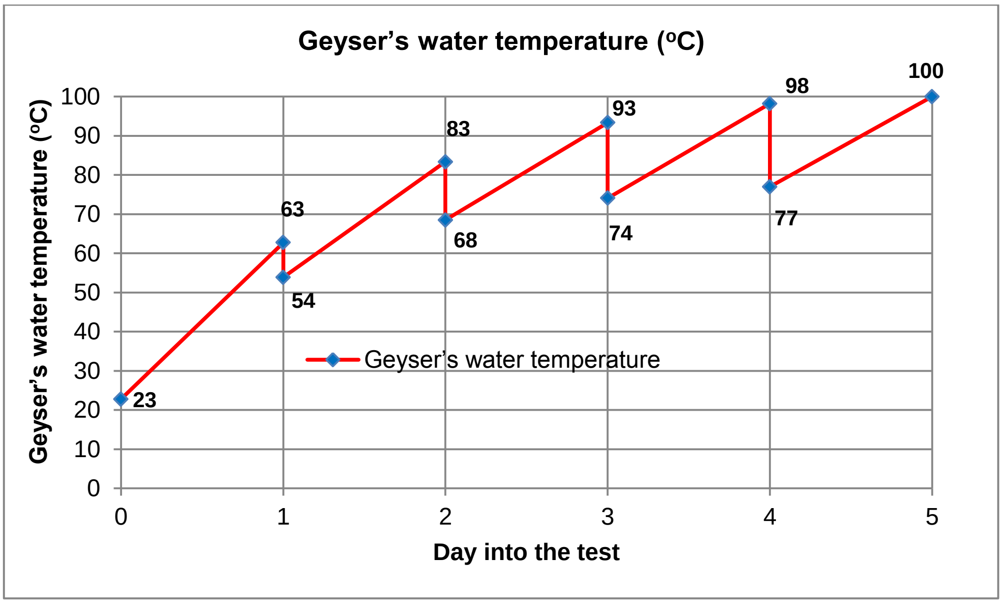

Figure 5.27: Heating and cooling of geyser's water temperature during Test No.6

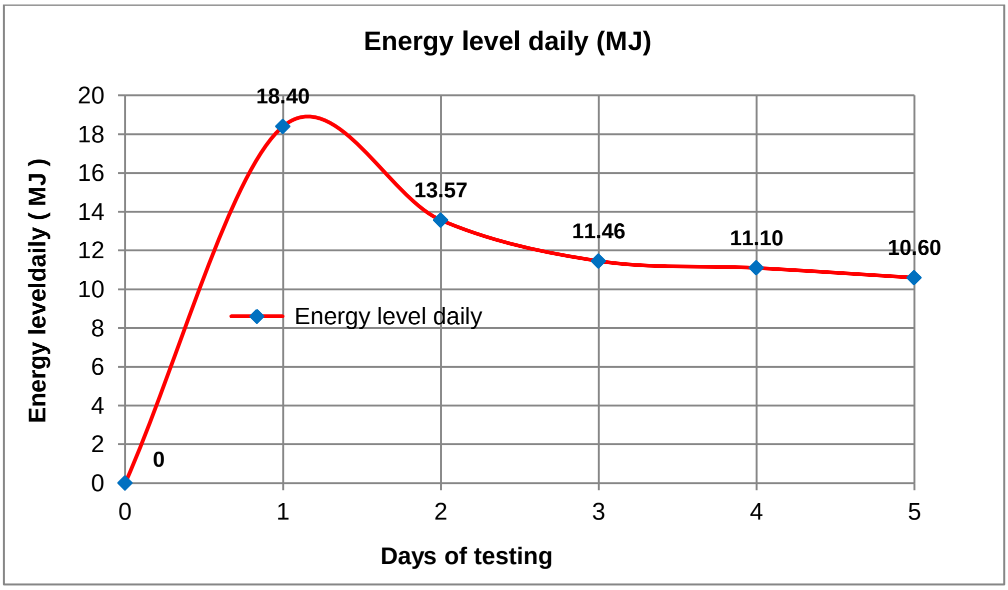

Figure 5.28: Level of daily system's energy acquisition (Test No.6)

The respective temperature drop during overnight cooling of the geyser resulted in an energy loss of approximately 29.56 MJ in total during the test period, as shown in Figure 5.29.

Figure 5.30 shows the distillate productivity, which began during the second day of the test and reached the total of 6300 ml.

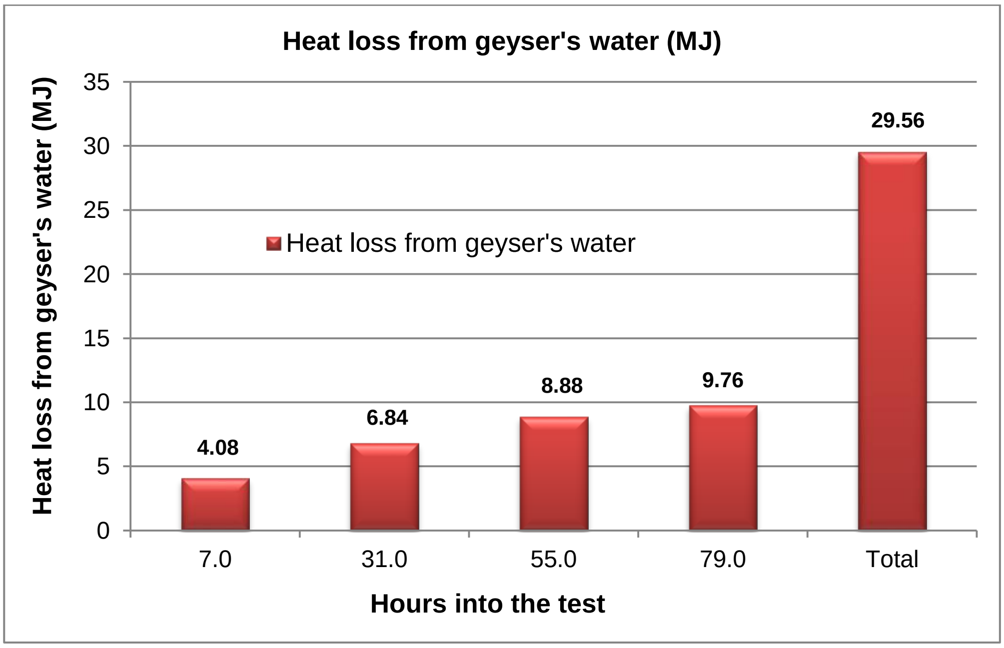

Figure 5.29: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.6

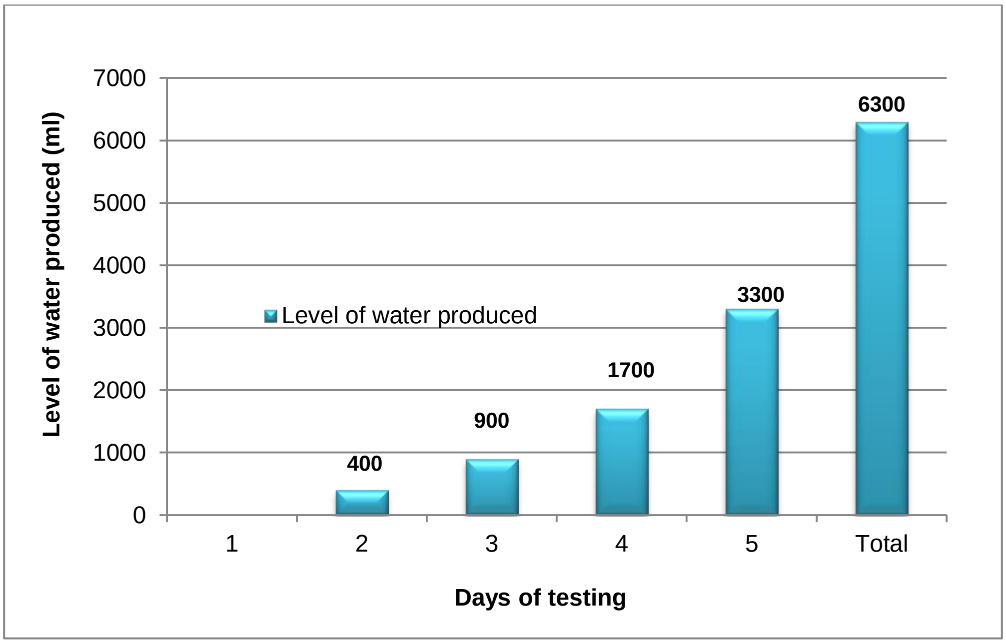

Figure 5.30: The amount of desalinated water harvested (daily and total) during Test No.6

The heating water efficiency was recorded between 73.7% and 33.5%, as shown in Figure 5.31.

The system's efficiency in terms of producing distilled water was recorded as reaching 26.96%, as shown in Figure 5.32.

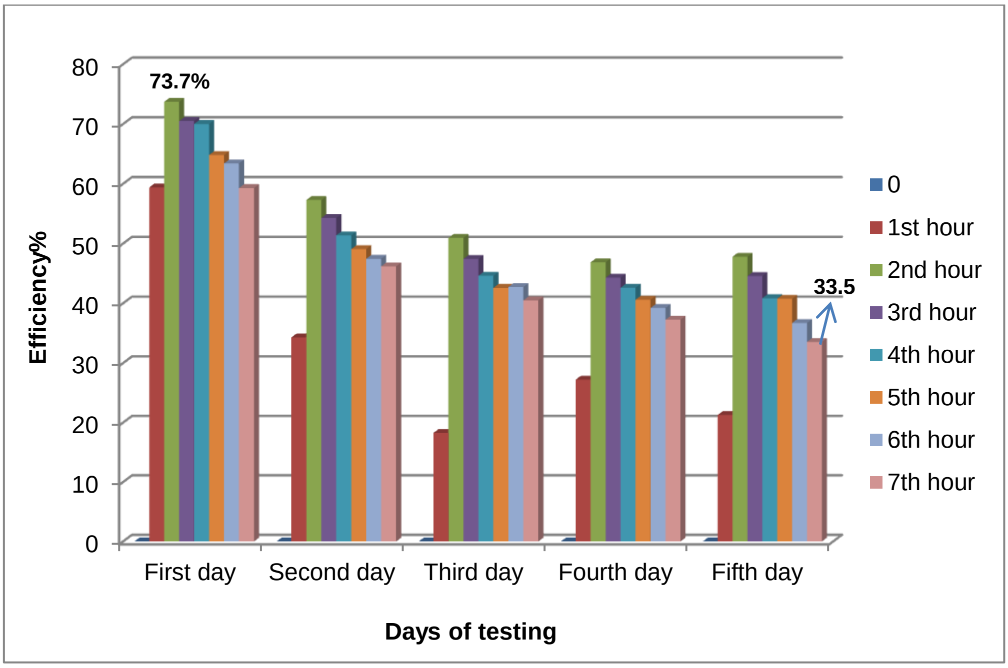

Figure 5.31: The system's daily and hourly efficiencies in terms of heating the water during Test No.6

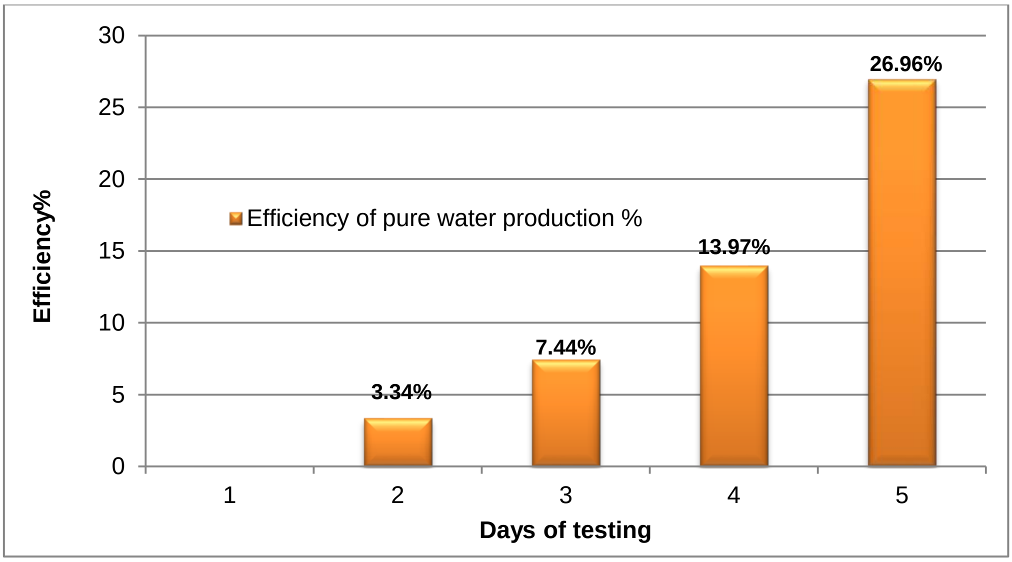

Figure 5.32: The daily efficiency of pure water production (Test No.6)

5.1.7 Results from the seventh test (system's performance test at pressure of 70kPa below atmospheric level)

In this test, the vacuum pressure of the geyser was reduced by 70 kPa below atmospheric level, using the Rotary Vane Vacuum Pump.

Figure 5.33 shows the temperature range of the geyser's water.

Figure 5.34 shows that the system acquired the total sum of approximately 59.59 MJ during the test.

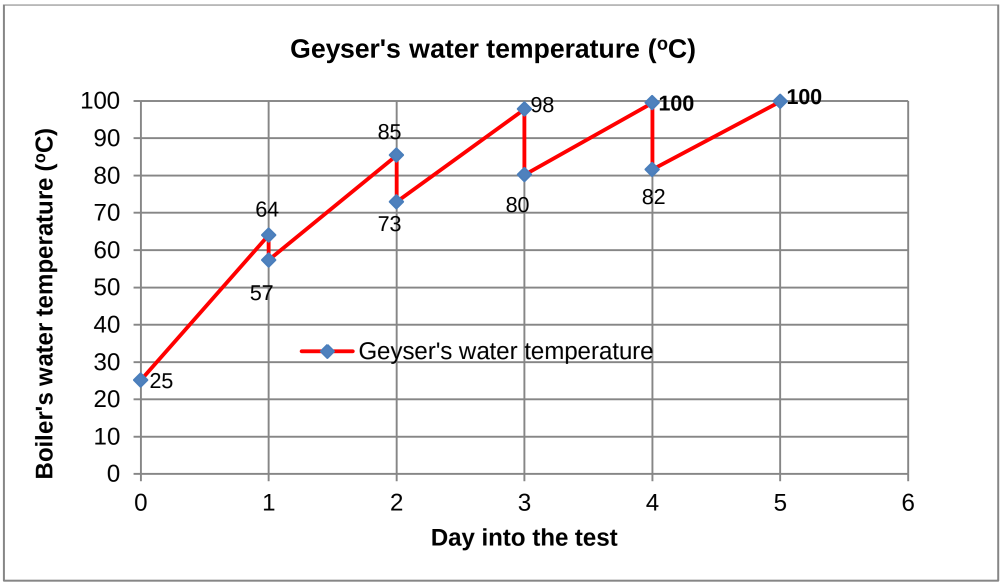

Figure 5.33: Heating and cooling of geyser's water temperature during Test No.7

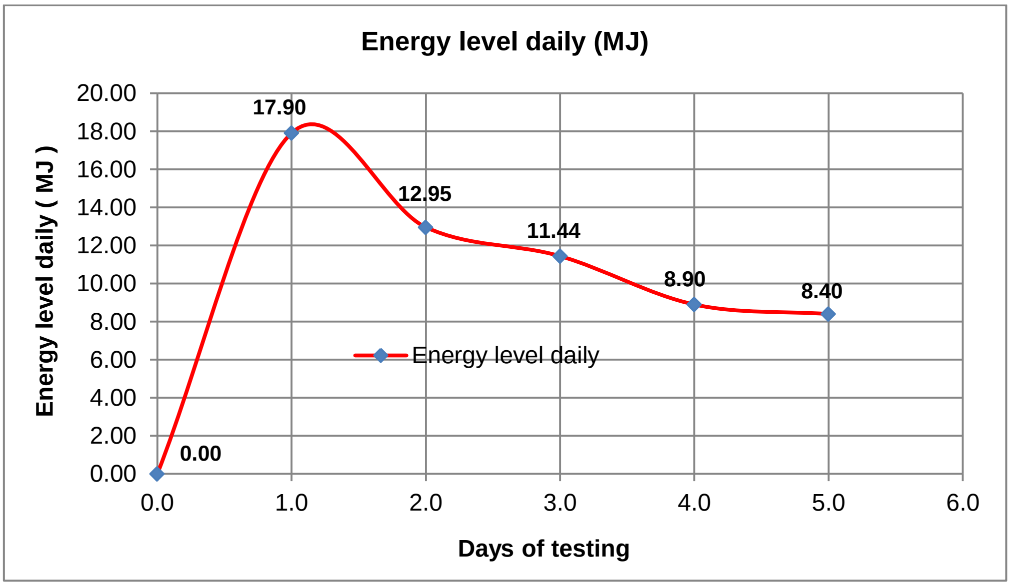

Figure 5.34: Level of daily system's energy acquisition during Test No.7

Figure 5.35 illustrates the level of daily heat loss from the geyser during each period of inactivity, which was a total of 25.19 MJ.

Figure 5.36 shows the amount of water distillate (daily and total). The results showed a respectable daily yield of potable water, totalling 7500 ml/test period, when the geyser's pressure was reduced to 70 kPa below atmospheric level.

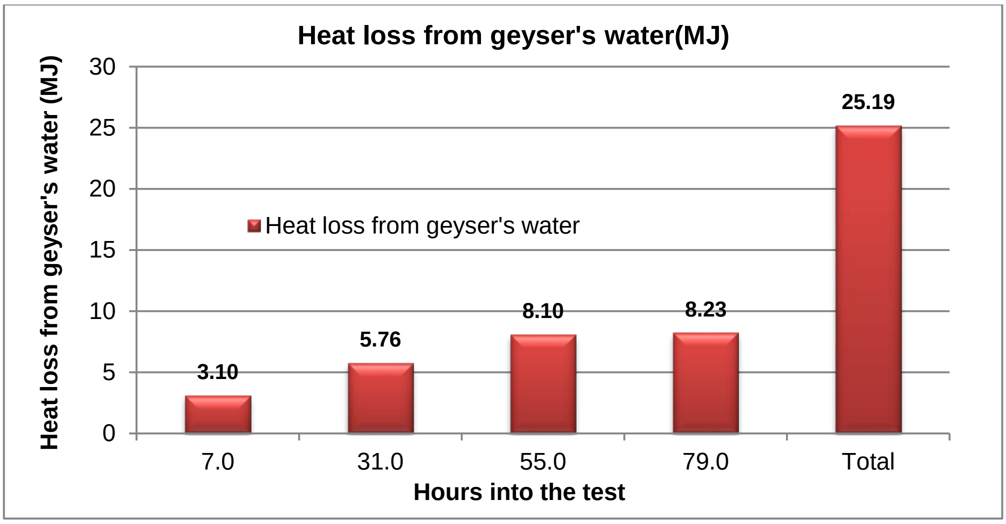

Figure 5.35: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.7

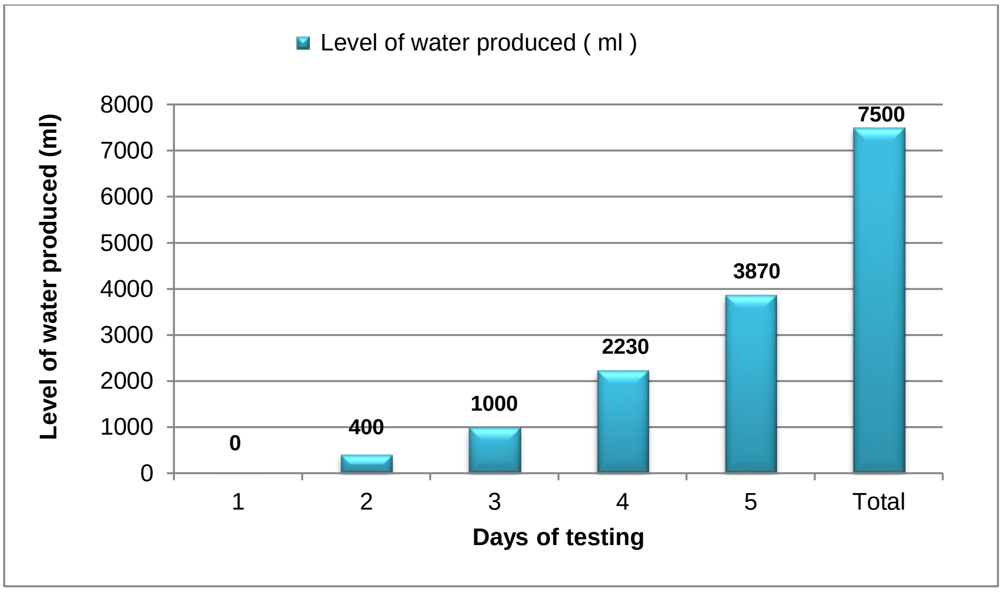

Figure 5.36: The amount of desalinated water harvested (daily and total) during Test No.7

The heating water efficiency was between 70.9% and 4.03%, as shown in Figure 5.37 The system's efficiency in terms of producing distilled water was recorded to reach 31.44% on the last day of the test, as shown in Figure 5.38

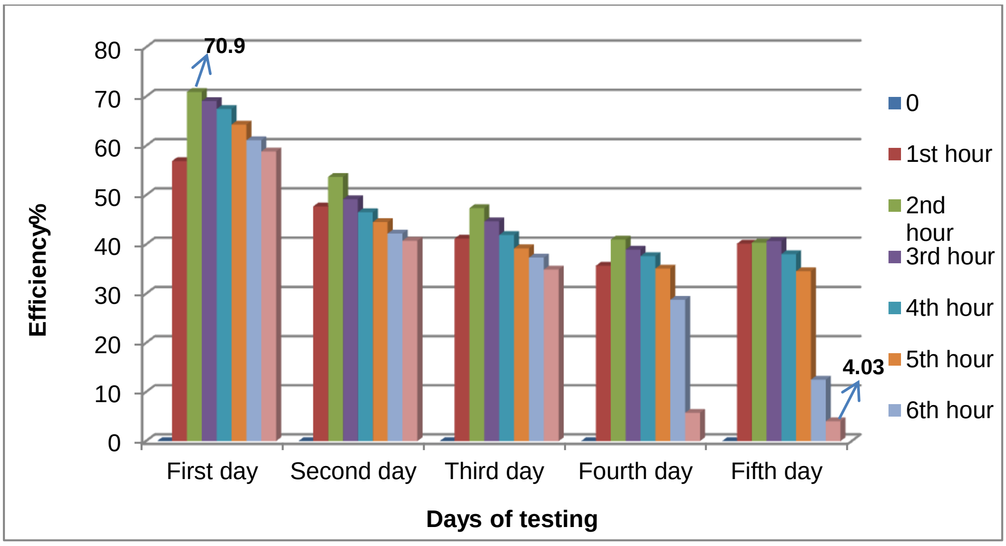

Figure 5.37: The system's hourly and daily efficiencies in terms of heating the water during Test No.7

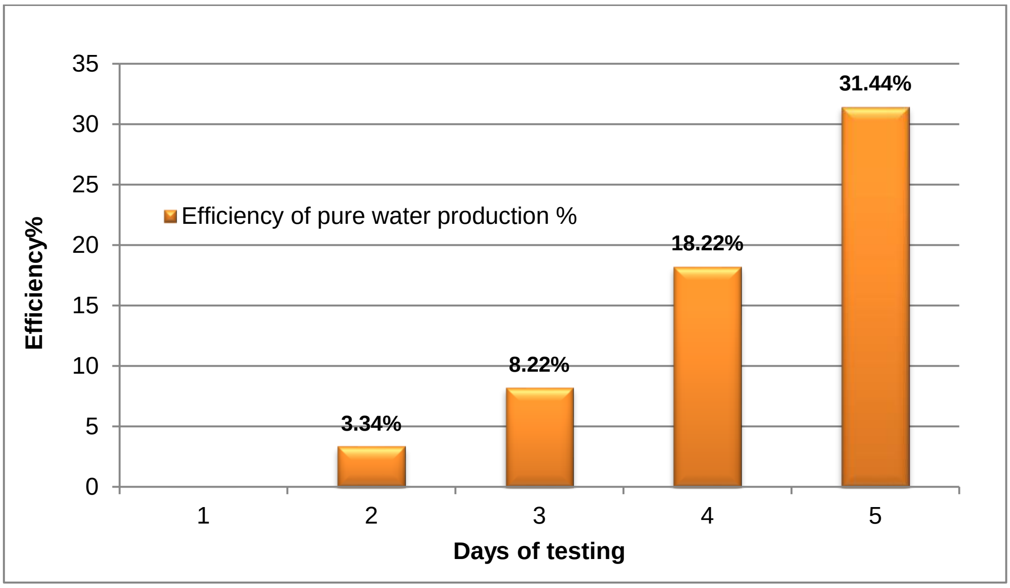

Figure 5.38: The efficiency of pure water production (Test No.7)

5.1.8 Results from the eighth test (extra layer of insulation material) at normal pressure)

Figure 5.39 shows the temperature range of the geyser's water during this test.

By saving energy, the system performance continues in this manner through the fourth and fifth days of the test, which significantly contributed to enhancing the yielded quantities of the pure water.

The system's energy acquisition during this test’s period, as shown in Figure 5.40, was approximately 55.80 MJ.

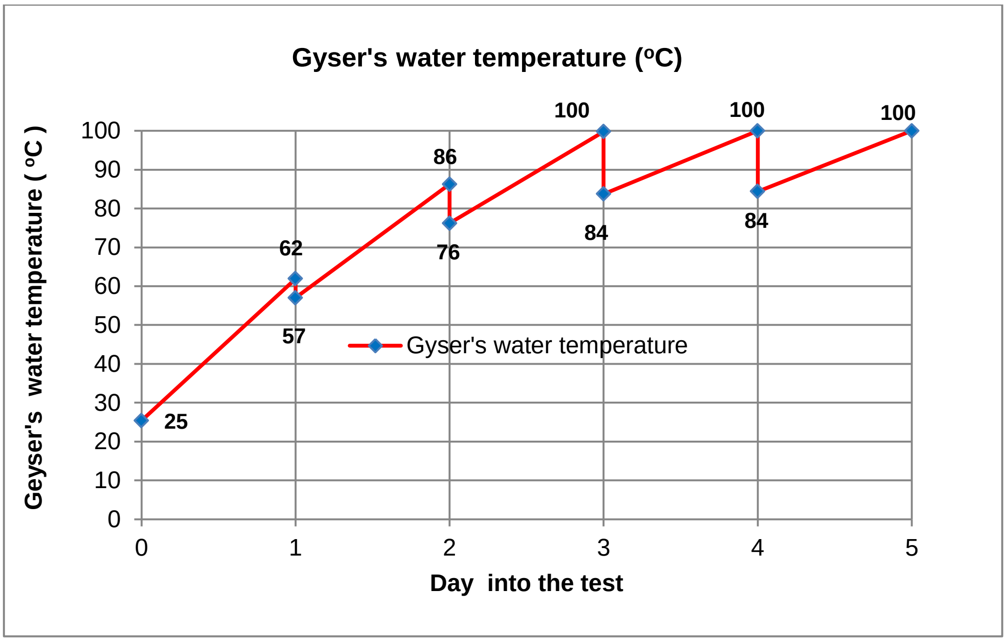

Figure 5.39: Heating and cooling of geyser’s water temperature during Test No.8

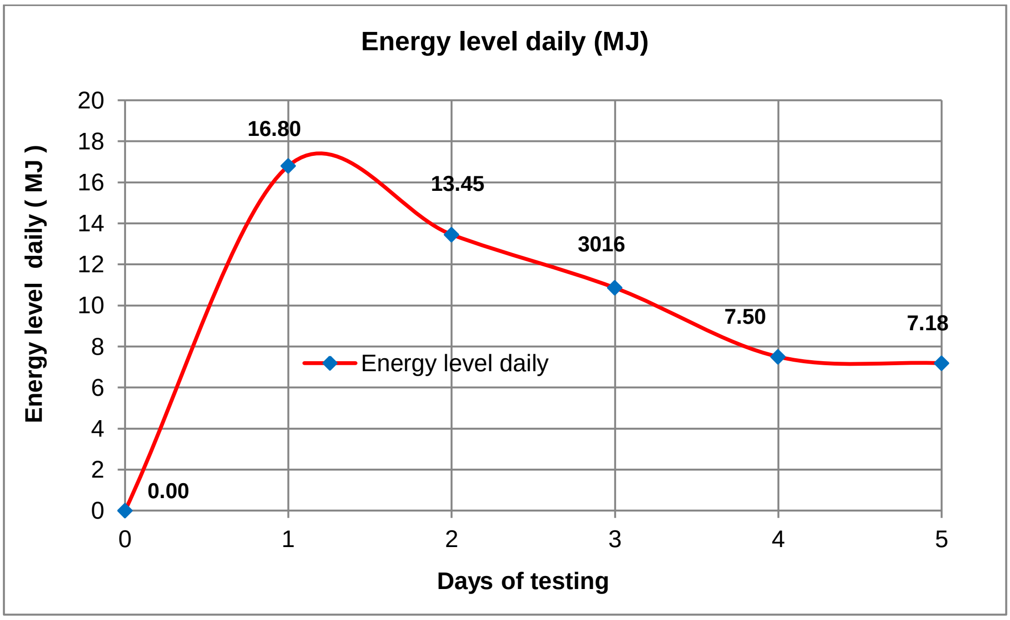

Figure 5.40: Level of daily system’s energy acquisition (Test No.8)

Figure 5.41 illustrates the extent of heat loss from the geyser during the inactivity periods and the total for the test: 21.45 MJ.

In terms of water productivity in this test, as shown in Figure 5.42; the results showed a reasonable daily yield of potable water totalling 9130 ml/test period.

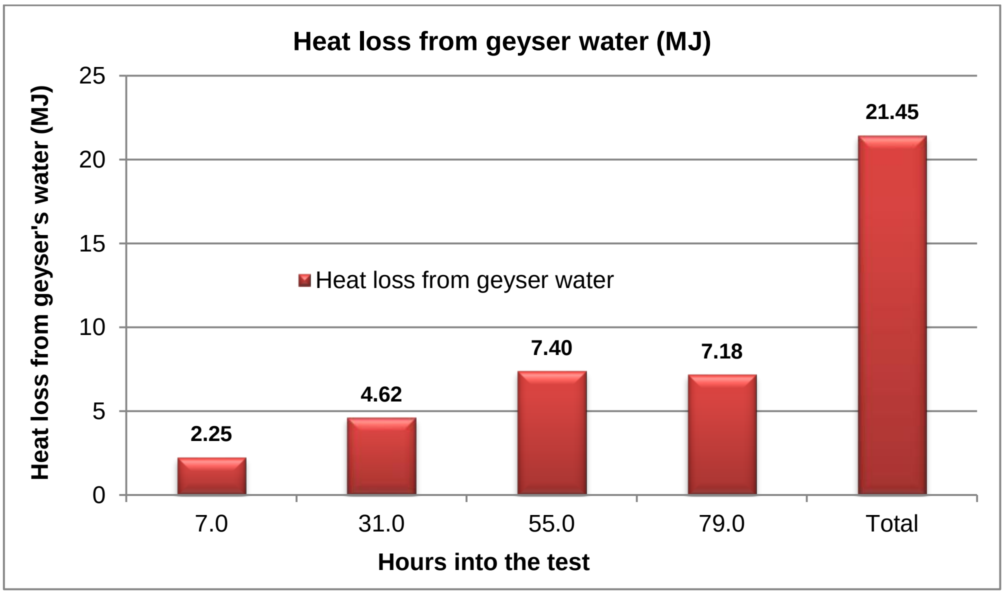

Figure 5.41: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.8

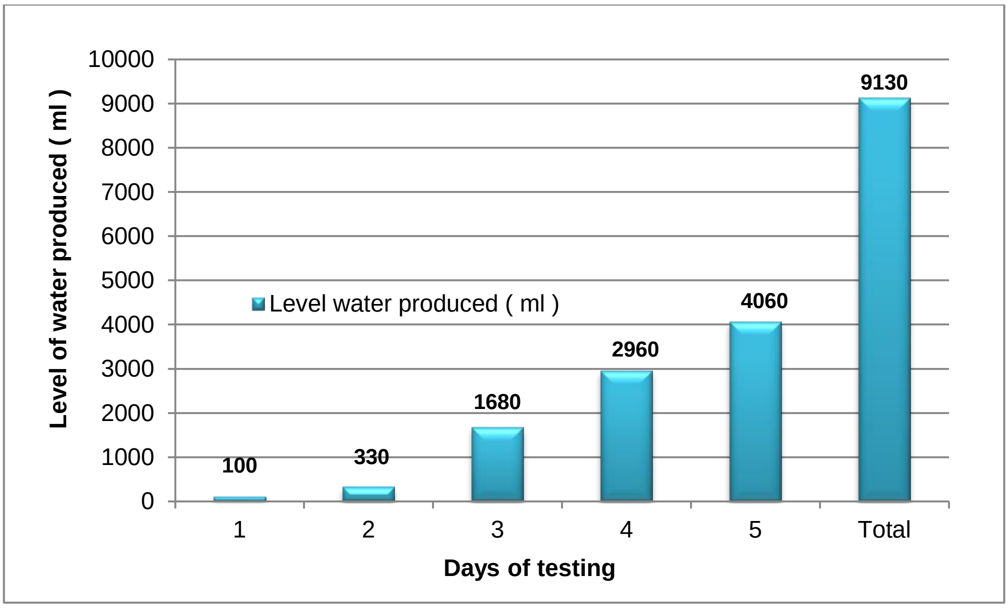

Figure 5.42: The amount of desalinated water harvested (daily and total) during Test No.8

The water heating efficiency was between 67.5% and 2.03%, as shown in Figure 5.43 The system's efficiency in terms of producing distilled water was recorded to reach 32.99 on the last day of the test, as shown in Figure 5.44.

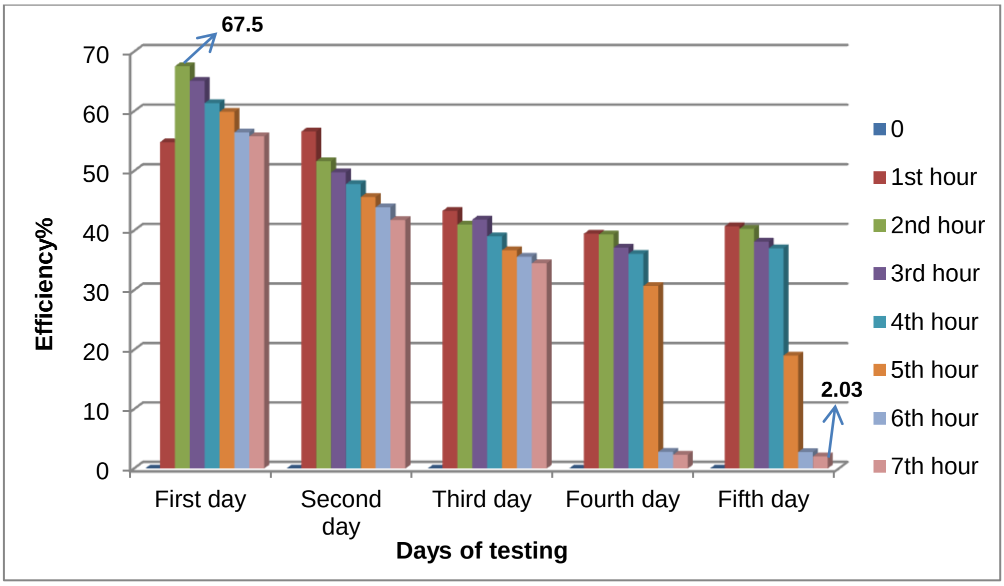

Figure 5.43: The system's hourly and daily efficiencies in terms of heating the water during Test No.8

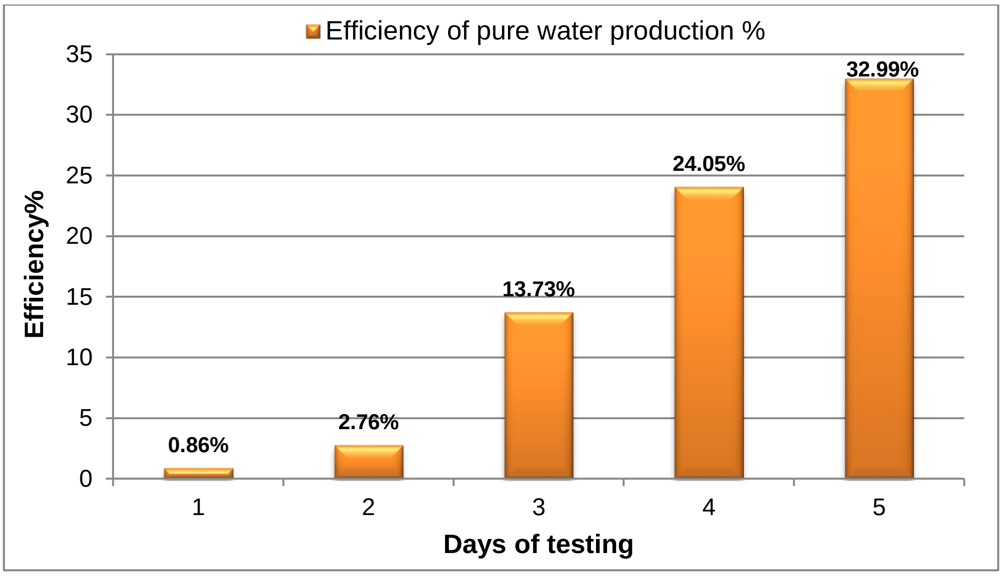

Figure 5.44: The efficiency of pure water production (Test No.8)

5.1.9 Results from the ninth test (extra layer of insulation material) at a pressure of 50 kPa below atmospheric level

A test was performed at a pressure of 50 kPa below atmospheric level, after the addition of the extra insulation on the geyser.

Figure 5.45 shows the temperature range of the geyser's water for the five days test.

Figure 5.46 shows that, during this test period, the system acquired approximately 67.46 MJ.

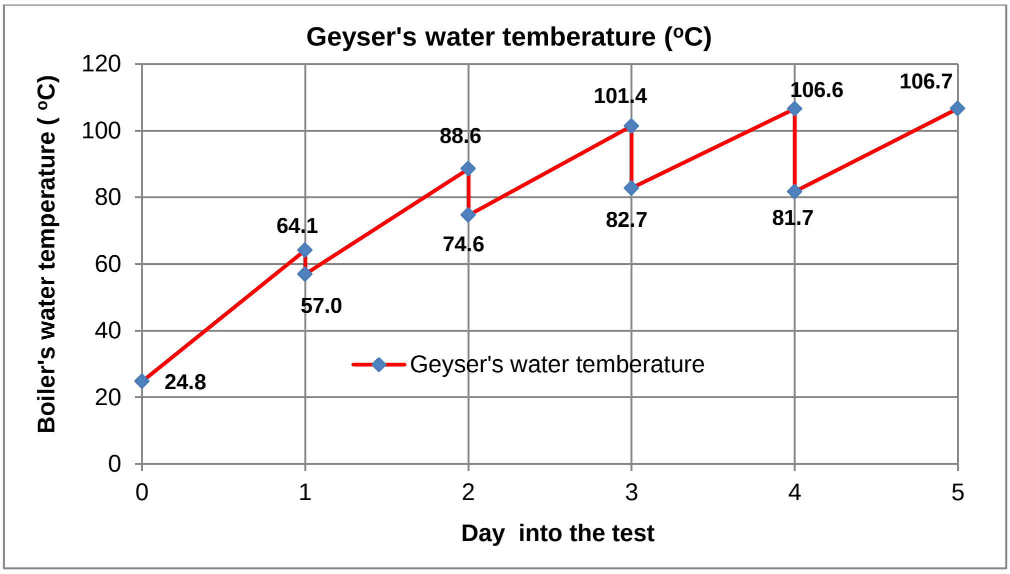

Figure 5.45: Heating and cooling of geyser’s water temperature during Test No.9

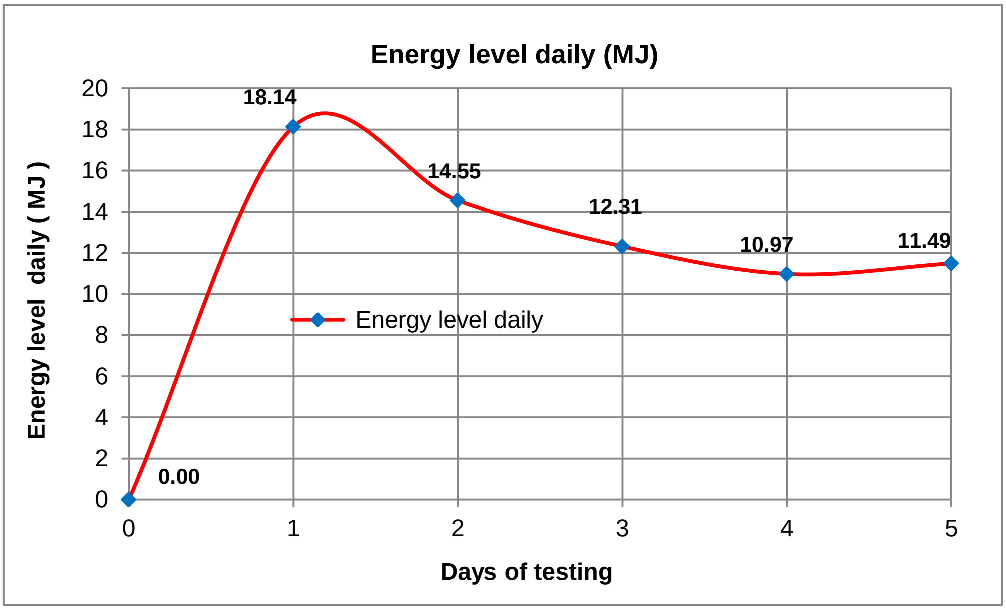

Figure 5.46: Level of daily system’s energy acquisition (Test No.9)

Figure 5.47 illustrates the level of heat loss from the geyser during each period of inactivity and the total amount for the test period, 29.74 MJ.

In terms of water productivity, the results showed a reasonable daily yield of potable water, totalling 950 ml/test period, as shown in Figure 5.48.

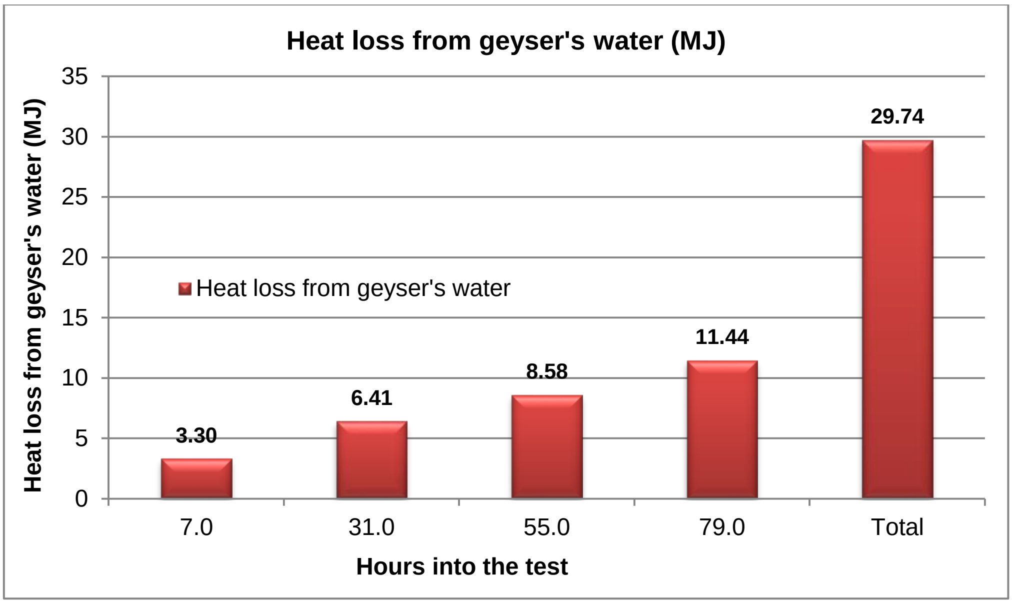

Figure 5.47: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.9

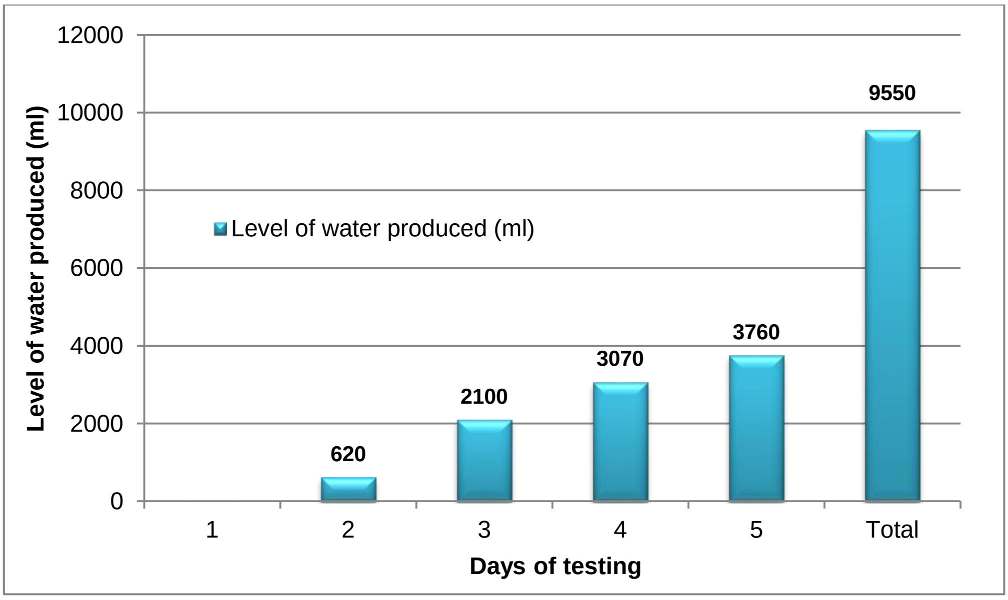

Figure 5.48: The amount of desalinated water harvested (daily and totally) during Test No.9

The heating water efficiency was between 72.2% and 34.9%, as shown in Figure 5.49 The system's efficiency in terms of producing distilled water reached 30.55% during the last day of the test, as shown in Figure 5.50.

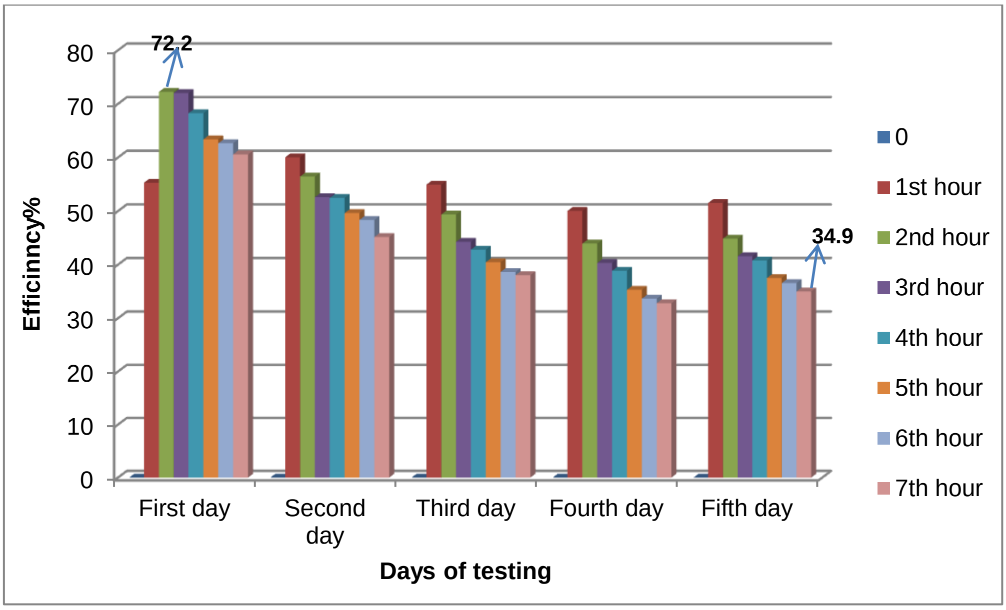

Figure 5.49: The system's hourly and daily efficiencies in terms of heating the water during Test No.9

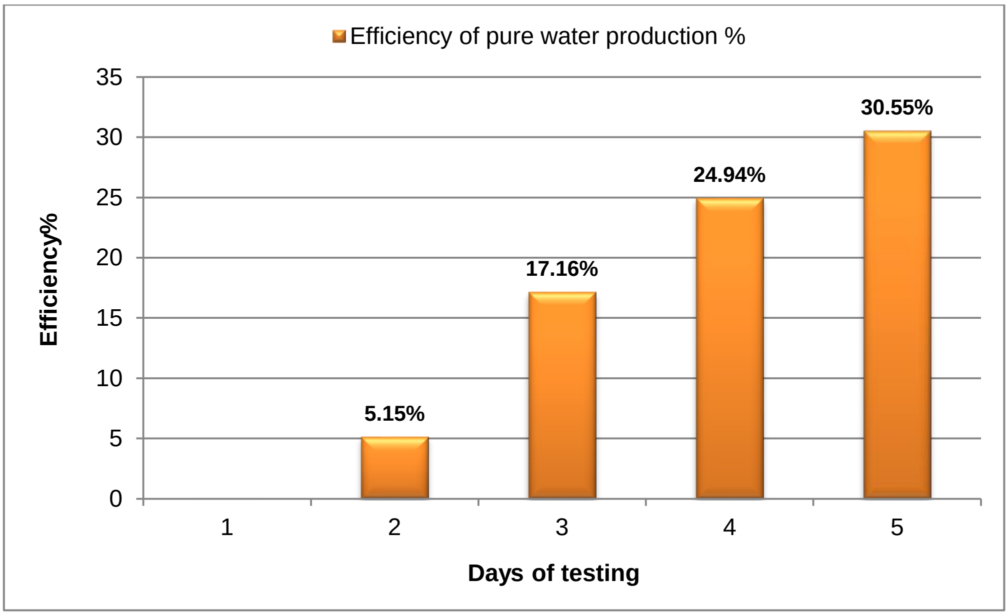

Figure 5.50: The efficiency of pure water production (Test No.9)

5.1.10 Results from the tenth test (extra layer of insulation material) at a pressure of 70kPa below atmospheric level

Figure 5.51 shows the temperature range of the geyser's water for the five days test. Figure 5.52 shows that, during this particular test's period, the system acquired approximately 64.31 MJ.

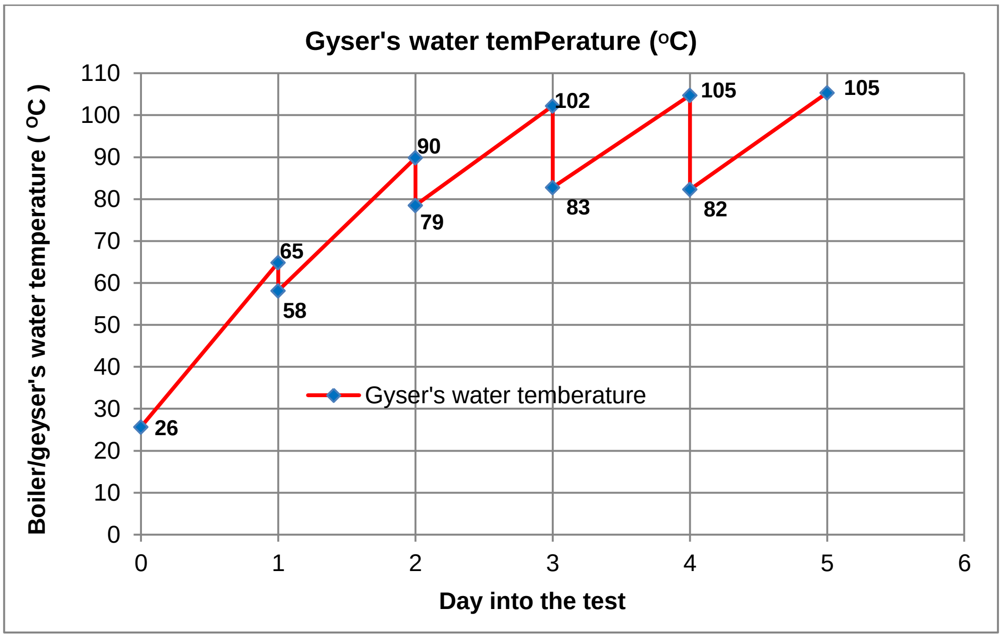

Figure 5.51: Heating and cooling of geyser's water temperature during Test No. 10

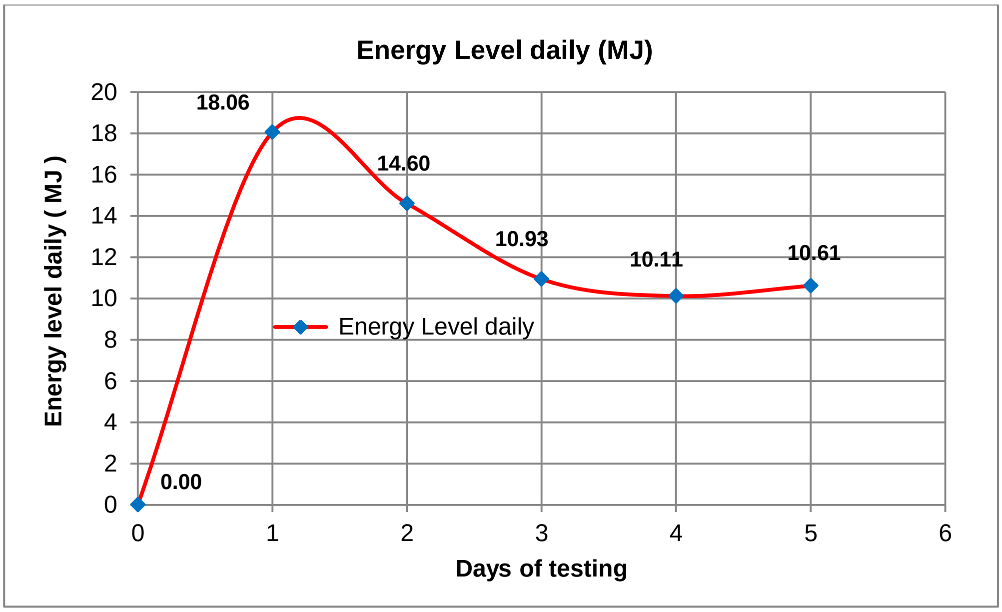

Figure 5.52: Level of daily system's energy acquisition (Test No.10)

Figure 5.53 illustrates the level of heat loss from the geyser during each period of inactivity, as well the total amount for the duration of this test, 27.61 MJ.

In terms of water productivity in this test, the yield of the pure water increased reaching10560 ml per test, period as shown in Figure 5.54.

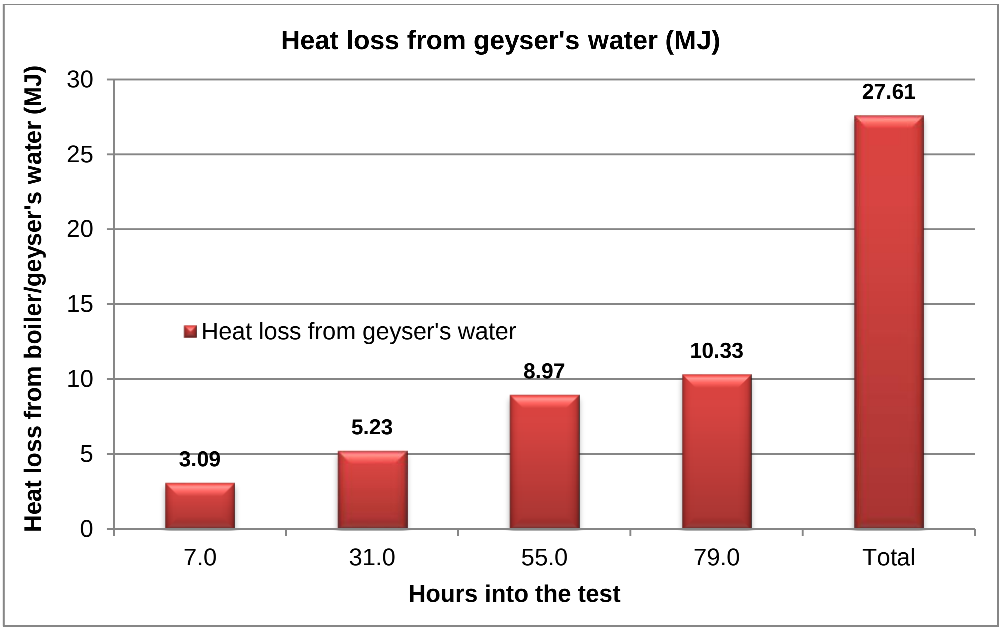

Figure 5.53: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.10

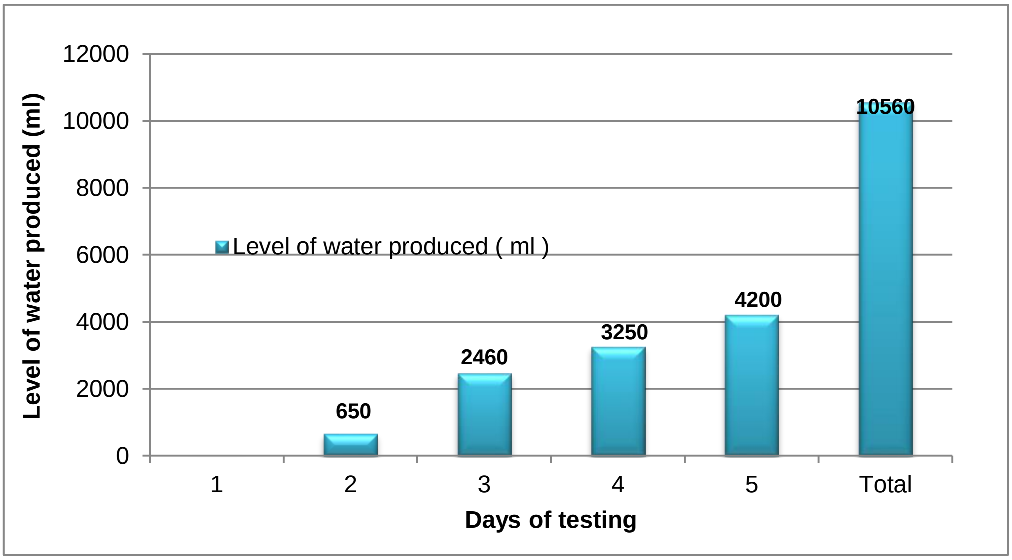

Figure 5.54: The amount of desalinated water harvested (daily and total) during Test No.10

The heating water efficiency was between 71.73% and 29.39%, as shown in Figure 5.55

The system's efficiency in terms of producing distilled water reached the level of 34.12% on the last day of the test, as shown in Figure 5.56.

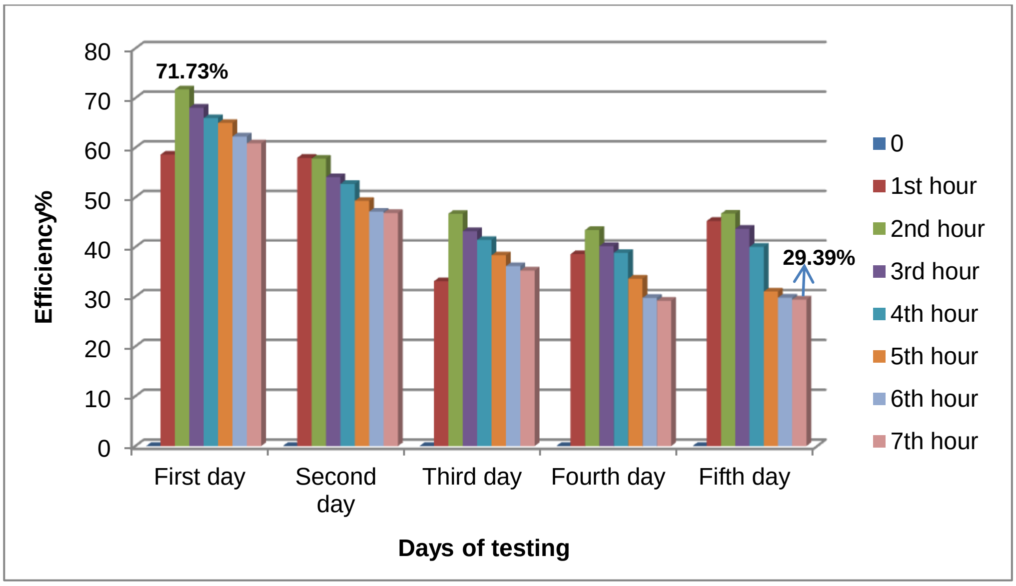

Figure 5.55: The system's hourly and daily efficiencies in terms of heating the water during Test No.10

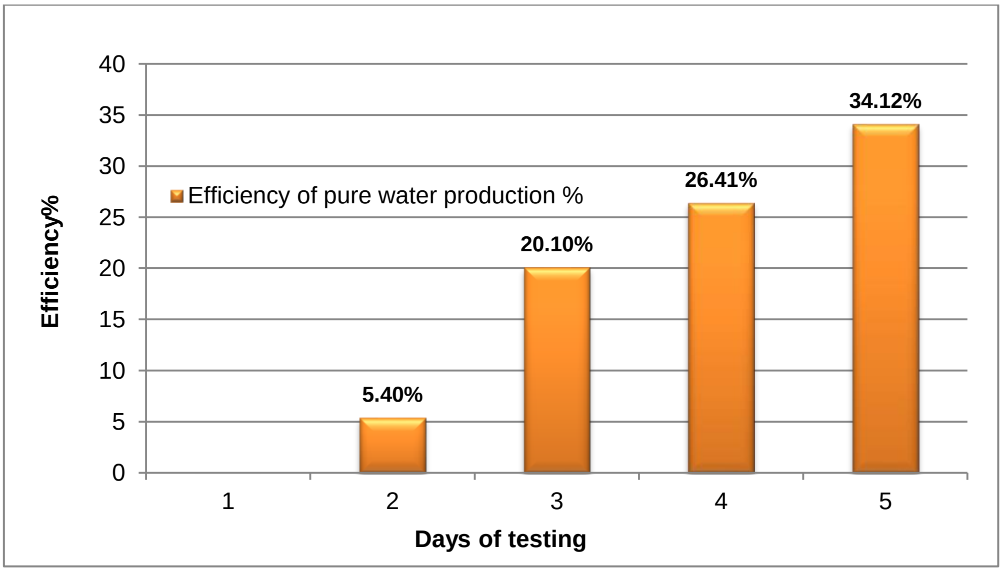

Figure 5.56: The efficiency of pure water production (Test No.10)

5.1.11 Results from the eleventh test, doubling the vapour pipe outlet (760 mm x2), at normal pressure, commercial insulation material

Figure 5.57 shows the temperature range of the geyser's water, while the system's energy acquisition, as shown in Figure 5.58, and was approximately 68.37 MJ.

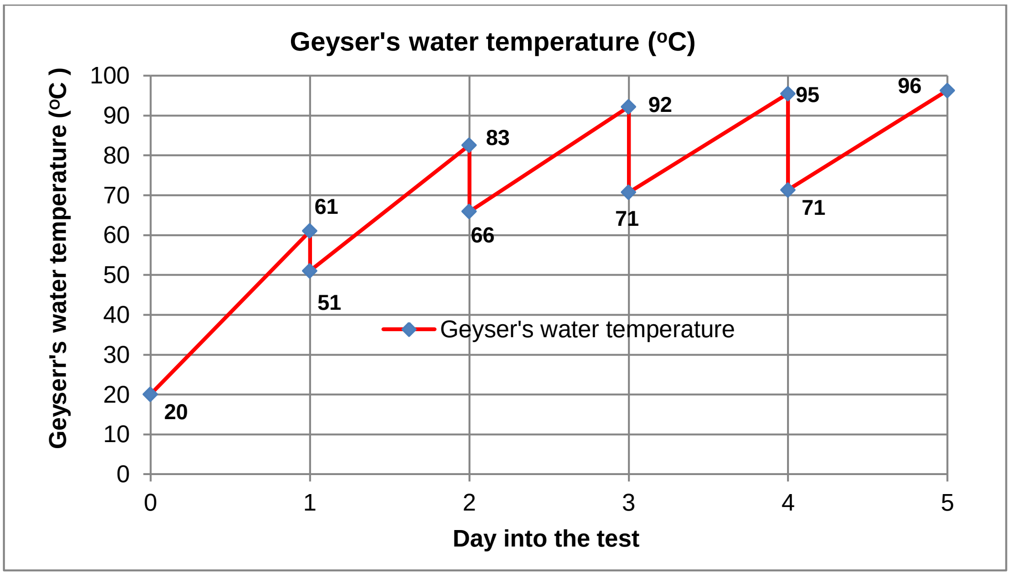

Figure 5.57: Heating and cooling of geyser’s water temperature during Test No. 11

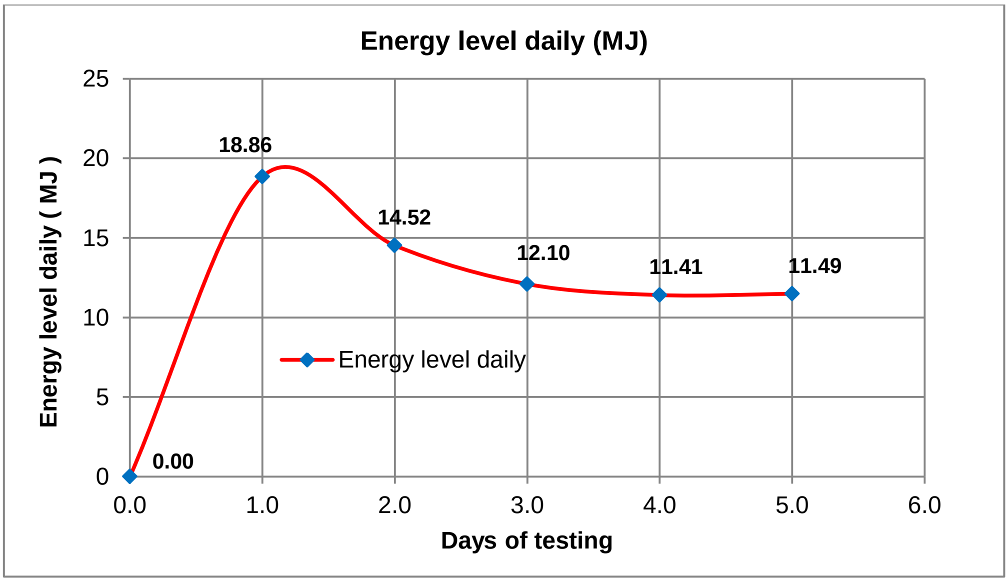

Figure 5.58: Level of daily system’s energy acquisition (Test No.11)

The energy losses during the inactivity periods of 17 hours daily under the test conditions totalled about 33.27 MJ, as shown in Figure 5.59.

In terms of water productivity in this test, the yield of pure water reached the level of 8300 ml/test period, as shown in Figure 5.60.

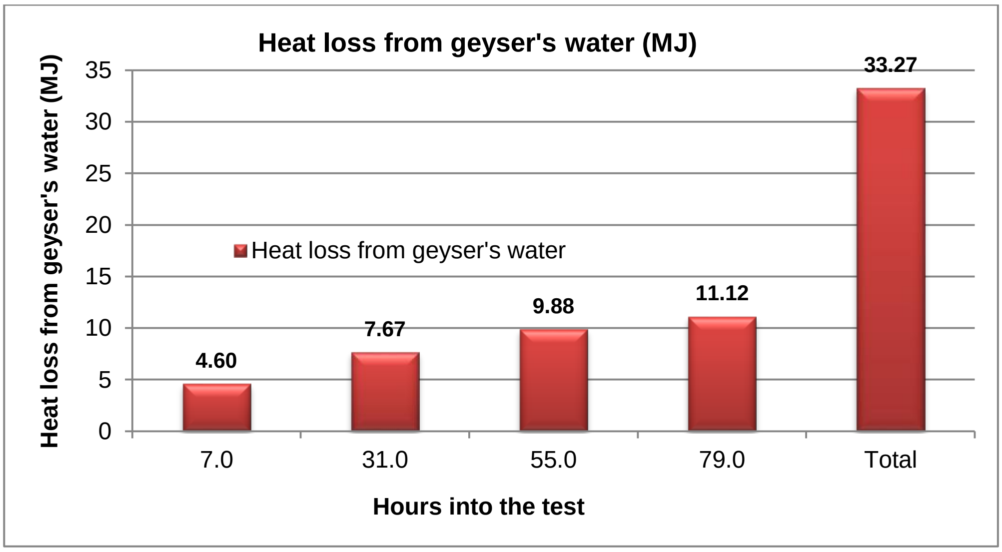

Figure 5.59: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.11

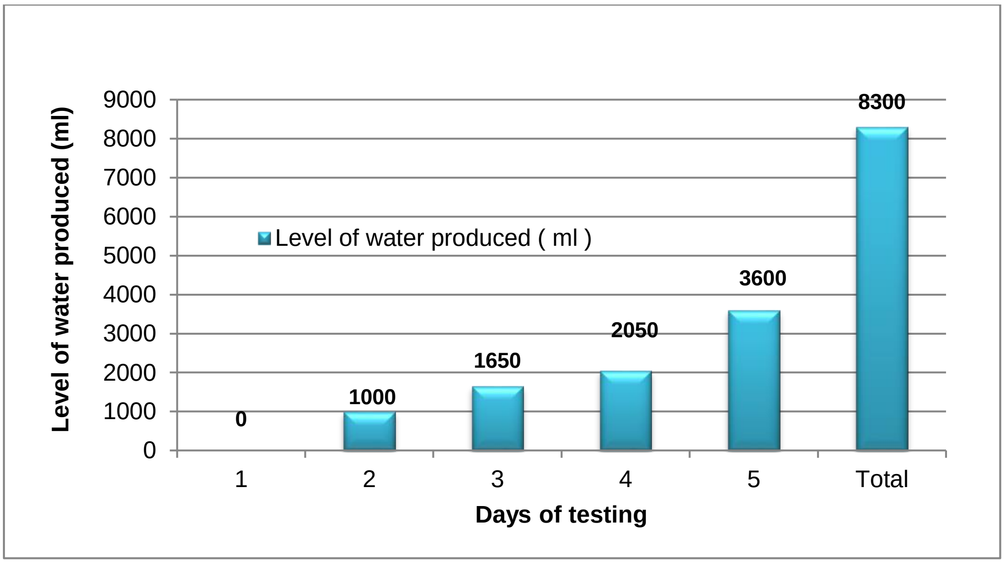

Figure 5.60: The amount of desalinated water harvested (daily and total) (Test No.11)

The heating water efficiency was between 77.1% and 32.8%, as shown in Figure 5.61

The system's efficiency in terms of producing distilled water was recorded to reach 29.58% on the last day of the test, as shown in Figure 5.62.

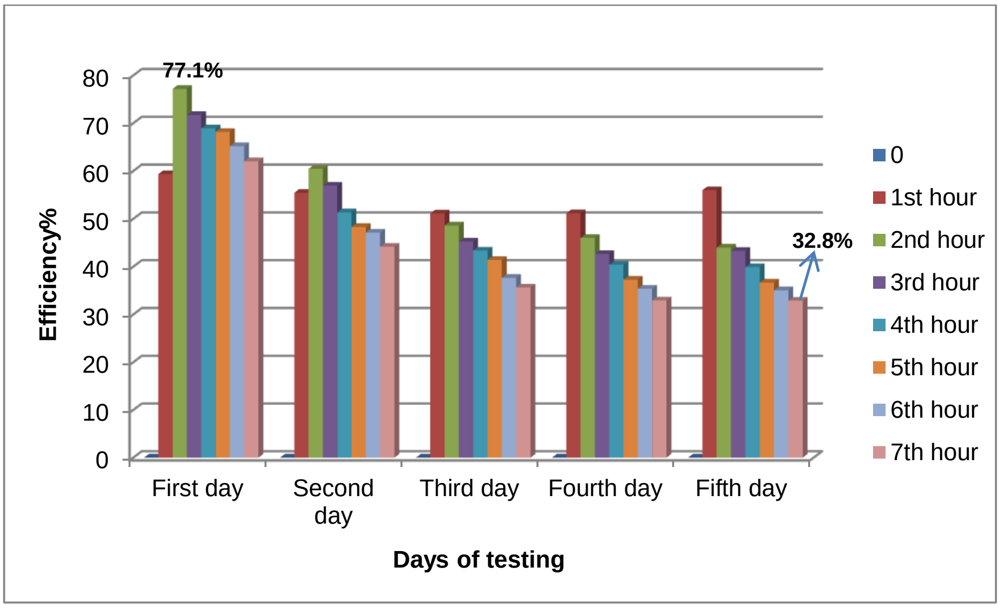

Figure 5.61: The system's hourly and daily efficiencies in terms of heating the water during Test No.11

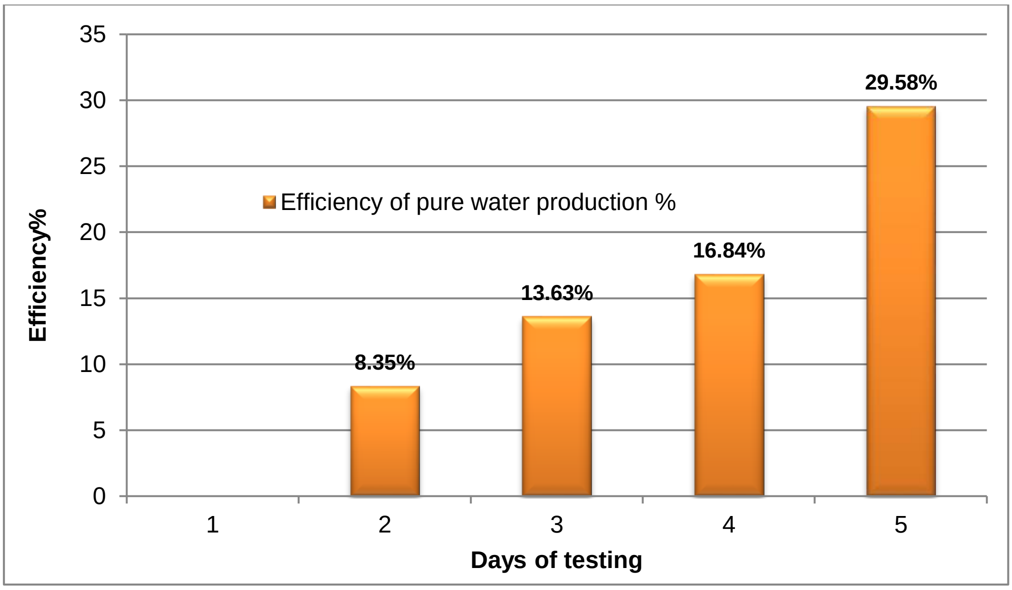

Figure 5.62: The efficiency of pure water production (Test No.11)

5.1.12 Results from the twelfth test, at a pressure of 70 kPa below atmospheric level with extra layer of insulation material

Figure 5.63 shows the temperature range of the geyser's water during the heating of the seven hour period over the five days. Figure 5.64 shows that during this test period, the system acquired approximately 65.39 MJ and that the energy losses were about 32.86 MJ, as shown in figure 5.64.

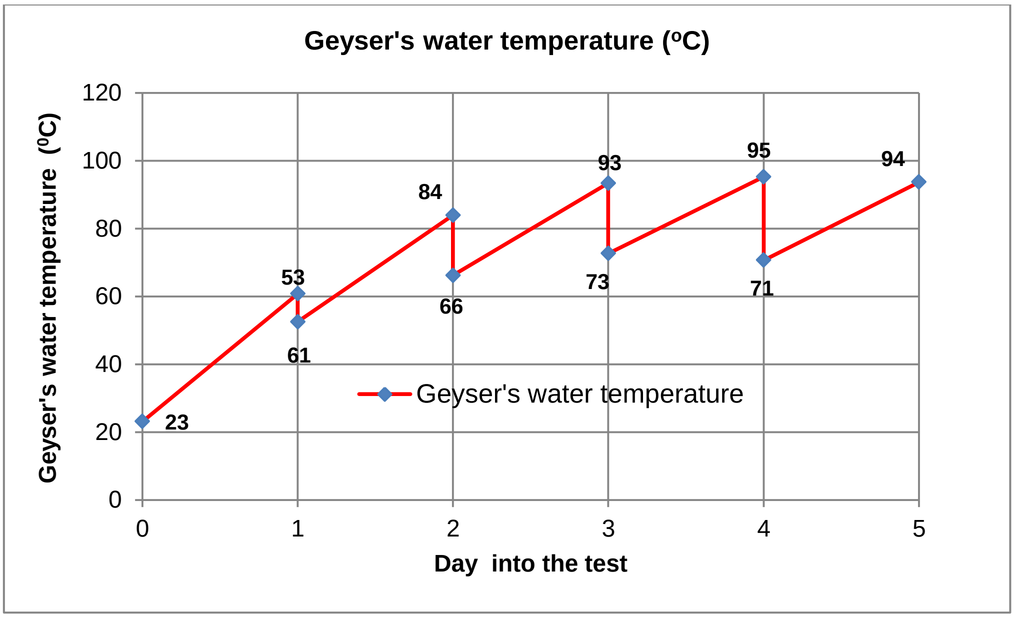

Figure 5.63: Heating and cooling of geyser's water temperature during Test No.12

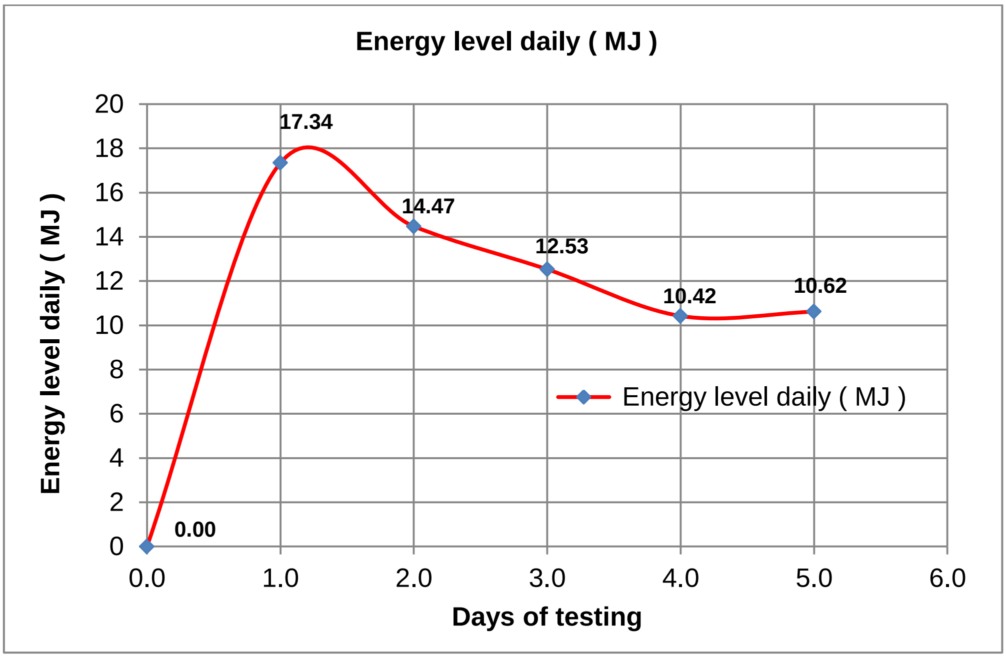

Figure 5.64: Level of daily system's energy acquisition (Test No.12)

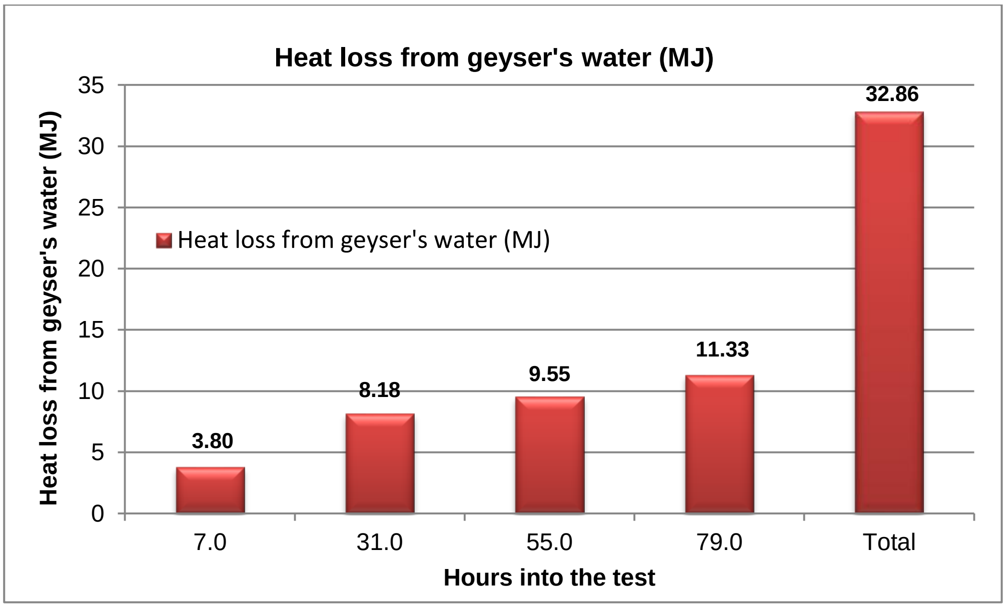

Figure 5.65: The levels of heat energy lost from the geyser during each of the intervals of non-irradiance (17 hours each) during Test No.12

The distilled water reached the level of 12750 ml/test period, as shown in Figure 5.66 The heating water efficiency was between 68.2% and 27.6%, as shown in Figure 5.67 The system's efficiency in terms of producing distilled water reached 38.21% on the last day of the test, as shown in figure 5.68. The calculation of the system's efficiency in terms of producing distilled water and the calculation of the system's efficiency in terms of heating the water (see no. 1&2 in Appendix E).

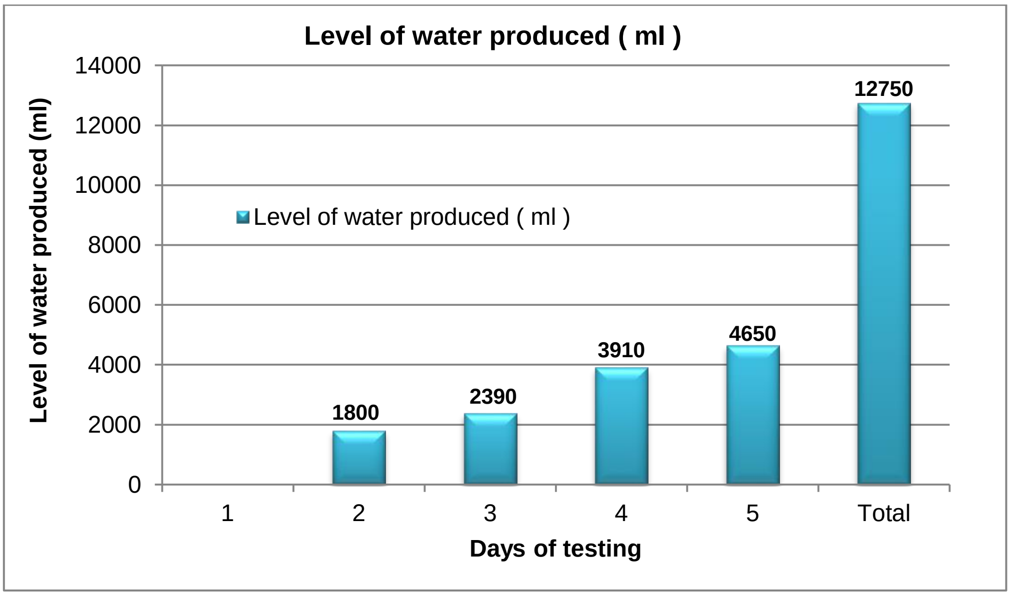

Figure 5.66: The amount of desalinated water harvested (daily and totally) during Test No.12

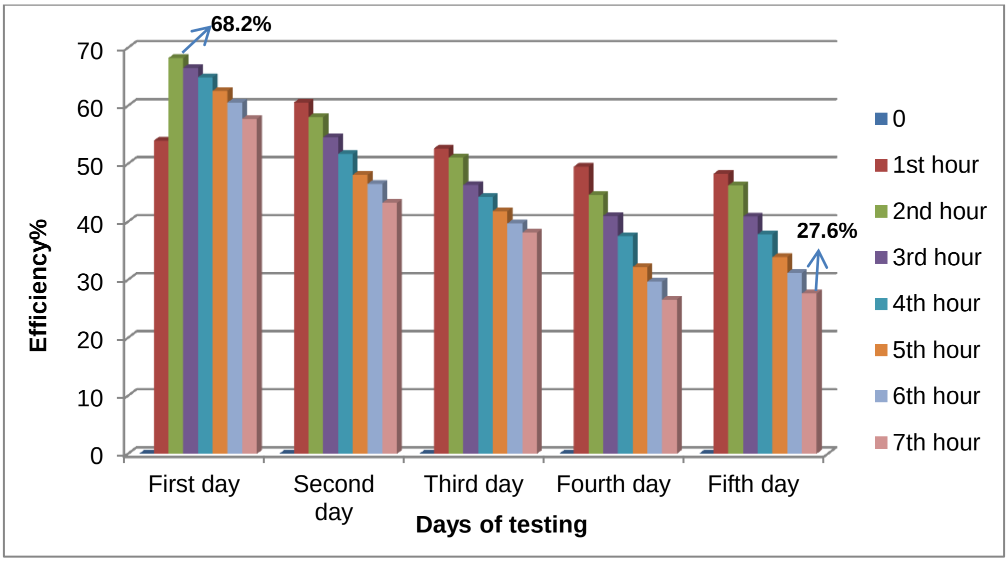

Figure 5.67: The system’s hourly and daily efficiencies in terms of heating the water during test No.12

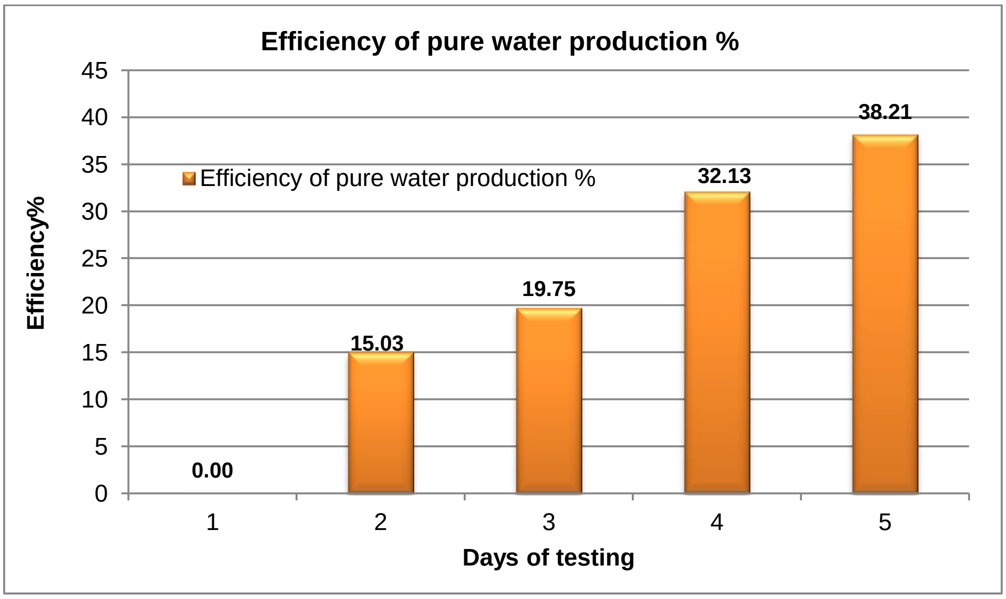

Figure 5.68: The efficiency of pure water production (Test No.12)

5.2 Brief summary of results from the experiments with the desalination prototype

Figure 5.69 is presented as a graphical representation of part of table 5.1, serving the purpose of easing the comparison of the prototype's performance in terms of its distillate yield after the various modifications and testing procedures that were adopted during this study.

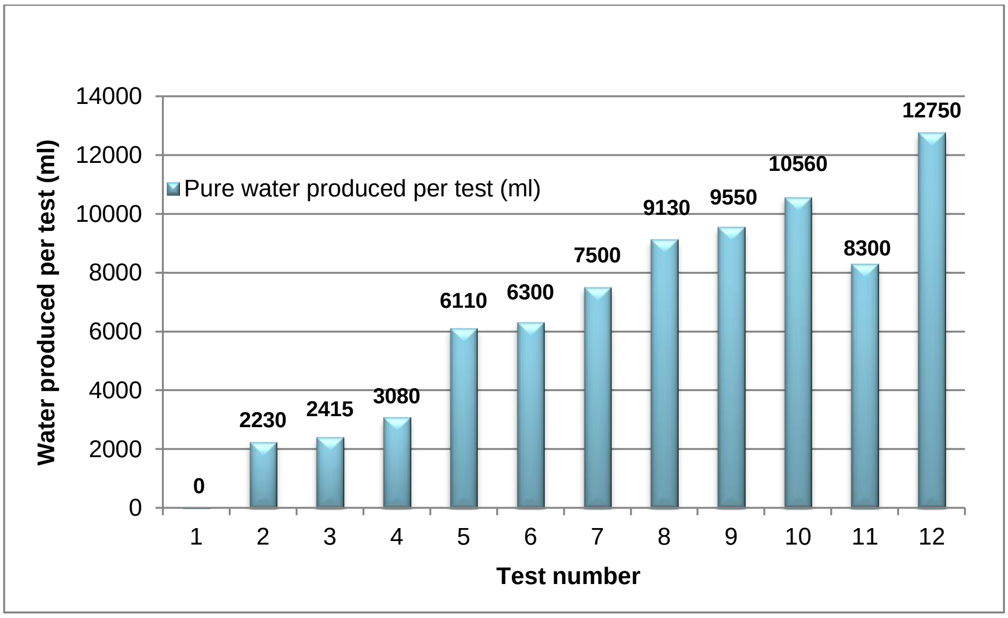

Figure 5.69: Comparison of total (five days) distillate yield from the twelve tests

The results from the first test of the plant, featuring the minor modification of replacing the electrical heating element with a small commercial heat exchanger and creating a space for the steam aggregation, did not yield any distillate. This was attributed to the fact that the commercial heat exchanger was too small and thus too little heat was being transferred by its surface inside the geyser.

Before initiating Test 2, the commercial heat exchanger was replaced with a (newly designed and manufactured) larger heat exchanger and the testing protocol was repeated, the results showing that water vapour was produced and drawn off as liquid/distillate. In order to increase the yield of distillate, more heat was required, therefore the heat exchanger was removed in Test 3 and the contents of the geyser were exposed directly to the heat in the collector's manifold. This resulted in an increase in the yield of distillate water.

Since water boils at a lower temperature when pressure is reduced, in Test 4 a pressure of 50 kPa below atmospheric was established in the geyser and this resulted in further improvement of distillate harvested.

In Test 5, having realised that the relatively small vapour outlet was restricting the vapour flow from the geyser the outlet from the geyser's side exit was moved to the top and its dia. was increased, the yield of distillate almost doubled.

In Test Six, lowering of the geyser pressure to 50 kPa below atmospheric pressure resulted in a further yield of distilled water.

In Test Seven, with a pressure of 70 kPa below atmospheric (the maximum vacuum pressure attempted during the tests) the productivity of distillate was further increased. However, it was noted that the vapour pipe outlet was still not wide enough to accommodate the vapour that was being generated.

In Test 8 it was sought to decrease heat losses from the geyser during the test time and overnight hence extra insulation material around the geyser contributed to improve the yield of distilled water, which was surpassed by Tests 9 and 10, performed at 50 kPa and 70 kPa below atmospheric pressure respectively.

Test 11 was performed as a result of the previous improvement on the yield of distilled water following the increase of the diameter of the geyser's vapour outlet in Test 5. By doubling the vapour outlet from the geyser, the difference in the distillate yield was considered, a major improvement when compared with Test 5, which was conducted at the same geyser's pressure and thermal insulation conditions.

Test 12 combined all the improvements and changes in the prototype that were attempted in previous tests and was undertaken at 70 kPa below atmospheric pressure. The system performance was superior to all previous attempts in raising the level of the yield of distillate.

In Figure 5.69 it has been shown that the system improved in fresh water yield as a result of raising the geyser's water temperature, by the various mechanical modifications described in each experiment, including increasing the size of the outlet pipe for the vapour to flow to the condenser, and lowering the boiling point of the water (at sub atmospheric pressures).

With the exception of experiments number five and eight where a minute or negligible amount of pure water was harvested in the first day, all other experiments did not yield any.

In experiment number one the system was tested as acquired from the vendor.

The fact that there was no pure water harvested throughout the entire test may be explained in that the water temperature did not even reach the level of 90 ℃. It is expected that there must have been some vapour in the geyser during the course of the experiment; however, the small outlet pipe probably impeded its flow to the condenser.

In the following two experiments (numbers two and three) after attempts were made to increase the geyser's water temperature, some pure water was obtained only in the fourth and fifth day of the experiments when the water temperature reached the high 90's ℃ level.

During experiment number four the system was operated at 50kPa below atmospheric conditions which lowered the boiling point of water. As a result the first day of the experiment still did not yield any pure water however, when the temperature reached low 90's ℃ the production of vapour was sufficiently high to push it through the condenser on the third day.

In experiment number six notwithstanding the provision of larger outflow pipe for the vapour, the system was not able to produce pure water on the first day as hoped, since experiment number 5 did produce a minute negligible amount (40 ml). But the system did perform better overall.

Figure 5.69, shown previously, serves the purpose of comparing the total yield of distillate from the prototype's tests that spanned a period of five days (each). The comparison of the yields of distilled water for the last day of each test is perhaps a more tangible factor to be examined, as it represents the maximum yield from the system upon reaching the point of "steady state" operation. The use of the term "steady state" here implies that the performance of the system reached its maximum and did not change on the sixth day or thereafter.

After the fifth day of the experiments it was not expected for the yields to significantly increase. This is evidenced by the levelling off of the water temperature in the geyser on the fourth and fifth days of the experiments.

The performance of the system in terms of producing a certain quantity of distilled water and its efficiency in doing so in the last day of the various tests is shown in figures 5.70 and 5.71 respectively.

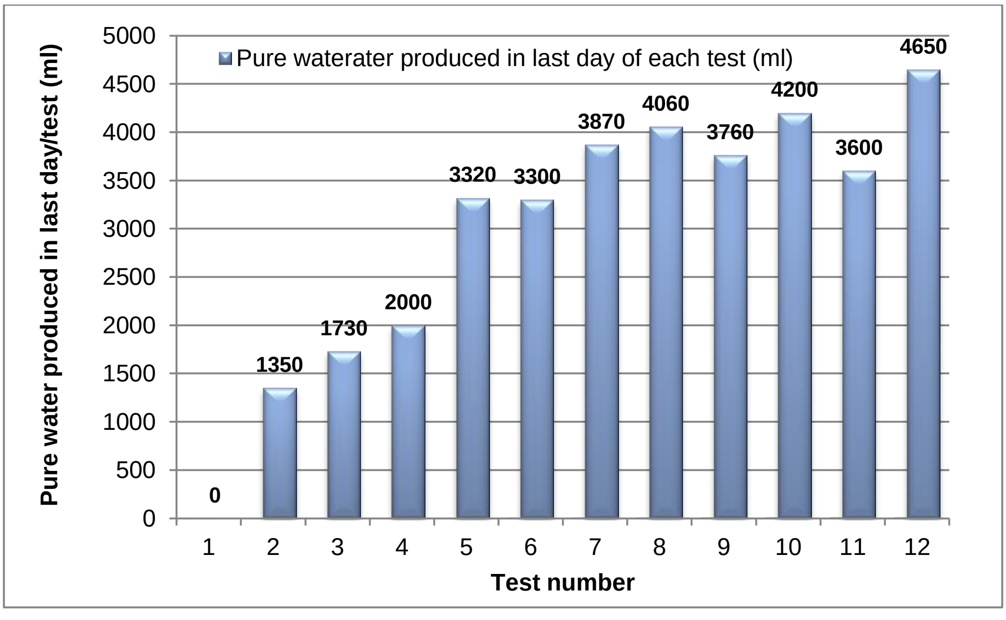

Figure 5.70: Comparison of the distillate yields from the last day per each test

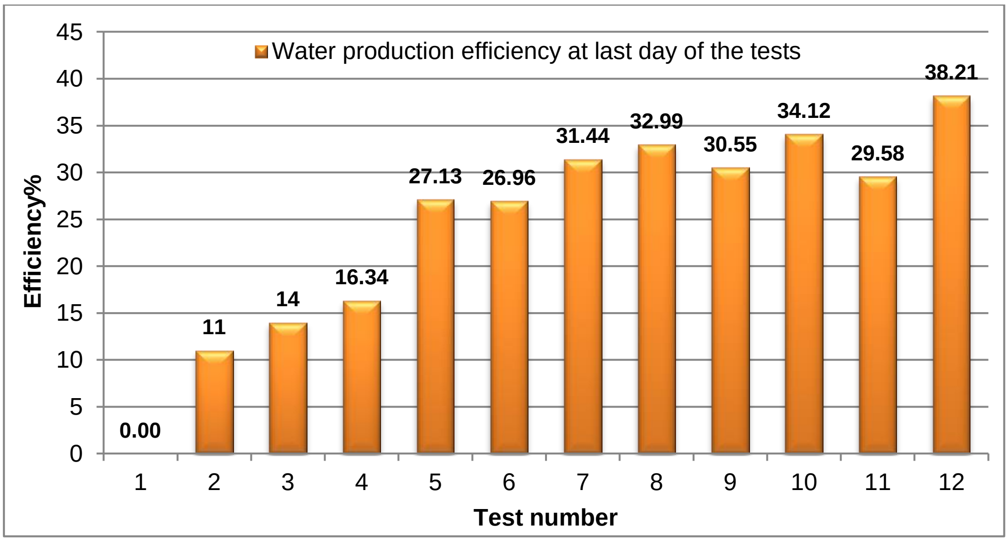

Figure 5.71: The efficiencies in terms of pure water production on the last day of each test

5.3 Results from testing the heat pipe performance with different working fluids

The purpose made testing apparatus, described in Chapter 3 Para. 6 and its subsections, was used in testing the performance of the heat pipes with four different working fluids. As already mentioned, the results from a test using one of the commercially available heat pipes was used as a benchmark in comparing their performance. The working fluids chosen were distilled water, methanol, acetone and ethanol.

The experiments were conducted for the purpose of improving or better discovering the effect on the thermal performance and efficiency of the heat pipe, which was recharged with various working fluids at the same filling ratio by infusing always the same amount of working fluid (10 ml).

5.3.1 Results from the experiments with the testing apparatus for the heat pipes

A summary of the results from testing the performance of the heat pipes with different working fluids appears in Table 5.2.

Figure 5.72 displays the behaviour of the temperature rise of the water in the tank of the heat pipe testing apparatus when testing each individual heat pipe, each containing a different fluid. Thus a direct comparison of their performance can be made.

Table 5.2: The initial and final temperatures of the water, ambient temperature and the efficiency% of each heat pipe containing a particular working fluid

	Description of the test	Initial& final temp. °C	Ambient temp. avg. °C	Efficiency%
1	Original heat pipe (Commercial)	16.2-71.8	21.8	57.1
2	Heat pipe with Pure water (Working fluid)	16.3-77.7	19.3	63.1
3	Heat pipe with Methanol (Working fluid)	16.4-75.3	19.3	60.5
4	Heat pipe with Acetone (Working fluid)	16.4-72.5	19.3	57.6
5	Heat pipe with Ethanol (Working fluid)	16.5-57.7	21.9	42.1

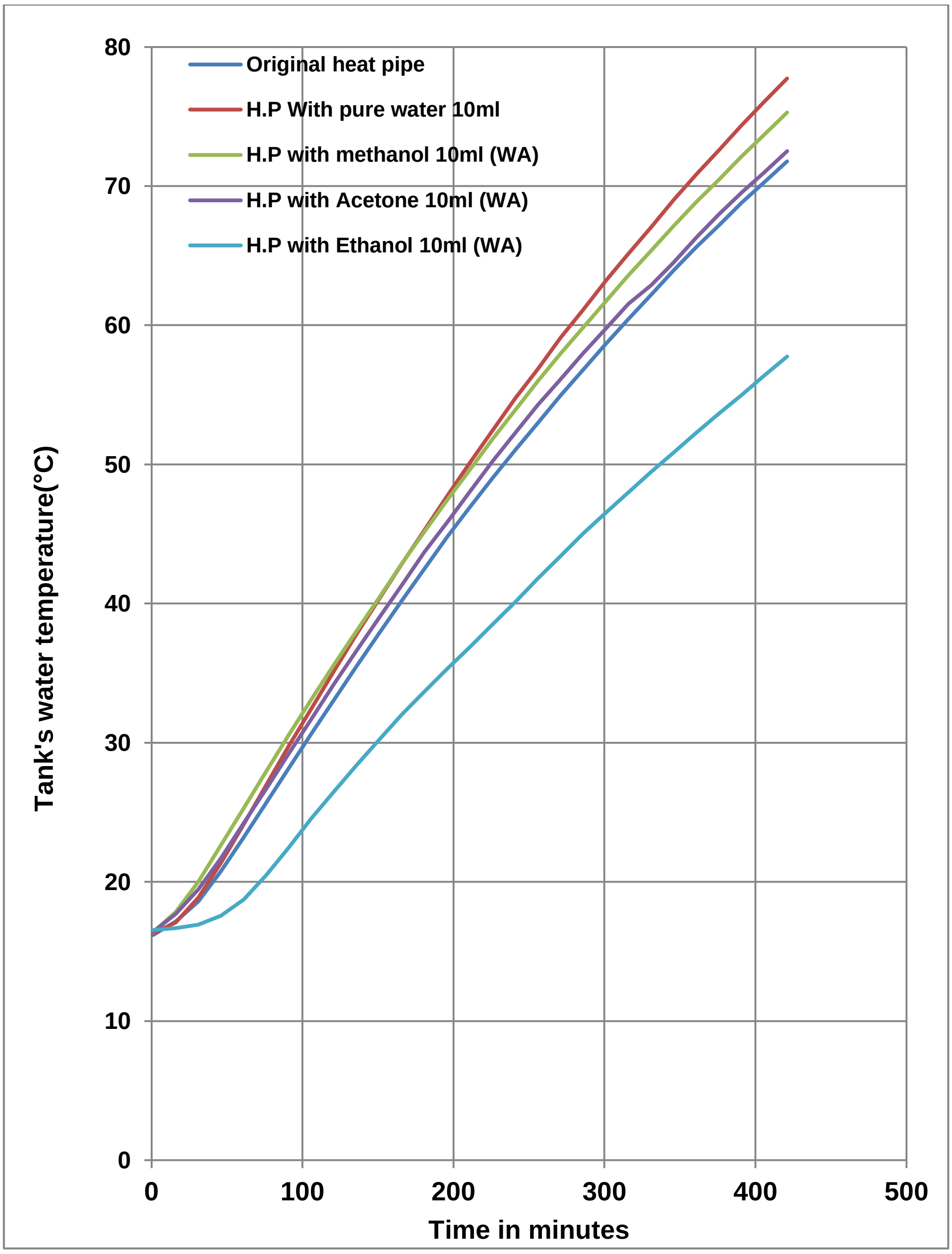

Figure 5.72: Average water temperature in the tank of the testing apparatus for each heat pipe tested containing a different working fluid

The efficiency of each heat pipe, characterised by the working fluid that it contains, is presented for comparison purposes in Figure 5.73. The addition of the average ambient temperature data during each test enables an enhanced or more informed comparison on the performance of the heat pipes. The ambient temperature plays a major role in the heat loss from the tank of the testing apparatus. This fact affects the heat loss from the water tank and hence affects the water's peak average temperature, reflecting in the heat pipe's efficiency calculation.

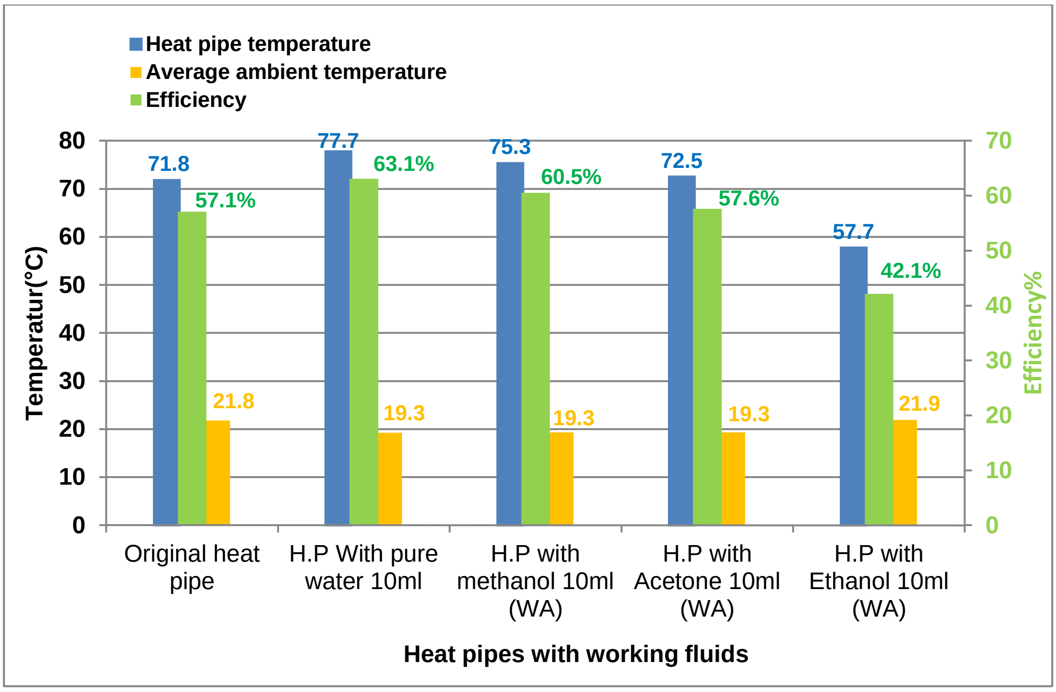

Figure 5.73: Efficiencies of the heat pipe, bulk water temperatures in the heat pipe testing apparatus tank and average ambient temperatures

5.3.2 Discussion of results with the testing apparatus for the heat pipes

The results of the experiments on different working fluids used in the evacuated tube heat pipe have shown that, of all the working fluids chosen in this study, i.e. pure water, methanol, acetone and ethanol, the former three performed well compared to the commercial working fluid.

In terms of ranking their performance, the pure water appeared superior to the others, with a thermal efficiency of 63.1%, followed by Methanol 60.5%, Acetone 57.6%, commercial working fluid 57.1% and Ethanol 42.1%. For a sample calculation of the heat pipe's efficiency in terms of heat transfer to the tank's water see no. 3 in Appendix E.

The averages of ambient temperatures during the tests when using methanol, water and acetone, as working fluids, were equal (19.3 ℃), which was colder/.lower than the average of ambient temperatures when testing with the commercial working fluid and ethanol in the heat pipe (21.8 ℃), as shown in figure 5.73.

It is not expected that such a small change in the ambient temperature would have affected the results significantly because the heat pipe’s testing apparatus had a well-insulated tank. The additional heat losses to the environment (had all experiments been performed at the lower ambient temperature of 19.3℃,) would be minimal and would have resulted in slightly lowering the efficiencies of the two heat pipes containing the commercial fluid and acetone respectively.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Solar water desalination and/or brackish water distillation processes can contribute to the reduction of fossil fuel consumption, rationalization of energy consumption and delivery of potable water . This project focussed on using commercially available state of the art solar water heating technology appropriate for use in remote regions. Solar energy applied to desalination offers a promising solution for covering the fundamental needs of power and water in remote coastal areas, suffering from the absence of the public electric grid and where the potable water scarcity is severe.

6.1 Conclusions

This thesis has contributed a novel approach to producing clean potable water by using the evacuated glass heat pipe technology in a solar energy powered water desalination process. The study illustrated and provided a benchmark on how to implement basic techniques to improve the performance of commercially available state of the art solar powered water heating equipment. The ever improving results of the harvest of potable water, relate to the modifications which have been done during twelve individual experiments.

The project culminated with an experimental parametric study of the performance or thermal efficiency of heat pipes where different fluids have been employed individually as the working fluid. Data from this part of the study provided much needed information to users of heat pipe technology.

The above tasks were accomplished by executing sound engineering procedures in all aspects of the project, from the initial concept to design and construction of the equipment. The experiments that followed were carefully performed and the data gathered was processed yielding reasonable results, by means of very basic thermodynamic and heat transfer principles.

Based upon the results obtained, this research’s objectives and expected outputs as outlined in the introductory chapter in sections 1.4 and 1.5 respectively, have been met.

6.1.1 Desalination unit

This study presents the work associated with the development of a prototype water desalination assembly which was tested within a laboratory. In a series of 12 distinct experiments, a commercially available domestic, evacuated tube (incorporating heat pipes) solar water heating system, with auxiliary equipment such as vacuum and circulating pumps, boiler, condenser etc. was systematically subjected to its components being modified/replaced. New equipment additions as well as process modifications were also made.

Using the science of classical thermodynamics and of heat transfer the performance of the prototype plant was evaluated on the basis of heat balance and energy transfer on the relevant components of the plant.

The following results were noted:

- The original heat exchanger that came with the geyser performed poorly, as water vaporisation could not be achieved since this was not its design function. The heat exchanger was replaced with a custom built heat exchanger which improved conditions in the geyser and water vapour was produced. A water volume of 2230 ml was extracted at normal atmospheric pressures (101.3 kPa).

- To determine if water vaporisation could take place without a heat exchanger, the inlet to the geyser was connected to the outlet of the solar collector's manifold and, conversely, the outlet of the geyser was connected to the inlet of the solar collector's manifold. A slight improvement to the distillate harvest (2415ml) at standard atmospheric pressure was noted.

- The pressure inside the geyser was reduced to 50kPa below atmospheric. This change in pressure resulted in a further improvement (3080ml) of distillate extracted.

- The geyser's outlet vapour pipe diameter was increased from 16 to 76 mm dia, which resulted in further increase in the yield of distillate water (6110 ml), almost double the previous yield at normal atmospheric conditions.

- Following the change in the geyser's outlet vapour pipe diameter, lowering the geyser's pressure to 50 kPa below atmosperic yielded a total of 6300 ml of distilled water. Further reducing the pressure to 70 kPa below atmospheric pressure resulted in a significant increase in the yield (7500 ml) of distilled water.

- Extra insulation material was added to the geyser, which improved the yield of distilled water to 9130 ml at normal atmospheric pressure.

- The system was retested at 50 and 70 kPa below atmospheric pressure and yielded 9550 and 10560 ml of distilled water respectivfely.

- Doubling of the outlet vapour pipe with another 76 mm dia. copper geyser's vapour pipe outlet without additional insulation and at normal atmospheric pressure yielded 8300 ml of distilled water.

- Finally, with further modifications, such as the extra insulation and the testing of the system with the geyser pressure at 70 kPa below atmospheric pressure, a yield of 12750 ml of distilled water was obtained.

The overall outcome of these experiments showed an improvement on the yield of desalinated water from 2230 to 12750 ml, thus raising the efficiency of pure water production from 11% to 38.2%.

6.1.2 Heat pipe experiments

A totally separate, newly designed and constructed apparatus was used to test the performance of a heat pipe with various "working" fluids. The "commercial working fluid" inside the heat pipe was replaced each time with a different "working" fluid and individual experiments were performed. The results of these experiments in terms of the thermal efficiency of the heat pipe were compared as follows:
The heat pipe containing the:

- "Commercial" working fluid – thermal efficiency 57.1%
- "Pure water" – thermal efficiency 63.1%
- "Methanol" – thermal efficiency 60.5%
- "Acetone" – thermal efficiency 57.6%
- "Ethanol" – thermal efficiency 42.1%.

From these experiments it is concluded that the thermal efficiency of the heat pipe was improved by 6% when distilled water was used, as opposed to the commercial working fluid. In the context of the heat pipe being used in an evacuated tube solar energy collector it is expected that such a system will improve its thermal efficiency (compared to the currently commercially available units), with heat pipes containing pure water, methanol or acetone (in this order) as working fluids.

6.2 Recommendations

All the experiments were carried out in the laboratory to avoid weather changes affecting the results. The laboratory was the ideal location for the experiments to be conducted because it facilitated, not only continuous uninterrupted functioning, but also fairly stable (weather proof) environmental conditions; however the prototype needs to be proven in a natural environment. In the natural environment, the condition~~s~~ of solar radiation, amount of daylight hours, weather or environmental conditions and seasonal variations will affect the yield of the distillate.

The system needs high quality insulation materials or perhaps an innovative method or process for reducing heat losses. State of the art insulation in hot water systems is the “geyser blanket” type of insulation which is continuously being improved with insulation materials, raising the “blanket’s” R-value (thermal resistance) to more than 1.25. It is also recommended that the hot water pipes be insulated. There are 2 insulation methods; the first method is using the geyser blanket material. The second method involves using pre-formed pipe sections that can be snapped over the pipes.
Generally, reducing the “geyser’s” pressure below atmospheric levels will enhance the harvest of distillate, as vapour will be forming earlier at lower temperatures, which is useful, for example during times when the Sun’s radiation is not sufficient. It is important to monitor the geyser to avoid its collapse during suction of the air out of it when reducing the system’s pressure. Attention should be directed toward strengthening the cylindrical vessel to avoid possible implosion of the “geyser” as a result of too much vacuum.

The experiments of solar desalination using evacuated tubes heat pipe technology requires specific and stringent safety measures to ensure the preservation of the glass tubes from breakage as a result of an accidental drop of a heavy object on the solar energy collector or during experiments, exposure to excessively intense light from the halogen lamps.

The results from the experiments indicated that the diameter of the outlet pipe for the extraction of the vapour from the geyser, plays a significant role in the harvest or production of pure potable water. The recommendation is to increase considerably the diameter of this pipe, so as to avoid restricting the vapour flow, thus enabling the production of distilled water at higher rates.

Finally, the aspect of different geometrical features inside the heat pipe, for example grooves, metal inserts, or wick materials could also be explored. Furthermore, a wider variety of “working” fluids could also be experimented with, and their performance compared to the currently commercially available heat pipe’s “working” fluid.

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APPENDIXES

Appendix A

Technical data for the evacuated tubes and heat pipe of the collector

1. Technical data – evacuated tube

Model	58/1800
Glass material	High-quality borosilicate glass 3.3
Outer glass tube diameter	58mm
Inner glass tube diameter	47mm
Outer glass tube length	1800mm
Glass wall thickness	2mm
Single tube weight	2.9Kg
High vacuum long-term stability	≤ 2X10-3 Pa
Absorption coefficient	Graded SS-ALNAL/Cu
Emittance	> 94%
Heat loss	< 6% (80°C)
Heat pipe type	$< 0.8 W/m^2 °C$
Heat pipe material	High efficiency extended lifetime
Heat pipe fluid	Non outgassing water based fluid (non-acetone)
Stagnation temperature	25 °C
Start-up temperature	250 °C
Start-up time	< 2 min
Freezing tolerance	-35 °C
Pressure resistance	6 bar
Hail resistance	Ø 25mm
Wind resistance	30m/s
Heat impact resistance	Damage 3 time alternating impact 25°C and 90°C

2. Technical data – evacuated tube heat pipe collectors

Model	ITS-58/1800-12
Evacuated tube heat pipe type	58/1800
Number of tubes	12
Manifold material	High purity copper
Connecting ports	2 x 22mm copper pipe
Manifold casing	Baked epoxy coated Aluminium Extrusion
Fitment area (m)	1m x 2m
Output power (yearly average kWh/day for Cape Town)	4.8

Appendix B

The detailed description of measuring instruments and auxiliary equipment

1. Circulating pump

The circulation pump has been installed (model type: GPD 20-6SB). Water is pumped between the geyser and solar collector manifold. The pump has three different speeds to control the flow of water into the system; maximum working pressure ten bar, while maximum working temperature for open system is 65 $^{\circ}C$ and for closed systems 110 ^{0}C (see Figure B.1).

Figure B.1: Circulating pump

Circulating pump technical data

Pump model	GPD 20-6SB	Input power (P1)	55W / 70W / 100W
Power supply	1Ph / 230v	Full load Amps	0.25 / 0.35 / 0.45
Inlet/outlet	20mm Bspm (union)	Max working press	10 bar
Weight (Kg)	2.75	Dimensions (mm)	130 x 130 x 130

2. Flow Meter

A TACOSETTER INLINE 100/130 flow meter is used for flow measurement and flow control into the system, as shown in Figure B.2

A. Facilitating easy direct reading of the set volume flow in l/min by means of a glycol scale, where temperature-resistance extends to 130 ℃.

B. Direct connection to a circulating pump.

C. A variable installation position controls the flow by means of a set-point adjuster.

D. Direct hydraulic balancing and control of flows at the intake manifold of circulating pumps.

E. Balancing valves allow an easy and accurate method of adjusting flow rates.

Figure B.2: Flow meter

3. Variable voltage transformer-Variac

The variable model: SB-10 incorporates a silicon steel loop, which is wrapped with copper wire, and allows the voltage output to be controlled as shown in Figure B.3

The specifications of the variable

Max. current	Capacity	Mount	Dimension H x Ø	Net (Weight)
10 A	2 KVA	5	156 X 235 mm	11 Kg.

Applications

A. Voltage Testing.

B. For electrical equipment that requires constant voltage (Prevent fluctuation in a distribution line).

C. Set your meter (calibration meters).

D. Use a variable-speed drive (smooth starter and speed adjustment for motor).

Main Characteristics

A. Provides smooth power.

B. Power factor equal to the conventional transformer.

C. Constant water pressure.

D. High performance.

E. Immediate response adjustments (rapid response).

F. The temperature slowly increases.

G. Robust structure made of steel.

Figure B.3: Variable Voltage Transformer-Variac

4. Solar Power Meter

Solar insolation is measured using a solar power meter (TES-1333) which is commonly used in meteorology, solar radiation measurement, solar power research, physics and optical laboratories, and solar transmission measurement as shown in Figure B.4

Figure B.4: Solar Power Meter

Specifications of the solar power meter

Display	3-1/2 digits.Max.indication1999
Range	2000 W/m 2 、634Btu/(ft 2 * h)
Resolution	1W/m2、1Btu/(ft2*h)
Spectral response	400-1100 nm
Accuracy	Typically within ± 10 W/m2 [±3 Btu / (ft2*h)] or ±5% , whichever is greater in sunlight; Additional temperature induced error ±0.38 W/m2 / ℃ [±0.12 Btu / (ft2*h)/ ℃] from 25 ℃
Angular accuracy	Cosine corrected <5% for angles <60 °
Drift	<±2% / per year
Calibration	User recalibration available
Over-input	Display shows" OL "
Sampling time	Approx. 0.4 second
Manu data memory and read	99 sets
Auto data memory	32000 sets (TES-1333R)
Battery	4pcs size AAA
Battery life	Approx. 100 hours
Operating temp and humidity	0 ℃ to 50 ℃below 80%RH
Storage temp and humidity	-10 ℃ to 60 ℃ below 70% RH
Weight	Approx. 165 g
Dimension	111(L)*64(W)*34(H)mm
Accessories	Carrying Case, Operation Manual, 4 pcs size AAA, RS232 cable(for TES-1333R), CD software (For TES-1333R)

5. The Data Logger

The data logger (Agilent 34972A) has been installed and consists of a three-aperture mainframe, complete with a built-in 6½ digit DMM and eight different switch and control modules. The device features built-in LAN and USB interfaces, which can connect it to any computer (PC or laptop) easily. The device has intuitive graphical web interface, and can be used remotely to record and monitor all data required. Using a flash drive, data can be uploaded (for example from the BenchLink Data Logger) into the 34972A and transferred to a computer, and imported into various applications for data analysis (see Figure B.5)

Figure B.5: Agilent 34972A Data Acquisition

6. The Thermocouples

A set of J-type thermocouples of were installed in both the experimental solar desalination prototype and the heat pipe tester, which were connected to the data logger (see Figure B.6).

Figure B.6: J type thermocouple

7. Rotary Vane Vacuum Pump

The vacuum pump uses an oil-sealed rotary operation, system consisting of two parts, is manufactured with the most recent techniques and designed especially to provide air cooling and refrigeration service. A 2f-3 Vacuum Pump was used to reduce the internal geyser pressure (see Figure B.7&8).

Design features

A. A compact construction: simple design and easy operation.
B. Ergonomic handle: Easy to carry and use.
C. Motor: Thermally protected.
D. Integrated gas ballast valve: It Helps keep the pump oil clean for a longer time.
E. Oil forced lubrication: Useful for long operation duration.
F. Anti-suck back valve: A safety feature prevents pump oil from being sucked into the system when the pump stops.

Figure B.7: Rotary vane vacuum pump

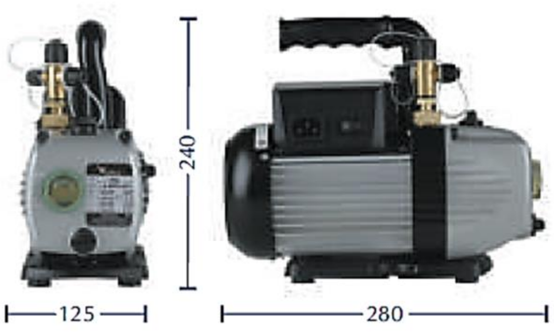

Figure B.8: Vacuum pump dimensions

The specifications of rotary vacuum pump, (www.telstar-vacuum.com)

Features	Units	Specifications
Free air displacement at 50/60 Hz	M^3/h	3/3.6
Number of stages		2
Factory vacuum rating	HPa/microns	0,03/25
Multi intake fittings		1/4” SAE
Nominal power	kW	0.18
Voltage 230V 50/60 Hz	rpm	2800/3360
Weight (with oil)	kg	7
Oil capacity	litres	0.3
Dimensions	mm	280x240x125

8. Pressure gauge

In order to help establish low and high pressure in the prototype, a vacuum pressure gauge was installed in the system (see Figure B.8).

Figure B.8: Vacuum pressure gauge

Appendix C

Data collected during the desalination prototype experiments

T_{m1} and T_{m2} are the inlet and outlet temperatures (in degrees centigrade), of the collector's manifold.

$T_{g\ Avg}$. is the average temperature from four locations in the geyser (T_{g1}, T_{g2}, T_{g3} and T_{g4}) were recorded hourly and used to calculate the amount of heat transferred. As shown in Figure C.1

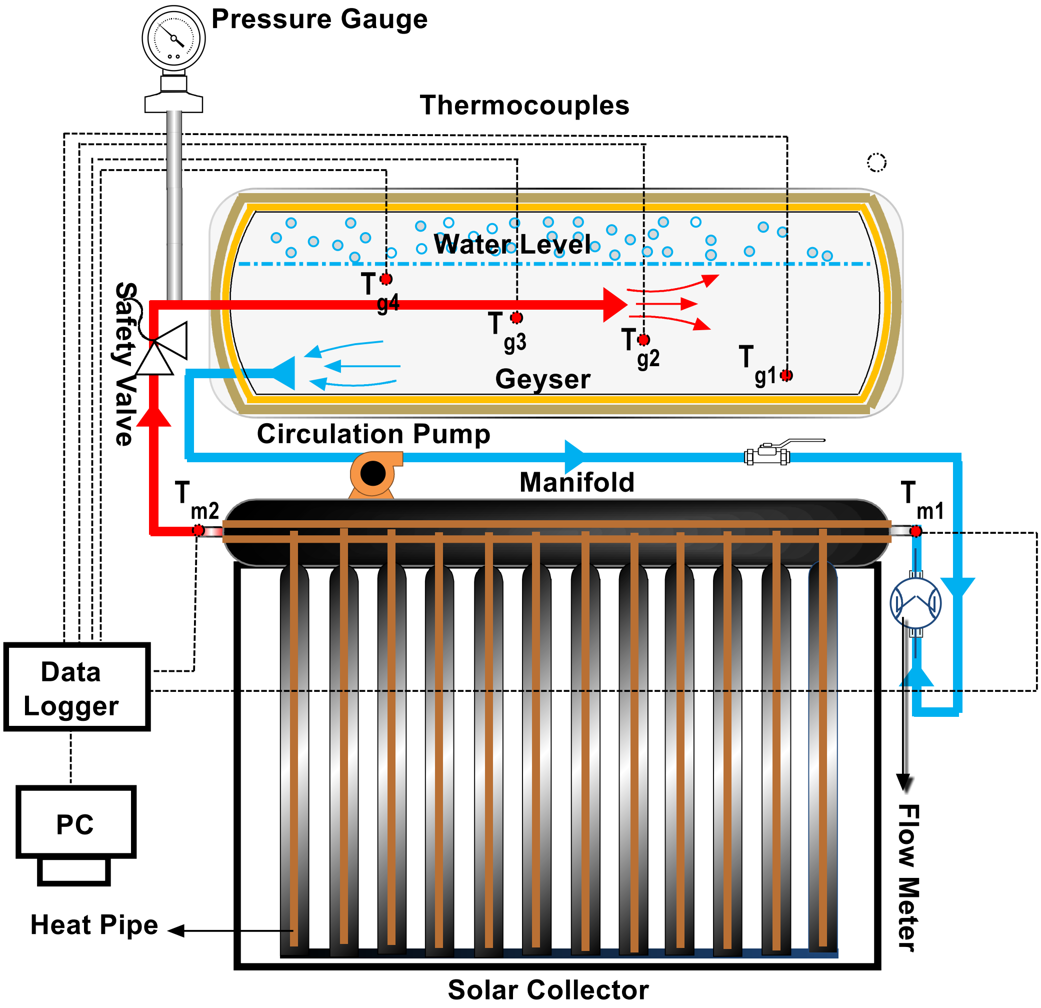

Figure C.1: Thermocouples' positions in the schematic diagram of the prototype solar water desalination plant

Experiment no. 1 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
07/05/2014 09:28:25:748	21.0	21.0	21.0	21.0	21.0	21.0	21.0	**00**
07/05/2014 10:28:25:748	30.7	32.6	25.9	25.3	25.5	25.5	25.6	
07/05/2014 11:28:25:748	35.1	37.0	30.7	30.1	30.3	30.3	30.4	
07/05/2014 12:28:25:748	40.7	42.6	36.7	36.3	36.3	36.3	36.4	
07/05/2014 13:28:25:748	45.5	47.4	41.7	41.3	41.1	41.3	41.3	
07/05/2014 14:28:25:748	49.6	51.5	46.0	45.8	45.8	45.8	45.9	
07/05/2014 15:28:25:748	54.0	55.9	50.8	50.6	50.6	50.6	50.6	
07/05/2014 16:28:25:748	57.4	59.2	54.4	54.0	53.6	54.0	54.0	
08/05/2014 09:28:25:748	46.0	46.0	46.0	46.0	46.0	46.0	46.0	**00**
08/05/2014 10:28:25:748	53.3	55.2	50.5	50.1	49.6	50.1	50.1	
08/05/2014 11:28:25:748	56.9	58.8	53.9	53.7	53.2	53.5	53.6	
08/05/2014 12:28:25:748	61.3	63.2	58.7	58.3	58.1	58.3	58.3	
08/05/2014 13:28:25:748	64.7	66.5	62.2	61.8	62.0	61.8	62.0	
08/05/2014 14:28:25:748	68.2	70.1	65.8	65.4	65.8	65.4	65.6	
08/05/2014 15:28:25:748	72.0	73.8	69.6	69.4	69.6	69.4	69.5	
08/05/2014 16:28:25:748	74.8	76.6	72.7	72.4	72.5	72.4	72.5	
09/05/2014 09:28:25:748	60.0	60.0	60.0	60.0	60.0	60.0	60.0	**00**
09/05/2014 10:28:25:748	65.6	67.3	63.2	63.0	62.8	62.8	62.9	
09/05/2014 11:28:25:748	68.8	70.7	66.6	66.4	66.2	66.2	66.3	
09/05/2014 12:28:25:748	71.4	73.3	69.4	69.0	69.2	69.0	69.1	
09/05/2014 13:28:25:748	74.4	76.3	72.2	72.0	72.2	71.8	72.0	
09/05/2014 14:28:25:748	76.4	78.3	74.4	74.2	74.4	74.0	74.2	
09/05/2014 15:28:25:748	80.0	81.8	78.1	77.8	77.9	77.8	77.9	
09/05/2014 16:28:25:748	83.4	85.2	81.5	81.1	81.5	81.1	81.3	
10/05/2014 09:28:25:748	65.0	65.0	65.0	65.0	65.0	65.0	65.0	**00**
10/05/2014 10:28:25:748	71.2	72.8	68.9	68.7	68.7	68.7	68.8	
10/05/2014 11:28:25:748	73.6	75.3	71.4	71.2	71.0	71.0	71.1	
10/05/2014 12:28:25:748	76.8	78.7	74.7	74.6	74.6	74.4	74.6	
10/05/2014 13:28:25:748	79.6	81.4	77.5	77.2	77.3	77.2	77.3	
10/05/2014 14:28:25:748	82.2	84.0	80.3	80.0	80.1	80.0	80.1	
10/05/2014 15:28:25:748	84.6	86.4	82.5	82.4	82.5	82.4	82.5	
10/05/2014 16:28:25:748	86.8	88.7	85.1	84.8	85.0	84.8	84.9	
11/05/2014 09:28:25:748	70.0	70.0	70.0	70.0	70.0	70.0	70.0	**00**
11/05/2014 10:28:25:748	74.9	76.8	72.9	72.7	72.7	72.5	72.7	
11/05/2014 11:28:25:748	77.2	78.8	75.1	74.7	74.7	74.7	74.8	
11/05/2014 12:28:25:748	79.6	81.4	77.7	77.3	77.5	77.3	77.5	
11/05/2014 13:28:25:748	83.0	84.8	81.1	80.7	80.9	80.7	80.9	
11/05/2014 14:28:25:748	84.6	86.4	82.7	82.5	82.9	82.4	82.6	
11/05/2014 15:28:25:748	88.0	89.8	85.3	85.5	85.4	85.6	85.5	
11/05/2014 16:28:25:748	90.2	92.0	88.3	88.3	88.3	88.1	88.3	
							Total	**00**

Experiment no. 2 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
04/06/2014 09:28:25:748	23.0	23.0	23.0	23.0	23.0	24.0	23.3	**0**
04/06/2014 10:28:25:748	32.0	33.2	25.9	26.1	25.9	26.1	26.0	
04/06/2014 11:28:25:748	37.3	38.2	31.9	31.8	31.8	31.7	31.8	
04/06/2014 12:28:25:748	41.7	43.0	37.8	37.7	37.9	37.8	37.8	
04/06/2014 13:28:25:748	47.2	48.1	43.8	43.7	43.7	43.6	43.7	
04/06/2014 14:28:25:748	52.1	53.4	49.7	49.6	49.5	49.6	49.6	
04/06/2014 15:28:25:748	57.3	58.2	55.6	55.5	55.5	55.4	55.5	
04/06/2014 16:28:25:748	61.8	63.1	61.3	61.3	61.3	61.3	61.3	
05/06/2014 09:28:25:748	53.0	53.0	53.0	53.0	53.0	53.0	53.0	**0**
05/06/2014 10:28:25:748	59.4	60.2	56.0	55.6	55.6	55.5	55.7	
05/06/201411:28:25:748	64.1	64.9	60.7	60.4	60.2	60.2	60.4	
05/06/2014 12:28:25:748	68.1	68.8	64.9	64.7	64.8	64.8	64.8	
05/06/2014 13:28:25:748	72.5	73.2	69.3	69.1	68.9	68.9	69.1	
05/06/2014 14:28:25:748	76.0	76.7	73.4	73.5	72.8	72.8	73.1	
05/06/2014 15:28:25:748	80.0	80.6	77.2	77.0	76.9	76.9	77.0	
05/06/2014 16:28:25:748	83.4	84.1	80.8	80.4	80.4	80.2	80.4	
06/06/2014 09:28:25:748	70.6	70.6	70.6	70.6	70.6	70.6	70.6	**0**
06/06/2014 10:28:25:748	74.3	74.8	71.7	71.6	71.5	71.7	71.6	
06/06/2014 11:28:25:748	78.3	79.1	75.5	75.3	75.3	75.3	75.4	
06/06/2014 12:28:25:748	81.3	82.0	78.8	78.8	78.8	78.8	78.8	
06/06/2014 13:28:25:748	84.9	85.7	82.3	82.3	82.1	82.1	82.2	
06/06/2014 14:28:25:748	88.4	89.1	85.8	85.4	85.8	85.4	85.6	
06/06/2014 15:28:25:748	91.8	92.5	88.8	89.0	88.8	88.8	88.9	
06/06/2014 16:28:25:748	93.9	94.6	91.5	91.3	90.6	91.1	91.1	
07/06/2014 09:28:25:748	77.8	77.8	77.8	77.8	77.8	77.8	77.8	**880**
07/06/2014 10:28:25:748	82.0	82.7	79.2	78.8	78.8	78.8	78.9	
07/06/2014 11:28:25:748	85.7	86.3	83.0	82.6	82.6	82.6	82.7	
07/06/2014 12:28:25:748	89.5	90.2	86.9	86.5	86.7	86.5	86.6	
07/06/2014 13:28:25:748	92.7	93.4	90.1	90.0	89.9	89.9	90.0	
07/06/2014 14:28:25:748	95.8	96.5	93.6	93.2	93.0	93.0	93.2	
07/06/2014 15:28:25:748	98.0	98.5	96.1	95.8	95.6	95.6	95.8	
07/06/2014 16:28:25:748	98.4	99.1	96.9	96.5	96.5	96.5	96.6	
08/06/2014 09:28:25:748	79.9	79.9	79.9	79.9	79.9	79.9	79.9	**1350**
08/06/2014 10:28:25:748	84.6	85.4	80.9	80.9	80.9	80.9	80.9	
08/06/2014 11:28:25:748	87.4	88.2	84.5	84.9	84.5	84.5	84.6	
08/06/2014 12:28:25:748	91.1	91.9	88.5	88.8	88.5	88.7	88.6	
08/06/2014 13:28:25:748	93.7	94.5	92.6	92.7	92.6	92.7	92.6	
08/06/2014 14:28:25:748	97.3	98.0	96.3	96.3	96.3	96.3	96.3	
08/06/2014 15:28:25:748	98.1	98.9	97.6	97.4	97.4	97.3	97.4	
08/06/2014 16:28:25:748	98.1	98.8	97.8	97.7	97.7	97.7	97.7	
							Total	**2230**

Experiment no. 3 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
02/09/2014 09:30:00:000	22.2	22.2	22.2	22.2	22.2	22.2	22.2	**0**
02/09/2014 10:30:00:000	27.2	28.4	27.2	27.2	27.4	27.4	27.3	
02/09/2014 11:30:00:000	33.6	34.8	33.5	33.5	33.3	33.5	33.5	
02/09/2014 12:30:00:000	39.3	40.4	39.5	39.6	39.8	39.6	39.6	
02/09/2014 13:30:00:000	45.2	46.3	45.7	45.7	45.6	45.7	45.7	
02/09/2014 14:30:00:000	50.8	52.0	51.6	51.7	51.8	51.5	51.6	
02/09/2014 15:30:00:000	56.5	57.6	57.3	57.3	57.3	57.3	57.3	
02/09/2014 16:30:00:000	61.4	62.5	62.3	62.3	62.3	62.3	62.3	
03/09/2014 09:30:00:000	53.5	53.5	53.5	53.5	53.5	53.5	53.5	**0**
03/09/2014 10:30:00:000	58.5	59.5	58.6	58.2	58.6	58.6	58.5	
03/09/2014 11:30:00:000	63.6	64.6	63.5	63.3	63.6	63.6	63.5	
03/09/2014 12:30:00:000	68.1	69.1	68.1	68.0	68.3	68.3	68.2	
03/09/2014 13:30:00:000	72.6	73.6	72.2	72.6	73.0	72.6	72.6	
03/09/2014 14:30:00:000	77.1	78.1	76.5	76.9	77.3	76.9	76.9	
03/09/2014 15:30:00:000	81.2	82.2	80.8	81.2	81.4	81.4	81.2	
03/09/2014 16:30:00:000	84.5	85.5	84.1	84.7	84.9	84.9	84.7	
04/09/2014 09:30:00:000	70.9	70.9	70.9	70.9	70.9	70.9	70.9	**0**
04/09/2014 10:30:00:000	74.6	75.6	74.3	74.7	74.7	74.7	74.6	
04/09/2014 11:30:00:000	78.8	79.8	78.6	78.8	78.9	78.8	78.8	
04/09/2014 12:30:00:000	82.7	83.7	82.5	82.8	82.8	82.7	82.7	
04/09/2014 13:30:00:000	86.5	87.5	86.4	86.7	86.7	86.6	86.6	
04/09/2014 14:30:00:000	90.0	91.0	89.9	90.3	90.3	90.3	90.2	
04/09/2014 15:30:00:000	93.3	94.3	93.2	93.6	93.8	93.6	93.5	
04/09/2014 16:30:00:000	96.7	97.7	96.5	96.7	96.9	96.9	96.8	
05/09/2014 09:30:00:000	78.8	78.8	78.8	78.8	78.8	78.8	78.8	**685**
05/09/2014 10:30:00:000	81.6	82.6	81.4	81.5	81.7	81.7	81.6	
05/09/2014 11:30:00:000	85.3	86.2	84.9	85.3	85.4	85.3	85.2	
05/09/2014 12:30:00:000	88.6	89.5	88.6	89.0	89.0	89.0	88.9	
05/09/2014 13:30:00:000	92.3	93.2	91.9	92.3	92.5	92.5	92.3	
05/09/2014 14:30:00:000	95.6	96.6	95.0	95.6	95.6	95.6	95.5	
05/09/2014 15:30:00:000	98.5	99.5	98.2	98.7	98.7	98.7	98.6	
05/09/2014 16:30:00:000	99.9	100.8	100.0	100.0	100.0	100.0	100.0	
06/09/2014 09:30:00:000	82.1	82.1	82.1	82.1	82.1	82.1	82.1	**1730**
06/09/2014 10:30:00:000	85.3	86.2	84.9	84.9	84.9	84.9	84.9	
06/09/2014 11:30:00:000	89.0	89.9	88.6	88.6	88.8	88.6	88.6	
06/09/2014 12:30:00:000	92.5	93.4	92.5	92.5	92.5	92.5	92.5	
06/09/2014 13:30:00:000	96.0	96.9	96.3	96.3	96.2	96.2	96.2	
06/09/2014 14:30:00:000	99.3	100.2	99.5	99.5	99.5	99.5	99.5	
06/09/2014 15:30:00:000	99.8	100.8	99.7	99.8	99.8	99.8	99.8	
06/09/2014 16:30:00:000	99.8	100.8	100.0	100.0	100.0	100.0	100.0	
							Total	**2415**

Experiment no. 4 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
18/09/2014 09:30:00:000	19.0	19.1	19.0	19.0	19.0	19.0	19.0	**0**
18/09/2014 10:30:00:000	24.5	25.5	24.1	24.1	24.5	24.5	24.3	
18/09/2014 11:30:00:000	30.4	31.5	30.1	30.1	30.2	30.3	30.2	
18/09/2014 12:30:00:000	36.8	37.8	36.0	36.0	36.0	36.1	36.0	
18/09/2014 13:30:00:000	42.1	43.2	41.6	41.5	42.3	42.1	41.9	
18/09/2014 14:30:00:000	47.6	48.7	47.4	47.6	47.8	47.7	47.6	
18/09/2014 15:30:00:000	52.9	54.0	53.3	53.3	53.2	53.3	53.3	
18/09/2014 16:30:00:000	58.0	59.1	58.9	58.9	58.9	58.8	58.9	
19/09/2014 09:30:00:000	51.6	51.6	51.6	51.6	51.6	51.6	51.6	**0**
19/09/2014 10:30:00:000	56.3	57.3	56.1	56.1	56.3	56.3	56.2	
19/09/2014 11:30:00:000	61.0	62.1	60.8	61.0	61.0	61.2	61.0	
19/09/2014 12:30:00:000	65.5	66.6	65.3	65.7	65.7	65.7	65.6	
19/09/2014 13:30:00:000	74.5	75.5	69.8	70.4	70.4	70.4	70.2	
19/09/2014 14:30:00:000	74.5	75.6	74.5	74.9	74.9	74.9	74.8	
19/09/2014 15:30:00:000	78.6	79.7	78.4	78.9	78.9	78.8	78.8	
19/09/2014 16:30:00:000	82.5	83.6	82.1	82.7	82.7	82.7	82.5	
20/09/2014 09:30:00:000	69.3	69.3	69.3	69.3	69.3	69.3	69.3	**200**
20/09/2014 10:30:00:000	73.2	74.1	72.4	73.0	73.0	73.2	72.9	
20/09/2014 11:30:00:000	77.3	78.0	76.5	77.1	77.1	77.1	77.0	
20/09/2014 12:30:00:000	81.2	81.9	80.2	81.0	81.0	81.0	80.8	
20/09/2014 13:30:00:000	84.7	85.6	84.1	84.7	84.7	84.7	84.6	
20/09/2014 14:30:00:000	88.4	89.1	87.7	88.4	88.4	88.4	88.2	
20/09/2014 15:30:00:000	91.5	92.3	91.0	91.7	91.7	91.7	91.5	
20/09/2014 16:30:00:000	94.5	95.2	93.8	94.3	94.3	94.3	94.2	
21/09/2014 09:30:00:000	78.0	78.0	78.0	78.0	78.0	78.0	78.0	**880**
21/09/2014 10:30:00:000	81.7	82.5	81.2	81.7	81.7	81.9	81.6	
21/09/2014 11:30:00:000	85.6	86.4	84.9	85.6	85.6	85.6	85.4	
21/09/2014 12:30:00:000	89.1	89.9	87.8	89.1	89.1	89.3	88.9	
21/09/2014 13:30:00:000	92.5	93.2	91.5	92.1	92.5	92.5	92.1	
21/09/2014 14:30:00:000	95.2	96.0	94.5	95.0	95.2	95.2	95.0	
21/09/2014 15:30:00:000	97.6	98.4	96.9	97.4	97.6	97.4	97.4	
21/09/2014 16:30:00:000	99.7	100.4	98.7	99.7	99.7	99.7	99.4	
22/09/2014 09:30:00:000	81.2	81.2	81.2	81.2	81.2	81.2	81.2	**2000**
22/09/2014 10:30:00:000	84.3	85.4	84.1	84.3	84.3	84.5	84.3	
22/09/2014 11:30:00:000	87.7	88.8	87.1	87.7	87.8	88.0	87.7	
22/09/2014 12:30:00:000	90.8	91.9	90.4	90.8	91.0	91.2	90.9	
22/09/2014 13:30:00:000	93.2	94.3	93.0	93.2	93.2	93.4	93.2	
22/09/2014 14:30:00:000	95.4	96.5	94.7	95.4	95.4	95.6	95.3	
22/09/2014 15:30:00:000	97.4	98.6	96.7	97.4	97.6	97.6	97.4	
22/09/2014 16:30:00:000	99.5	100.6	99.3	99.5	99.5	99.5	99.4	
							Total	**3080**

Experiment no. 5 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
17/11/2014 09:29:31:985	21.6	21.6	21.6	21.6	21.6	21.6	21.6	**40**
17/11/2014 10:29:31:985	26.9	28.0	26.7	26.6	26.7	26.8	26.7	
17/11/2014 11:29:31:985	33.0	34.1	32.8	32.7	32.8	32.9	32.8	
17/11/2014 12:29:31:985	38.9	39.9	38.6	38.6	38.7	38.8	38.7	
11/17/2014 13:29:31:985	44.6	45.7	44.4	44.3	44.5	44.6	44.4	
17/11/2014 14:29:31:985	50.2	51.2	50.0	50.0	50.1	50.2	50.1	
17/11/2014 15:29:31:985	55.5	56.5	55.4	55.3	55.4	55.5	55.4	
17/11/2014 16:29:31:985	60.6	61.6	60.5	60.4	60.5	60.7	60.5	
18/11/2014 09:29:31:985	54.0	54.0	54.0	54.0	54.0	54.0	54.0	**420**
18/11/2014 10:29:31:985	58.9	59.9	58.7	58.7	58.7	58.8	58.7	
11/18/2014 11:29:31:985	63.6	64.5	63.5	63.4	63.5	63.6	63.5	
18/11/2014 12:29:31:985	68.2	69.1	68.1	68.0	68.1	68.2	68.1	
18/11/2014 13:29:31:985	72.6	73.5	72.5	72.4	72.5	72.6	72.5	
18/11/2014 14:29:31:985	76.8	77.7	76.7	76.6	76.7	76.8	76.7	
11/18/2014 15:29:31:985	80.8	81.7	80.7	80.7	80.8	80.9	80.8	
18/11/2014 16:29:31:985	84.7	85.6	84.6	84.6	84.7	84.8	84.7	
19/11/2014 09:29:31:985	71.5	71.5	71.5	71.5	71.5	71.5	71.5	**950**
19/11/2014 10:29:31:985	75.3	76.2	75.2	75.2	75.3	75.3	75.3	
19/11/2014 11:29:31:985	79.3	80.2	79.2	79.2	79.3	79.3	79.2	
19/11/2014 12:29:31:985	83.0	83.9	83.0	83.0	83.0	83.1	83.0	
19/11/2014 13:29:31:985	86.7	87.6	86.6	86.6	86.7	86.8	86.7	
19/11/2014 14:29:31:985	90.2	91.0	90.1	90.1	90.2	90.2	90.1	
19/11/2014 15:29:31:985	93.5	94.3	93.4	93.4	93.5	93.6	93.5	
19/11/2014 16:29:31:985	96.6	97.5	96.6	96.6	96.7	96.7	96.6	
20/11/2014 09:29:31:985	78.8	78.8	78.8	78.8	78.8	78.8	78.8	**1380**
20/11/2014 10:29:31:985	81.9	82.8	81.8	81.8	81.9	81.9	81.9	
20/11/2014 11:29:31:985	85.3	86.1	85.2	85.2	85.3	85.4	85.3	
20/11/2014 12:29:31:985	88.6	89.4	88.5	88.4	88.5	88.6	88.5	
20/11/2014 13:29:31:985	91.7	92.4	91.6	91.5	91.6	91.7	91.6	
20/11/2014 14:29:31:985	94.6	95.3	94.5	94.5	94.5	94.6	94.5	
20/11/2014 15:29:31:985	97.4	98.1	97.3	97.3	97.4	97.4	97.3	
20/11/2014 16:29:31:985	99.8	100.5	99.7	99.8	99.8	99.8	99.8	
21/11/2014 09:29:31:985	80.6	80.6	80.6	80.6	80.6	80.6	80.6	**3320**
21/11/2014 10:29:31:985	84.0	84.9	83.9	83.8	83.9	84.0	83.9	
21/11/2014 11:29:31:985	87.9	88.8	87.9	87.8	87.9	88.0	87.9	
21/11/2014 12:29:31:985	91.7	92.6	91.6	91.6	91.6	91.8	91.7	
21/11/2014 13:29:31:985	95.3	96.2	95.2	95.2	95.2	95.4	95.3	
21/11/2014 14:29:31:985	98.6	99.5	98.6	98.6	98.6	98.7	98.6	
21/11/2014 15:29:31:985	99.8	100.7	99.7	99.8	99.8	99.8	99.8	
21/11/2014 16:29:31:985	99.8	100.7	99.9	99.9	99.9	99.9	99.9	
							Total	**6110**

Experiment no. 6 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg}$.	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
06/04/2015 09:23:16:907	22.8	22.8	22.8	22.8	22.8	22.8	22.8	**0**
06/04/2015 10:23:16:907	28.2	29.4	27.9	27.9	28.1	27.8	27.9	
06/04/2015 11:23:16:907	34.5	35.8	34.3	34.3	34.5	34.2	34.3	
06/04/2015 12:23:16:907	40.6	41.8	40.3	40.4	40.6	40.4	40.4	
06/04/2015 13:23:16:907	46.7	47.8	46.4	46.4	46.6	46.5	46.5	
06/04/2015 14:23:16:907	52.2	53.4	52.0	52.0	52.3	52.1	52.1	
06/04/2015 15:23:16:907	57.8	58.9	57.5	57.6	57.7	57.6	57.6	
06/04/2015 16:23:16:907	62.8	63.9	62.6	62.7	62.9	62.7	62.7	
07/04/2015 09:23:16:907	53.9	53.9	53.9	53.9	53.9	53.9	53.9	**400**
07/04/2015 10:23:16:907	57.0	58.2	56.8	56.8	57.0	56.8	56.8	
07/04/2015 11:23:16:907	61.9	63.0	61.7	61.8	62.0	61.8	61.8	
07/04/2015 12:23:16:907	66.6	67.7	66.4	66.5	66.6	66.5	66.5	
07/04/2015 13:23:16:907	71.0	72.1	70.9	70.9	71.1	71.0	71.0	
07/04/2015 14:23:16:907	75.3	76.4	75.1	75.2	75.3	75.2	75.2	
07/04/2015 15:23:16:907	79.4	80.5	79.2	79.3	79.4	79.4	79.3	
07/04/2015 16:23:16:907	83.3	84.4	83.2	83.3	83.4	83.4	83.3	
08/04/2015 09:23:16:907	68.5	68.5	68.5	68.5	68.5	68.5	68.5	**900**
08/04/2015 10:23:16:907	70.2	71.4	70.0	70.0	70.2	70.0	70.1	
08/04/2015 11:23:16:907	74.6	75.7	74.4	74.4	74.6	74.5	74.5	
08/04/2015 12:23:16:907	78.7	79.7	78.5	78.6	78.7	78.6	78.6	
08/04/2015 13:23:16:907	82.5	83.6	82.4	82.4	82.6	82.5	82.5	
08/04/2015 14:23:16:907	86.2	87.2	86.1	86.1	86.3	86.2	86.2	
04/08/2015 15:23:16:907	89.8	90.9	89.7	89.8	90.0	89.9	89.9	
08/04/2015 16:23:16:907	93.3	94.4	93.2	93.3	93.5	93.4	93.4	
09/04/2015 09:23:16:907	74.1	74.1	74.1	74.1	74.1	74.1	74.1	**1700**
09/04/2015 10:23:16:907	76.6	77.6	76.4	76.4	76.6	76.4	76.4	
09/04/2015 11:23:16:907	80.6	81.6	80.4	80.5	80.6	80.5	80.5	
09/04/2015 12:23:16:907	84.3	85.4	84.2	84.3	84.5	84.4	84.3	
09/04/2015 13:23:16:907	88.1	89.1	87.9	88.0	88.2	88.1	88.0	
09/04/2015 14:23:16:907	91.6	92.6	91.4	91.5	91.7	91.6	91.6	
09/04/2015 15:23:16:907	95.0	96.0	94.8	94.9	95.1	95.0	95.0	
09/04/2015 16:23:16:907	98.2	99.2	98.1	98.1	98.3	98.2	98.2	
10/04/2015 09:23:16:907	77.0	77.0	77.0	77.0	77.0	77.0	77.0	**3300**
10/04/2015 10:23:16:907	78.9	79.9	78.7	78.8	78.9	78.9	78.8	
10/04/2015 11:23:16:907	83.0	84.1	82.8	82.9	83.1	83.0	83.0	
10/04/2015 12:23:16:907	86.9	87.9	86.7	86.8	86.9	86.9	86.8	
10/04/2015 13:23:16:907	90.4	91.4	90.3	90.3	90.5	90.4	90.4	
10/04/2015 14:23:16:907	93.9	94.9	93.8	93.9	94.0	94.0	93.9	
10/04/2015 15:23:16:907	97.1	98.0	97.0	97.1	97.2	97.1	97.1	
10/04/2015 16:23:16:907	100.2	101.2	100.0	100.0	100.0	100.0	100.0	
							Total	**6300**

Experiment no. 7 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
08/12/2014 09:28:25:732	25.2	25.2	25.2	25.2	25.2	25.2	25.2	**0**
08/12/2014 10:28:25:732	30.2	31.5	30.1	29.9	30.2	30.2	30.1	
08/12/2014 11:28:25:732	36.4	37.6	36.2	36.1	36.3	36.3	36.2	
08/12/2014 12:28:25:732	42.3	43.5	42.2	42.1	42.2	42.3	42.2	
08/12/2014 13:28:25:732	48.2	49.3	48.0	47.9	48.1	48.2	48.1	
08/12/2014 14:28:25:732	53.8	54.8	53.6	53.5	53.7	53.7	53.6	
08/12/2014 15:28:25:732	59.0	60.1	58.9	58.8	59.0	59.0	58.9	
08/12/2014 16:28:25:732	64.1	65.1	64.0	63.9	64.1	64.2	64.0	
09/12/2014 09:28:25:732	57.3	57.3	57.3	57.3	57.3	57.3	57.3	**400**
09/12/2014 10:28:25:732	61.5	62.6	61.4	61.3	61.5	61.5	61.4	
09/12/2014 11:28:25:732	66.2	67.1	66.1	66.0	66.1	66.2	66.1	
09/12/2014 12:28:25:732	70.4	71.3	70.3	70.3	70.4	70.4	70.4	
09/12/2014 13:28:25:732	74.5	75.4	74.3	74.3	74.4	74.5	74.4	
09/12/2014 14:28:25:732	78.3	79.2	78.2	78.2	78.3	78.3	78.2	
09/12/2014 15:28:25:732	82.0	82.8	81.8	81.8	82.0	82.0	81.9	
09/12/2014 16:28:25:732	85.5	86.3	85.4	85.4	85.5	85.5	85.4	
10/12/2014 09:28:25:732	72.9	72.9	72.9	72.9	72.9	72.9	72.9	**1000**
10/12/2014 10:28:25:732	76.6	77.6	76.5	76.4	76.5	76.5	76.5	
10/12/2014 11:28:25:732	80.7	81.6	80.6	80.5	80.7	80.7	80.6	
10/12/2014 12:28:25:732	84.5	85.4	84.4	84.4	84.5	84.6	84.5	
10/12/2014 13:28:25:732	88.1	89.0	88.1	88.0	88.1	88.2	88.1	
10/12/2014 14:28:25:732	91.5	92.4	91.4	91.4	91.6	91.6	91.5	
10/12/2014 15:28:25:732	94.7	95.6	94.7	94.7	94.8	94.8	94.7	
10/12/2014 16:28:25:732	97.7	98.6	97.7	97.7	97.8	97.8	97.8	
11/12/2014 09:28:25:732	80.2	80.2	80.2	80.2	80.2	80.2	80.2	**2230**
11/12/2014 10:28:25:732	83.3	84.3	83.2	83.2	83.3	83.3	83.3	
11/12/2014 11:28:25:732	86.9	87.8	86.8	86.7	86.9	86.9	86.8	
11/12/2014 12:28:25:732	90.2	91.1	90.2	90.1	90.3	90.3	90.2	
11/12/2014 13:28:25:732	93.5	94.4	93.4	93.4	93.5	93.6	93.5	
11/12/2014 14:28:25:732	96.5	97.4	96.4	96.4	96.6	96.6	96.5	
11/12/2014 15:28:25:732	99.4	100.3	99.0	99.0	99.0	99.0	99.0	
11/12/2014 16:28:25:732	99.7	100.7	99.5	99.5	99.5	99.5	99.5	
12/12/2014 09:28:25:732	81.6	81.6	81.6	81.6	81.6	81.6	81.6	**3870**
12/12/2014 10:28:25:732	85.1	86.1	85.1	85.1	85.1	85.1	85.1	
12/12/2014 11:28:25:732	88.6	89.5	88.5	88.5	88.6	88.7	88.6	
12/12/2014 12:28:25:732	92.1	93.0	92.1	92.0	92.2	92.2	92.1	
12/12/2014 13:28:25:732	95.4	96.3	95.3	95.4	95.5	95.5	95.4	
12/12/2014 14:28:25:732	98.4	99.3	98.3	98.4	98.5	98.5	98.4	
12/12/2014 15:28:25:732	101.2	102.1	99.5	99.5	99.5	99.5	99.5	
12/12/2014 16:28:25:732	99.9	100.8	99.8	99.8	99.9	99.9	99.9	
							Total	**7500**

Experiment no. 8 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
26/01/2015 09:44:58:220	25.4	25.4	25.4	25.4	25.4	25.4	25.4	**100**
26/01/2015 10:44:58:220	30.3	31.5	30.1	30.1	30.2	30.2	30.2	
26/01/2015 11:44:58:220	36.2	37.3	36.1	36.0	36.0	36.0	36.0	
26/01/2015 12:44:58:220	41.9	43.0	41.7	41.7	41.5	41.7	41.7	
26/01/2015 13:44:58:220	47.2	48.3	47.0	47.0	46.8	47.1	47.0	
26/01/2015 14:44:58:220	52.4	53.4	52.2	52.2	51.9	52.3	52.2	
26/01/2015 15:44:58:220	57.3	58.3	57.1	57.2	56.8	57.2	57.1	
26/01/2015 16:44:58:220	62.1	63.1	62.0	62.0	61.5	62.1	61.9	
27/01/2015 09:44:58:220	57.0	57.0	57.0	57.0	57.0	57.0	57.0	**330**
27/01/2015 10:44:58:220	62.1	63.2	62.0	62.0	61.6	62.1	61.9	
27/01/2015 11:44:58:220	66.6	67.6	66.5	66.5	66.1	66.6	66.4	
27/01/2015 12:44:58:220	70.9	71.9	70.8	70.8	70.4	70.9	70.7	
27/01/2015 13:44:58:220	75.1	76.0	75.0	75.0	74.4	75.1	74.9	
27/01/2015 14:44:58:220	79.1	80.0	78.9	78.9	78.4	79.0	78.8	
27/01/2015 15:44:58:220	82.8	83.7	82.7	82.8	82.2	82.8	82.6	
27/01/2015 16:44:58:220	86.4	87.3	86.3	86.4	85.7	86.5	86.2	
28/01/2015 09:44:58:220	76.2	76.2	76.2	76.2	76.2	76.2	76.2	**1680**
28/01/2015 10:44:58:220	80.2	81.1	80.1	80.1	79.5	80.2	80.0	
28/01/2015 11:44:58:220	83.7	84.7	83.6	83.6	83.0	83.8	83.5	
28/01/2015 12:44:58:220	87.3	88.3	87.3	87.3	86.6	87.4	87.1	
28/01/2015 13:44:58:220	90.7	91.7	90.7	90.6	90.0	90.8	90.5	
28/01/2015 14:44:58:220	93.9	94.8	93.8	93.8	93.2	94.0	93.7	
28/01/2015 15:44:58:220	97.0	97.9	96.9	96.9	96.3	97.0	96.8	
28/01/2015 16:44:58:220	99.9	101.0	99.9	99.9	99.4	100.0	99.8	
29/01/2015 09:44:58:220	83.7	83.7	83.7	83.7	83.7	83.7	83.7	**2960**
29/01/2015 10:44:58:220	87.3	88.4	87.3	87.3	86.6	87.3	87.1	
29/01/2015 11:44:58:220	90.7	91.7	90.7	90.7	90.1	90.8	90.5	
29/01/2015 12:44:58:220	93.9	94.9	93.9	93.9	93.3	94.0	93.8	
29/01/2015 13:44:58:220	97.1	98.0	97.0	97.0	96.4	97.2	96.9	
29/01/2015 14:44:58:220	99.7	100.7	99.6	99.7	99.2	99.8	99.6	
29/01/2015 15:44:58:220	99.7	100.8	99.8	99.8	99.8	99.8	99.8	
29/01/2015 16:44:58:220	99.7	100.7	100.0	100.0	100.0	100.0	100.0	
30/01/2015 09:44:58:220	84.4	84.4	84.4	84.4	84.4	84.4	84.4	**4060**
30/01/2015 10:44:58:220	88.1	89.1	88.0	88.1	87.5	88.1	87.9	
30/01/2015 11:44:58:220	91.6	92.6	91.5	91.6	91.0	91.7	91.4	
30/01/2015 12:44:58:220	94.9	95.9	94.8	94.8	94.2	95.0	94.7	
30/01/2015 13:44:58:220	98.1	99.1	98.0	98.1	97.5	98.2	97.9	
30/01/2015 14:44:58:220	99.7	100.7	99.6	99.7	99.2	99.8	99.6	
30/01/2015 15:44:58:220	99.7	100.7	99.8	99.8	99.8	99.9	99.8	
30/01/2015 16:44:58:220	99.7	100.7	100.0	100.0	100.0	100.0	100.0	
							Total	**9130**

Experiment no. 9 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
16/03/2015 09:21:16:406	24.8	24.8	24.8	24.8	24.8	24.8	24.8	**0**
16/03/2015 10:21:16:406	29.7	30.9	29.5	29.5	29.6	29.6	29.5	
16/03/2015 11:21:16:406	35.9	37.1	35.8	35.7	35.8	35.9	35.8	
16/03/2015 12:21:16:406	42.2	43.3	42.0	42.0	42.0	42.1	42.0	
16/03/2015 13:21:16:406	48.0	49.2	47.9	47.9	48.0	48.0	48.0	
16/03/2015 14:21:16:406	53.5	54.6	53.4	53.4	53.5	53.6	53.5	
16/03/2015 15:21:16:406	59.0	60.0	58.8	58.8	58.9	59.0	58.9	
16/03/2015 16:21:16:406	64.2	65.2	64.1	64.1	64.2	64.2	64.1	
16/03/2015 09:21:16:406	57.0	58.1	57.0	57.0	57.0	57.0	57.0	**620**
17/03/2015 10:21:16:406	62.3	63.4	62.1	62.1	62.2	62.2	62.2	
17/03/2015 11:21:16:406	67.1	68.2	67.0	67.0	67.1	67.1	67.1	
17/03/2015 12:21:16:406	71.7	72.8	71.5	71.5	71.7	71.7	71.6	
17/03/2015 13:21:16:406	76.2	77.3	76.1	76.1	76.2	76.3	76.2	
17/03/2015 14:21:16:406	80.5	81.6	80.4	80.4	80.5	80.6	80.5	
17/03/2015 15:21:16:406	84.7	85.8	84.6	84.6	84.7	84.7	84.6	
17/03/2015 16:21:16:406	88.6	89.6	88.5	88.5	88.6	88.7	88.6	
18/03/2015 09:21:16:406	74.6	74.6	74.6	74.6	74.6	74.6	74.6	**2100**
18/03/2015 10:21:16:406	79.5	80.6	79.4	79.4	79.4	79.4	79.4	
18/03/2015 11:21:16:406	83.7	84.8	83.6	83.6	83.7	83.8	83.7	
18/03/2015 12:21:16:406	87.5	88.6	87.4	87.5	87.5	87.6	87.5	
18/03/2015 13:21:16:406	91.2	92.3	91.1	91.2	91.3	91.3	91.2	
18/03/2015 14:21:16:406	94.7	95.7	94.6	94.7	94.8	94.8	94.7	
18/03/2015 15:21:16:406	98.1	99.1	98.0	98.0	98.1	98.2	98.1	
18/03/2015 16:21:16:406	101.4	102.4	101.3	101.3	101.4	101.5	101.4	
19/03/2015 09:21:16:406	82.7	82.7	82.7	82.7	82.7	82.7	82.7	**3070**
19/03/2015 10:21:16:406	87.1	88.1	87.0	87.0	87.1	87.1	87.1	
19/03/2015 11:21:16:406	90.9	91.9	90.8	90.8	90.9	90.9	90.9	
19/03/2015 12:21:16:406	94.4	95.4	94.3	94.3	94.4	94.5	94.4	
19/03/2015 13:21:16:406	97.7	98.7	97.7	97.7	97.8	97.9	97.7	
19/03/2015 14:21:16:406	100.8	101.8	100.7	100.8	100.8	100.9	100.8	
19/03/2015 15:21:16:406	103.7	104.7	103.6	103.7	103.8	103.8	103.7	
19/03/2015 16:21:16:406	106.5	107.5	106.5	106.5	106.6	106.7	106.6	
20/03/2015 09:21:16:406	81.7	81.7	81.7	81.7	81.7	81.7	81.7	**3760**
20/03/2015 10:21:16:406	86.2	87.3	86.1	86.2	86.1	86.3	86.2	
20/03/2015 11:21:16:406	90.0	91.0	90.0	90.0	90.1	90.2	90.1	
20/03/2015 12:21:16:406	93.7	94.7	93.6	93.6	93.7	93.8	93.7	
20/03/2015 13:21:16:406	97.2	98.2	97.1	97.1	97.2	97.4	97.2	
20/03/2015 14:21:16:406	100.4	101.4	100.4	100.4	100.5	100.6	100.5	
20/03/2015 15:21:16:406	103.6	104.6	103.5	103.6	103.6	103.7	103.6	
20/03/2015 16:21:16:406	106.6	107.6	106.6	106.6	106.7	106.7	106.7	
							Total	**9550**

Experiment no. 10 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
09/02/2015 09:24:49:780	25.7	25.7	25.7	25.7	25.7	25.7	25.7	**0**
09/02/201510:24:49:780	30.9	32.2	30.7	30.6	30.8	30.8	30.7	
09/02/2015 11:24:49:780	37.1	38.3	36.9	36.9	37.0	37.1	37.0	
09/02/2015 12:24:49:780	43.0	44.1	42.8	42.8	42.9	43.0	42.9	
09/02/2015 13:24:49:780	48.8	49.9	48.5	48.4	48.6	48.7	48.6	
09/02/2015 14:24:49:780	54.3	55.4	54.1	54.1	54.2	54.3	54.2	
09/02/2015 15:24:49:780	59.7	60.8	59.5	59.5	59.6	59.7	59.6	
09/02/2015 16:24:49:780	65.0	66.0	64.8	64.8	64.9	65.0	64.9	
10/02/2015 09:24:49:780	58.2	58.2	58.2	58.2	58.2	58.2	58.2	**650**
10/02/2015 10:24:49:780	63.3	64.4	63.1	63.1	63.2	63.3	63.2	
10/02/2015 11:24:49:780	68.2	69.3	68.1	68.1	68.2	68.3	68.2	
10/02/2015 12:24:49:780	73.0	74.0	72.8	72.8	72.9	73.0	72.9	
10/02/2015 13:24:49:780	77.5	78.5	77.3	77.4	77.5	77.6	77.4	
10/02/2015 14:24:49:780	81.8	82.7	81.6	81.7	81.7	81.8	81.7	
10/02/2015 15:24:49:780	85.8	86.8	85.7	85.7	85.8	85.9	85.8	
10/02/2015 16:24:49:780	89.9	90.9	89.7	89.8	89.9	90.0	89.9	
11/02/2015 09:24:49:780	78.5	78.5	78.5	78.5	78.5	78.5	78.5	**2460**
11/02/2015 10:24:49:780	81.4	82.5	81.3	81.3	81.4	81.5	81.4	
11/02/2015 11:24:49:780	85.4	86.5	85.3	85.4	85.4	85.5	85.4	
11/02/2015 12:24:49:780	89.1	90.2	89.1	89.1	89.2	89.3	89.2	
11/02/2015 13:24:49:780	92.7	93.8	92.6	92.7	92.8	92.9	92.7	
11/02/2015 14:24:49:780	96.1	97.1	96.0	96.0	96.1	96.2	96.1	
11/02/2015 15:24:49:780	99.2	100.2	99.1	99.1	99.2	99.3	99.2	
11/02/2015 16:24:49:780	102.2	103.2	102.1	102.2	102.3	102.3	102.2	
12/02/2015 09:24:49:780	82.8	82.8	82.8	82.8	82.8	82.8	82.8	**3250**
12/02/2015 10:24:49:780	86.2	87.3	86.0	86.1	86.1	86.2	86.1	
12/02/2015 11:24:49:780	89.9	91.0	89.8	89.8	89.9	90.0	89.9	
12/02/2015 12:24:49:780	93.3	94.4	93.3	93.3	93.4	93.5	93.4	
12/02/2015 13:24:49:780	96.7	97.8	96.6	96.7	96.7	96.8	96.7	
12/02/2015 14:24:49:780	99.6	100.6	99.5	99.6	99.7	99.7	99.6	
12/02/2015 15:24:49:780	102.2	103.2	102.1	102.2	102.3	102.3	102.2	
12/02/2015 16:24:49:780	104.7	105.7	104.6	104.7	104.8	104.8	104.7	
13/02/2015 09:24:49:780	82.3	82.3	82.3	82.3	82.3	82.3	82.3	**4200**
13/02/2015 10:24:49:780	86.3	87.3	86.1	86.2	86.2	86.4	86.2	
13/02/2015 11:24:49:780	90.3	91.3	90.2	90.3	90.3	90.4	90.3	
13/02/2015 12:24:49:780	94.1	95.1	94.0	94.0	94.1	94.1	94.1	
13/02/2015 13:24:49:780	97.5	98.5	97.4	97.5	97.5	97.6	97.5	
13/02/2015 14:24:49:780	100.2	101.2	100.1	100.2	100.2	100.3	100.2	
13/02/2015 15:24:49:780	102.8	103.8	102.7	102.8	102.8	102.9	102.8	
13/02/2015 16:24:49:780	105.3	106.3	105.2	105.3	105.4	105.4	105.3	
							Total	**10560**

Experiment no. 11 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
03/05/2015 09:23:56:334	20.1	20.1	20.1	20.1	20.1	20.1	20.1	0
03/05/2015 10:23:56:334	25.4	26.6	25.2	25.2	25.3	25.1	25.2	
03/05/2015 11:23:56:334	32.1	33.3	31.9	31.8	31.9	32.0	31.9	
03/05/2015 12:23:56:334	38.3	39.5	38.1	38.0	38.1	38.2	38.1	
03/05/2015 13:23:56:334	44.2	45.4	44.1	44.0	44.1	44.2	44.1	
03/05/2015 14:23:56:334	50.1	51.2	50.0	49.9	50.0	50.1	50.0	
03/05/2015 15:23:56:334	55.8	56.9	55.6	55.5	55.7	55.8	55.6	
03/05/2015 16:23:56:334	20.1	20.1	20.1	20.1	20.1	20.1	20.1	
04/05/2015 09:23:56:334	51.0	51.0	51.0	51.0	51.0	51.0	51.0	1000
04/05/2015 10:23:56:334	56.0	57.0	55.8	55.8	55.8	55.9	55.8	
04/05/2015 11:23:56:334	61.2	62.2	61.0	61.0	61.1	61.2	61.1	
04/05/2015 12:23:56:334	66.1	67.2	66.0	66.0	66.0	66.1	66.0	
04/05/2015 13:23:56:334	70.5	71.5	70.4	70.4	70.5	70.6	70.5	
04/05/2015 14:23:56:334	74.8	75.7	74.6	74.6	74.7	74.8	74.6	
04/05/2015 15:23:56:334	78.8	79.7	78.7	78.7	78.7	78.8	78.7	
04/05/2015 16:23:56:334	82.6	83.6	82.5	82.5	82.6	82.7	82.6	
05/05/2015 09:23:56:334	65.9	65.9	65.9	65.9	65.9	65.9	65.9	1650
05/05/2015 10:23:56:334	70.4	71.4	70.3	70.3	70.3	70.5	70.3	
05/05/2015 11:23:56:334	74.6	75.6	74.5	74.5	74.6	74.7	74.6	
05/05/2015 12:23:56:334	78.5	79.5	78.4	78.4	78.5	78.6	78.5	
05/05/2015 13:23:56:334	82.2	83.2	82.2	82.2	82.2	82.3	82.2	
05/05/2015 14:23:56:334	85.8	86.8	85.7	85.8	85.9	85.9	85.8	
05/05/2015 15:23:56:334	89.1	90.0	89.0	89.1	89.1	89.2	89.1	
05/05/2015 16:23:56:334	92.2	93.1	92.1	92.1	92.2	92.3	92.2	
06/05/2015 09:23:56:334	70.7	70.7	70.7	70.7	70.7	70.7	70.7	2050
06/05/2015 10:23:56:334	75.2	76.2	75.1	75.1	75.1	75.2	75.2	
05/06/2015 11:23:56:334	79.2	80.2	79.1	79.1	79.1	79.2	79.1	
06/05/2015 12:23:56:334	82.9	83.8	82.8	82.8	82.8	82.9	82.8	
06/05/2015 13:23:56:334	86.4	87.3	86.3	86.3	86.3	86.5	86.3	
06/05/2015 14:23:56:334	89.6	90.5	89.5	89.5	89.6	89.7	89.6	
06/05/2015 15:23:56:334	92.6	93.6	92.5	92.6	92.7	92.8	92.6	
06/05/2015 16:23:56:334	95.4	96.4	95.5	95.5	95.5	95.6	95.5	
07/05/2015 09:23:56:334	71.3	71.3	71.3	71.3	71.3	71.3	71.3	3600
07/05/2015 10:23:56:334	76.3	77.3	76.2	76.2	76.1	76.3	76.2	
07/05/2015 11:23:56:334	80.1	81.1	80.0	80.0	79.9	80.1	80.0	
07/05/2015 12:23:56:334	83.8	84.8	83.7	83.7	83.7	83.9	83.8	
07/05/2015 13:23:56:334	87.3	88.2	87.2	87.2	87.2	87.3	87.2	
07/05/2015 14:23:56:334	90.4	91.3	90.3	90.4	90.3	90.5	90.4	
07/05/2015 15:23:56:334	93.4	94.4	93.4	93.4	93.4	93.6	93.4	
07/05/2015 16:23:56:334	96.3	97.3	96.2	96.3	96.2	96.4	96.3	
							Total	**8300**

Experiment no. 12 of the desalination prototype

Date &Time of test	T_{m1}	T_{m2}	T_{g1}	T_{g2}	T_{g3}	T_{g4}	$T_{g\ Avg.}$	Distillate
	°C	°C	°C	°C	°C	°C	°C	ml
11/05/2015 09:23:36:152	23.1	23.1	23.1	23.1	23.1	23.1	23.1	**0**
11/05/2015 10:23:36:152	28.0	29.3	27.8	27.8	27.8	27.8	27.8	
11/05/2015 11:23:36:152	33.9	35.1	33.6	33.7	33.7	33.8	33.7	
11/05/2015 12:23:36:152	39.6	40.8	39.4	39.4	39.5	39.5	39.5	
11/05/2015 13:23:36:152	45.2	46.4	45.0	45.1	45.1	45.2	45.1	
11/05/2015 14:23:36:152	50.7	51.8	50.4	50.5	50.5	50.6	50.5	
11/05/2015 15:23:36:152	55.9	57.0	55.7	55.8	55.8	55.8	55.8	
11/05/2015 16:23:36:152	60.9	62.0	60.7	60.8	60.8	60.8	60.8	
12/05/2015 09:23:36:152	52.5	52.5	52.5	52.5	52.5	52.5	52.5	**1800**
12/05/2015 10:23:36:152	58.0	59.1	57.7	57.8	57.7	57.8	57.8	
12/05/2015 11:23:36:152	62.9	64.0	62.7	62.8	62.8	62.9	62.8	
12/05/2015 12:23:36:152	67.6	68.7	67.4	67.5	67.5	67.6	67.5	
12/05/2015 13:23:36:152	72.1	73.1	71.9	72.0	72.0	72.1	72.0	
12/05/2015 14:23:36:152	76.3	77.2	76.1	76.1	76.1	76.3	76.2	
12/05/2015 15:23:36:152	80.2	81.2	80.1	80.2	80.2	80.3	80.2	
12/05/2015 16:23:36:152	84.0	85.0	83.8	83.9	83.9	84.1	83.9	
13/05/2015 09:23:36:152	66.2	66.2	66.2	66.2	66.2	66.2	66.2	**2390**
13/05/2015 10:23:36:152	70.8	71.9	70.7	70.8	70.7	70.8	70.7	
13/05/2015 11:23:36:152	75.2	76.3	75.1	75.2	75.1	75.3	75.2	
13/05/2015 12:23:36:152	79.3	80.3	79.1	79.2	79.1	79.3	79.2	
13/05/2015 13:23:36:152	83.1	84.1	82.9	83.0	83.0	83.1	83.0	
13/05/2015 14:23:36:152	86.7	87.7	86.6	86.7	86.6	86.8	86.6	
13/05/2015 15:23:36:152	90.2	91.1	90.0	90.1	90.1	90.2	90.1	
13/05/2015 16:23:36:152	93.4	94.4	93.3	93.4	93.4	93.5	93.4	
14/05/2015 09:23:36:152	72.6	72.6	72.6	72.6	72.6	72.6	72.6	**3910**
14/05/2015 10:23:36:152	77.1	78.2	76.9	77.0	76.8	77.1	76.9	
14/05/2015 11:23:36:152	80.9	81.9	80.7	80.8	80.7	80.9	80.8	
14/05/2015 12:23:36:152	84.4	85.5	84.3	84.4	84.3	84.5	84.4	
14/05/2015 13:23:36:152	87.6	88.7	87.5	87.6	87.6	87.7	87.6	
14/05/2015 14:23:36:152	90.5	91.4	90.3	90.4	90.4	90.5	90.4	
14/05/2015 15:23:36:152	93.0	94.0	92.9	93.0	93.0	93.1	93.0	
14/05/2015 16:23:36:152	95.3	96.3	95.2	95.3	95.3	95.4	95.3	
15/05/2015 09:23:36:152	70.7	70.7	70.7	70.7	70.7	70.7	70.7	**4650**
15/05/2015 10:23:36:152	75.0	76.1	74.8	75.0	74.6	75.1	74.9	
15/05/2015 11:23:36:152	79.0	80.0	78.8	78.9	78.7	79.0	78.9	
15/05/2015 12:23:36:152	82.5	83.5	82.3	82.5	82.3	82.6	82.4	
15/05/2015 13:23:36:152	85.8	86.8	85.6	85.7	85.6	85.8	85.7	
15/05/2015 14:23:36:152	88.7	89.7	88.5	88.7	88.5	88.8	88.6	
15/05/2015 15:23:36:152	91.4	92.4	91.2	91.4	91.3	91.4	91.3	
15/05/2015 16:23:36:152	93.8	94.7	93.6	93.8	93.6	93.8	93.7	
							Total	**12750**

Appendix D

Data collected during the heat pipe tests for various working fluids

Testing the heat pipe containing Original Fluid (as obtained commercially)

	Date &Time	T1 at top Of the tank	T2 at Bottom Of the tank	T avg.	T_{a1}	T_{a2}	T_{a3}	$T_{a\ avg.}$
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	08/26/2015 09:03:18:127	16.4	16.0	16.2	18.1	18.6	18.3	18.3
2	08/26/2015 09:18:18:112	18.2	16.1	17.2	23.2	19.9	19.1	20.7
3	08/26/2015 09:33:18:112	20.1	17.1	18.6	23.9	20.3	19.6	21.2
4	08/26/2015 09:48:18:112	22.5	19.1	20.8	24.2	20.5	19.9	21.5
5	08/26/2015 10:03:18:112	25.0	21.4	23.2	24.3	20.6	19.9	21.6
6	08/26/2015 10:18:18:112	27.5	23.9	25.7	24.2	20.6	19.8	21.5
7	08/26/2015 10:33:18:112	29.9	26.4	28.2	24.2	20.5	19.8	21.5
8	08/26/2015 10:48:18:112	32.4	28.9	30.7	24.3	20.5	19.9	21.6
9	08/26/2015 11:03:18:112	34.8	31.3	33.1	24.3	20.4	19.9	21.5
10	08/26/2015 11:18:18:112	37.2	33.8	35.5	24.4	20.5	20.0	21.7
11	08/26/2015 11:33:18:112	39.7	36.2	37.9	24.4	20.6	20.1	21.7
12	08/26/2015 11:48:18:112	42.0	38.5	40.2	24.5	20.8	20.2	21.8
13	08/26/2015 12:03:18:112	44.3	40.8	42.5	24.6	20.9	20.3	21.9
14	08/26/2015 12:18:18:112	46.7	43.0	44.8	24.7	20.8	20.3	21.9
15	08/26/2015 12:33:18:112	48.8	45.1	46.9	24.6	20.8	20.3	21.9
16	08/26/2015 12:48:18:112	50.9	47.1	49.0	24.6	20.8	20.2	21.9
17	08/26/2015 13:03:18:112	53.0	49.1	51.0	24.5	20.8	20.2	21.8
18	08/26/2015 13:18:18:112	54.9	51.1	53.0	24.6	20.8	20.2	21.9
19	08/26/2015 13:33:18:112	57.0	52.9	55.0	24.8	20.9	20.2	22.0
20	08/26/2015 13:48:18:112	58.8	54.8	56.8	24.8	20.8	20.2	22.0
21	08/26/2015 14:03:18:112	60.8	56.6	58.7	24.9	20.9	20.2	22.0
22	08/26/2015 14:18:18:112	62.5	58.3	60.4	25.0	20.9	20.3	22.0
23	08/26/2015 14:33:18:112	64.4	60.1	62.2	25.1	21.1	20.4	22.2
24	08/26/2015 14:48:18:112	66.2	61.7	64.0	25.0	21.1	20.6	22.2
25	08/26/2015 15:03:18:112	67.9	63.4	65.6	25.0	21.0	20.4	22.1
26	08/26/2015 15:18:18:112	69.5	64.9	67.2	25.2	21.0	20.4	22.2
27	08/26/2015 15:33:18:112	71.1	66.5	68.8	25.3	21.1	20.5	22.3
28	08/26/2015 15:48:18:112	72.6	68.0	70.3	25.2	21.1	20.5	22.3
29	08/26/2015 16:03:18:112	74.2	69.4	71.8	25.3	21.1	20.5	22.3

Testing the heat pipe containing pure water as a working fluid

	Date &Time	T_1 at top of the tank	T_2 at Bottom of the tank	$T_{avg.}$	T_{a1}	T_{a2}	T_{a3}	$T_{a\ avg.}$
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	09/09/2015 09:01:20:061	16.4	16.1	16.3	17.6	18.1	17.9	17.9
2	09/09/2015 09:16:20:046	17.9	16.2	17.1	23.4	19.7	19.0	20.7
3	09/09/2015 09:31:20:046	20.5	17.3	18.9	24.0	20.3	19.6	21.3
4	09/09/2015 09:46:20:046	23.3	19.4	21.3	24.4	20.6	19.9	21.7
5	09/09/2015 10:01:20:046	26.3	22.0	24.1	24.8	20.9	20.2	22.0
6	09/09/2015 10:16:20:046	29.1	24.8	27.0	24.9	21.1	20.4	22.1
7	09/09/2015 10:31:20:046	31.9	27.7	29.8	24.8	21.1	20.4	22.1
8	09/09/2015 10:46:20:046	34.5	30.4	32.5	24.9	21.1	20.4	22.2
9	09/09/2015 11:01:20:046	37.2	33.2	35.2	24.8	21.1	20.5	22.1
10	09/09/2015 11:16:20:046	39.8	35.9	37.8	24.8	21.2	20.4	22.2
11	09/09/2015 11:31:20:046	42.3	38.5	40.4	24.8	21.2	20.4	22.2
12	09/09/2015 11:46:20:046	44.8	41.0	42.9	24.8	21.2	20.4	22.1
13	09/09/2015 12:01:20:046	47.2	43.4	45.3	24.7	21.1	20.4	22.1
14	09/09/2015 12:16:20:046	49.7	45.9	47.8	24.7	21.1	20.3	22.1
15	09/09/2015 12:31:20:046	52.1	48.2	50.1	24.7	21.1	20.3	22.0
16	09/09/2015 12:46:20:046	54.4	50.5	52.4	24.9	21.0	20.3	22.1
17	09/09/2015 13:01:20:046	56.8	52.7	54.8	25.0	21.0	20.2	22.1
18	09/09/2015 13:16:20:046	58.8	54.9	56.9	25.0	21.0	20.2	22.1
19	09/09/2015 13:31:20:046	61.2	57.0	59.1	24.9	20.9	20.2	22.0
20	09/09/2015 13:46:20:046	63.2	59.1	61.1	25.0	20.9	20.2	22.0
21	09/09/2015 14:01:20:046	65.3	61.1	63.2	24.9	20.9	20.2	22.0
22	09/09/2015 14:16:20:046	67.2	63.1	65.2	25.0	20.9	20.2	22.1
23	09/09/2015 14:31:20:046	69.2	64.9	67.1	25.2	21.0	20.3	22.2
24	09/09/2015 14:46:20:046	71.2	66.8	69.0	25.5	21.0	20.3	22.3
25	09/09/2015 15:01:20:046	73.1	68.6	70.8	25.4	21.1	20.3	22.3
26	09/09/2015 15:16:20:046	74.9	70.4	72.6	25.4	21.1	20.4	22.3
27	09/09/2015 15:31:20:046	76.7	72.1	74.4	25.5	21.1	20.4	22.3
28	09/09/2015 15:46:20:046	78.4	73.7	76.1	25.4	21.1	20.4	22.3
29	09/09/2015 16:01:20:046	80.1	75.4	77.7	25.4	21.1	20.4	22.3

Testing the heat pipe containing Methanol as a working fluid

	Date &Time	T1 at top of the tank	T2 at Bottom of the tank	T avg.	T_{a1}	T_{a2}	T_{a3}	$T_{a\ avg.}$
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	07/28/2015 09:14:22:483	17.2	15.6	16.4	20.5	16.4	15.9	17.6
2	07/28/2015 09:29:22:483	19.2	16.5	17.8	21.3	17.5	16.7	18.5
3	07/28/2015 09:44:22:483	21.6	18.4	20.0	21.8	17.9	17.1	18.9
4	07/28/2015 09:59:22:483	24.4	20.9	22.6	21.9	18.2	17.4	19.2
5	07/28/2015 10:14:22:483	27.0	23.6	25.3	22.2	18.4	17.6	19.4
6	07/28/2015 10:29:22:483	29.6	26.3	27.9	22.3	18.5	17.7	19.5
7	07/28/2015 10:44:22:483	32.2	28.9	30.6	22.2	18.5	17.7	19.5
8	07/28/2015 10:59:22:483	34.8	31.5	33.1	22.3	18.6	17.7	19.6
9	07/28/2015 11:14:22:483	37.2	34.1	35.6	22.3	18.7	17.8	19.6
10	07/28/2015 11:29:22:483	39.6	36.5	38.0	22.3	18.7	17.7	19.5
11	07/28/2015 11:44:22:483	42.0	38.9	40.5	22.2	18.3	17.7	19.4
12	07/28/2015 11:59:22:483	44.5	41.3	42.9	22.2	18.3	17.7	19.4
13	07/28/2015 12:14:22:483	46.8	43.6	45.2	22.2	18.2	17.6	19.3
14	07/28/2015 12:29:22:483	49.1	45.8	47.5	22.2	18.2	17.6	19.3
15	07/28/2015 12:44:22:483	51.2	48.0	49.6	22.1	18.1	17.5	19.2
16	07/28/2015 12:59:22:483	53.5	50.2	51.8	22.0	18.1	17.5	19.2
17	07/28/2015 13:14:22:483	55.6	52.3	53.9	22.0	18.0	17.4	19.2
18	07/28/2015 13:29:22:483	57.7	54.3	56.0	21.9	18.1	17.4	19.2
19	07/28/2015 13:44:22:483	59.7	56.2	58.0	22.2	18.1	17.4	19.2
20	07/28/2015 13:59:22:483	61.6	58.1	59.8	22.1	18.1	17.4	19.2
21	07/28/2015 14:14:22:483	63.5	60.0	61.7	22.2	18.1	17.4	19.2
22	07/28/2015 14:29:22:483	65.4	61.8	63.6	22.2	18.1	17.4	19.2
23	07/28/2015 14:44:22:483	67.2	63.6	65.4	22.2	18.2	17.5	19.3
24	07/28/2015 14:59:22:483	69.0	65.3	67.1	22.3	18.2	17.6	19.4
25	07/28/2015 15:14:22:483	70.7	67.0	68.9	22.4	18.2	17.6	19.4
26	07/28/2015 15:29:22:483	72.4	68.6	70.5	22.4	18.2	17.6	19.4
27	07/28/2015 15:44:22:483	74.1	70.2	72.2	22.4	18.3	17.7	19.5
28	07/28/2015 15:59:22:483	75.7	71.8	73.7	22.5	18.3	17.7	19.5
29	07/28/2015 16:14:22:483	77.3	73.3	75.3	22.5	18.3	17.8	19.6

Testing of the heat pipe containing Acetone as a working fluid

	Date &Time	T1 at top of the tank	T2 at Bottom of the tank	$T_{Avg.}$	T_{a1}	T_{a2}	T_{a3}	$T_{a\ avg.}$
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	07/30/2015 09:17:45:160	16.8	15.9	16.4	21.5	17.4	16.6	18.5
2	07/30/2015 09:32:45:160	18.9	16.5	17.7	22.0	18.0	17.1	19.0
3	07/30/2015 09:47:45:160	20.9	18.0	19.5	21.9	18.0	17.2	19.0
4	07/30/2015 10:02:45:160	23.2	20.1	21.7	22.1	18.1	17.3	19.2
5	07/30/2015 10:17:45:160	25.9	22.6	24.2	22.1	17.9	17.4	19.1
6	07/30/2015 10:32:45:160	28.3	25.1	26.7	22.1	18.0	17.4	19.1
7	07/30/2015 10:47:45:160	30.8	27.7	29.2	22.2	18.1	17.5	19.3
8	07/30/2015 11:02:45:160	33.2	30.2	31.7	22.3	18.3	17.6	19.4
9	07/30/2015 11:17:45:160	35.8	32.7	34.2	22.5	18.7	18.0	19.7
10	07/30/2015 11:32:45:160	38.2	35.1	36.6	22.8	19.4	18.7	20.3
11	07/30/2015 11:47:45:160	40.6	37.5	39.0	23.3	19.9	19.3	20.8
12	07/30/2015 12:02:45:160	42.9	39.8	41.4	23.2	19.8	19.2	20.8
13	07/30/2015 12:17:45:160	45.3	42.1	43.7	22.7	19.3	18.8	20.3
14	07/30/2015 12:32:45:160	47.4	44.3	45.9	21.9	18.4	18.0	19.4
15	07/30/2015 12:47:45:160	49.7	46.4	48.1	21.7	18.2	17.8	19.2
16	07/30/2015 13:02:45:160	51.9	48.5	50.2	21.3	18.1	17.7	19.1
17	07/30/2015 13:17:45:160	54.0	50.5	52.3	21.3	18.0	17.7	19.0
18	07/30/2015 13:32:45:160	56.0	52.5	54.3	21.6	18.1	17.7	19.1
19	07/30/2015 13:47:45:160	57.8	54.4	56.1	21.5	18.1	17.7	19.1
20	07/30/2015 14:02:45:160	59.8	56.2	58.0	21.7	18.0	17.7	19.1
21	07/30/2015 14:17:45:160	61.6	57.9	59.8	21.8	18.1	17.7	19.2
22	07/30/2015 14:32:45:160	63.4	59.7	61.5	21.4	18.0	17.7	19.0
23	07/30/2015 14:47:45:160	64.4	61.3	62.9	21.2	18.1	17.7	19.0
24	07/30/2015 15:02:45:160	66.1	62.9	64.5	22.1	18.7	18.1	19.6
25	07/30/2015 15:17:45:160	68.1	64.5	66.3	22.2	18.7	18.1	19.7
26	07/30/2015 15:32:45:160	69.9	66.1	68.0	22.2	18.6	18.1	19.7
27	07/30/2015 15:47:45:160	71.5	67.6	69.6	22.4	18.7	18.2	19.8
28	07/30/2015 16:02:45:160	73.0	69.0	71.0	22.5	18.7	18.2	19.8
29	07/30/2015 16:17:45:160	74.5	70.5	72.5	22.5	18.7	18.2	19.8

Testing of the heat pipe containing Ethanol as a working fluid

	Date &Time	T1 at top of the tank	T2 at Bottom of the tank	$T_{avg.}$	T_{a1}	T_{a2}	T_{a3}	$T_{a\ avg.}$
		(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)
1	09/22/2015 08:27:02:991	16.7	16.4	16.5	18.0	18.4	18.1	18.1
2	09/22/2015 08:42:02:975	16.9	16.5	16.7	23.9	19.8	18.9	20.9
3	09/22/2015 08:57:02:975	17.2	16.6	16.9	24.3	20.2	19.4	21.3
4	09/22/2015 09:12:02:975	18.3	16.9	17.6	24.6	20.3	19.6	21.5
5	09/22/2015 09:27:02:975	19.7	17.7	18.7	24.6	20.5	19.9	21.6
6	09/22/2015 09:42:02:975	21.5	19.5	20.5	25.0	21.0	20.2	22.1
7	09/22/2015 09:57:02:975	23.5	21.5	22.5	25.5	21.4	20.6	22.5
8	09/22/2015 10:12:02:975	25.6	23.6	24.6	25.9	21.7	20.9	22.8
9	09/22/2015 10:27:02:975	27.4	25.6	26.5	26.0	21.8	21.0	22.9
10	09/22/2015 10:42:02:975	29.3	27.5	28.4	26.1	21.9	21.0	23.0
11	09/22/2015 10:57:02:975	31.1	29.4	30.2	26.1	21.8	21.0	23.0
12	09/22/2015 11:12:02:975	32.9	31.2	32.0	26.0	21.9	21.0	23.0
13	09/22/2015 11:27:02:975	34.5	32.9	33.7	26.0	21.7	20.9	22.9
14	09/22/2015 11:42:02:975	36.1	34.5	35.3	25.6	21.2	20.7	22.5
15	09/22/2015 11:57:02:975	37.6	36.1	36.9	25.4	20.9	20.5	22.3
16	09/22/2015 12:13:02:975	39.4	37.8	38.6	25.3	21.0	20.5	22.2
17	09/22/2015 12:27:02:975	40.9	39.4	40.1	25.4	21.0	20.5	22.3
18	09/22/2015 12:42:02:975	42.6	41.0	41.8	25.3	21.1	20.6	22.3
19	09/22/2015 12:57:02:975	44.2	42.6	43.4	25.5	21.2	20.6	22.4
20	09/22/2015 13:12:02:975	45.9	44.2	45.0	25.5	21.3	20.7	22.5
21	09/22/2015 13:27:02:975	47.4	45.7	46.5	25.4	21.3	20.7	22.4
22	09/22/2015 13:42:02:975	48.8	47.1	48.0	25.4	21.2	20.6	22.4
23	09/22/2015 13:57:02:975	50.3	48.6	49.5	25.4	21.3	20.7	22.4
24	09/22/2015 14:12:02:975	51.7	50.0	50.9	25.4	21.3	20.7	22.5
25	09/22/2015 14:27:02:975	53.2	51.4	52.3	25.5	21.4	20.8	22.6
26	09/22/2015 14:42:02:975	54.6	52.7	53.7	25.6	21.4	20.8	22.6
27	09/22/2015 14:57:02:975	55.9	54.1	55.0	25.6	21.5	20.8	22.6
28	09/22/2015 15:12:02:975	57.4	55.5	56.4	25.8	21.6	20.9	22.7
29	09/22/2015 15:27:02:975	58.7	56.8	57.7	25.8	21.6	20.9	22.8

Appendix E

Sample calculations of different experiments

1. Sample calculation of the system's efficiency in terms of heating the water

The system's efficiency was calculated using the expression below:

$$\mathbf{Efficiency} = \frac{\mathbf{Output}}{\mathbf{Input}} \times \mathbf{100\%} = \frac{Q}{A_c G_t}$$

$$\mathrm{Q} = \mathrm{m}\ \mathrm{C_p}\ (\mathrm{T_{avg2}} - \mathrm{T_{avg1}})/\Delta \mathrm{t}$$

$$\eta_s = \frac{m\ C_p\ (T_{avg2} - T_{avg1})/\Delta \mathrm{t}}{A_c G_t} \times 100$$

Where η_s, is the system's efficiency (%), Q is the heat that went into the increase of the geyser's bulk water temperature, having a mass m = 110 kg. i.e. equivalent to the 110 litres, T_{avg1} and T_{avg2} are the average bulk water temperatures in the geyser, recorded during a time lapse or interval (Δt) of one hour (3600 seconds) apart, Cp is the specific heat of water (4186.6) $Joules/kg\,^\circ\ C$. The average bulk water temperature was obtained from four locations in the geyser.

$\mathrm{A_c}$, is the solar collector's area($\mathrm{m^2}$) and $\mathrm{G_t}$, is the solar radiation on the collector's surface ($\mathrm{W/m^2}$).

1. Output

The calculation for the efficiency shown here is for the first day of the twelfth test when the average water temperature T_{avg1} = 27.8 °C increased to T_{avg2} = 33.7 °C)

$$Q = (33.7 - 27.8) \times (110 \times 4186.6) = \mathbf{2717103.4}\,J$$

2. Input

$$A_c \times G_t \times t = (1.6254 m^2 * 682 \mathrm{W/m^2} \times 3600 s) = \mathbf{3990672}\,J$$

Thus,

$$\eta\% = (2717103.4/3990672) \times 100 = \mathbf{68.2}\%$$

2. Sample calculation of the system’s efficiency in terms of producing distilled water during the last day of the five days tests.

The efficiency of the solar desalination plant is calculated using the following formula which involves the enthalpy of the change of phase of water from saturated liquid to saturated vapour.

$$\mathbf{Efficiency} = \frac{\mathbf{Output}}{\mathbf{Input}} \times \mathbf{100}\%$$

$$\boldsymbol{\eta_{sd}} = \left(\frac{\boldsymbol{Q_v\ \emptyset_p}}{\boldsymbol{I}}\right) \times \mathbf{100}\%$$

Where η_{sd}, is the system’s desalination efficiency (%) in terms of producing distilled water.

$\mathrm{Q_v}$ (kJ/kg), is the energy associated with the enthalpy necessary to evaporate 1 kg of brackish water at the system’s temperature °C;

$\emptyset_\mathrm{p}$ is the productivity of pure water by the plant in litres (where litres can be converted to kg) and I is the total energy received by the system’s collector in kJ.

$\mathrm{Q_v} \cong \mathbf{2295.3}\ \boldsymbol{kJ/kg}$, the energy required to evaporate 1 kg of brackish water at a temperature about 83.27 °C.

$\emptyset_{\boldsymbol{p}}$ = total amount of Water harvested at test’s last day in litres = $4.65\ \mathrm{l}$ or

$\mathbf{4.65}\ \boldsymbol{Kg}$ **(Assuming a water density of 1000 kg/m^3).**

$\boldsymbol{I}$ Total radiation in kJ is calculated by

R = (the solar simulator’s irradiance) =
$682\ \mathrm{w/m^2} \times (\mathrm{collector'sarea})1.6254\mathrm{m^2} = 1108.5\ \mathrm{w} = \mathbf{1.1085}\boldsymbol{kW}$

$$\mathbf{1.1085}\ \boldsymbol{k}\mathbf{W} \times ((\text{duration of the day's test})\mathbf{7}\boldsymbol{h} \times \mathbf{3600}\boldsymbol{s/h}) = \mathbf{27934.2}\ \boldsymbol{kJ}$$

$$\mathrm{Efficiency} = \frac{2295.3\ \mathrm{kJ/kg} \times 4.65\ \mathrm{kg}}{27934.2\ \mathrm{kJ}} \times 100\%$$

The efficiency in this case $= \mathbf{38.2}\%$

3. Sample calculation of the heat pipe efficiency in terms of heat transfer to the tank’s water

The efficiency of the heat pipe is calculated using the following formula, which involves the change of the internal energy of the water contained in the system’s tank.

$$\mathbf{Efficiency} = \frac{\mathbf{Output}}{\mathbf{Input}} \times \mathbf{100}\%$$

$$\eta_{hp} = \frac{(\Delta Q_u)}{I \times t} m \times 100\%$$

Where η_{hp} is the heat pipe’s efficiency (%) in terms of heat transfer to the tank’s water.

ΔQ_u (kJ/kg), is the change in the internal energy of the water in the tester’s tank that depends on the temperature T and pressure P of the system.

t is the duration of the time for the test (7 h x 3600 h/s); $m(kg)$, is the mass of the water in the tank and $I(kW)$, is the total solar radiation on the evacuated tube heat pipe, which is the irradiance R, kW/m^2 from the solar simulator multiplied by the heat pipe’s receiving area of ($0.08084\ m^2$).

1. Output

$$\Delta E(kJ) = \Delta Q_u \times m$$

$$\Delta E(kJ) = (Q_2 - Q_1)(kj/\text{kg}) \times m(kg)$$

This sample calculation refers to the case of the heat pipe containing pure water as the working fluid; the initial and final temperatures obtained were 16.3 and $77.7\,^\circ\ C$ respectively.

$$\Delta E = (Q_{77.7} - Q_{16.3}) \times m$$

Linear interpolation was used to find the energy transferred between the temperatures from a standard table of saturated water.

$$\Delta \boldsymbol{E}(\boldsymbol{J}) = (325.3192 - 68.42258) \times 1000 \times 4 = \mathbf{1027586.48}\,\boldsymbol{J}$$

2. Input

$$R = 800\ W/m^2$$

Assumed surface area of the evacuated tube heat pipe $= 1.72m\ (length) \times 0.047m\ (dia) = 0.08084\ m^2$

$$I = 800W/m^2\ \times 0.068\ m^2 = \mathbf{64.672}\ \boldsymbol{W}$$

$$\boldsymbol{t}(\boldsymbol{s}) = \mathbf{7}\boldsymbol{h} \times \mathbf{3600}\boldsymbol{s} = \mathbf{25200}\ \boldsymbol{s}$$

$$\boldsymbol{I} \times \boldsymbol{t} = \mathbf{64.672}\ \boldsymbol{w}\ \times \mathbf{25200}\ \boldsymbol{s}\ = \mathbf{1629734.4}\boldsymbol{J}$$

Thus,

$$\eta\% = (\mathbf{1027586.48}\boldsymbol{J}/\mathbf{1629734.4}\boldsymbol{J})\ \times 100 = \mathbf{63.1}\%$$