Design And Fabrication of a Solar Hand Washing Cistern Using An Integrated Solar Collector

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

I dedicate this work to my late father who had all along believed in education as being the best investment anyone can make.

ACKNOWLEDGEMENT

I gratefully acknowledge the dedication and timely guidance from my supervisors Dr. Kamau, Prof. Kinyuaand Dr. Timonah.Withouttheir input, successful completion of this study would not have been possible. I appreciate the promptness with which they handled all the arising issues.

I also appreciate the patience and support of my family for understanding that we had to spend less time together because of my studies, and that sometimes I needed quiet time, when they wanted to talk. For them it is a sacrifice in many ways.

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ABBREVIATIONS AND ACRONYMS

ICS	Integrated collector-storage
SWH	Solar water heater
NGO	Non-governmental organization
ICSSWH	Integrated collector-storage solar water heater
FPTU	Flat Plate Thermosiphonic Units
PV	Photovoltaic
FAO	Food and Agricultural Organization
GOK	Government of Kenya
GPS	Global Positioning System

ABSTRACT

This study examines the problem of providing small volume, hot water, for purposes of sanitation in Kenyan informal food establishments. It explores the effectiveness of small batch heaters, also known as integrated collector storage solar water heaters (ICSSWH), for this purpose. Locally available materials were used for the fabrication. The comparison of the thermal efficiency at different orientations of the cistern relative to the suns path across the sky was evaluated. Also examined was the effect of tilt angle on thermal efficiency and on the uniformity of temperatures throughout the load. Performance of the collector with no cover, with a glass cover and with a plastic cover was analyzed, as well as the performance of the absorber with a finned absorber versus a plain absorber. The results of this indicatesis that the device can be used to substitute the charcoal cisterns. It delivers hot water at a suitable temperature for hand washing and at a low cost(it is long lasting, portable, and easy to use and requires no plumbing to cold water sources in order to push out the heated water). The best angle of inclination for optimum operation was found to be between 45° to 60°. The cistern worked best with a finned other than a plain absorber. The study results indicated that adding baffles to the underside of the collector aided in proper mixing of water to reduce the vertical temperature stratification. This occurred as a result of induced thermal currents which provided a mixing action of the water across the vertical layers in the collector tank.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Many people, Non-Governmental Organizations (NGO’s) and governments are working hard to cut greenhouse gases emissions arising from unsustainable biomass combustion. Between 1990 and 2000, Africa’s forests and woodlands receded faster than the global average; deforestation in Africa took place at an average of 0.8 percent, as compared to the world average of 0.2 percent according to the food and agricultural organization (FAO, 2005).

There are many possible ways to conserve forests including improvements to energy efficiency, energy saving and increase in renewable energy deployment, for instance wind and solar power, hydrogen produced from renewable sources, bio fuels and natural gas. To cut greenhouse gases, there is also the potential to capture the carbon dioxide emitted from fossil fuels and store it underground. In addition to reducing the gases we emit to the atmosphere, we can also increase the amount of gases we take out of the atmosphere. Plants and trees absorb CO_2 as they grow, "sequestering" carbon naturally. Increasing forestlands and making changes to the way we use trees for energy could increase the amount of carbon we are storing.

In developing countries, increasing forest cover is a big challenge since firewood and charcoal fuel are widely used for cooking and heating water (Vedeld*et al*., 2004). Heating water for washing, bathing or cooking is an expensive and time-consuming process (Rasheed, 1995) in the household and takes a significant portion of the home energy budget. This is especially so where there are young ones. Renewable energy and specifically, solar hot water systems, could present a sustainable solution for poor households, but only if the upfront prices of these systems were competitive as compared to other fuels for instance charcoal. Imported solar devices are rarely in the affordable price range of average households. Therefore a need exists to encourage locally fabricated solar water heating systems, using local materials, to enhance penetration of solar energy use. The simple prototype device demonstrated in this study can help increase usage of renewable energy technologies.

In domestic settings and food outlets, hot water is used for hygiene purposes like dish washing, clothes washing, cleaning soiled babies, hand washing and so on. These are daily activities that happen many times a day, every day. Hence, ways are needed to encourage energy conservation in these activities by promoting energy-efficient practices and technologies, as well as increasing use of non-polluting energy sources. In this study, it is demonstrated that solar water heating could be an appropriate technology to use in implementing portable hot water cisterns for hand washing. Most informal food outlets operate in squeezed spaces or in open air. Therefore portability of such a hot water cistern is important because the solar water heating device will need to be stored inside a cramped space at the end of the day, for security. Such a cistern can be used for camping too. Piped water and necessary plumbing to connect such a solar cistern to a running water source is not normally available in such establishments.

For hand washing, warm water is more pleasant to use than cold. Hands readily became contaminated after defecation, even with the use of toilet paper (Han *et al.*, 1986). Studies have shown washing after stool contact is far from universal and the use of soap still rarer (Huttly *et al.*, 1994).

1.2 Statement of the problem

According to the Government of Kenya (GOK), any person who sells, prepares, packages, conveys, stores or displays for sale any food under unsanitary conditions shall be guilty of an offence (GOK, 2010). To adhere to this law, authorities require that food outlets also provide warm water for staff and clientele to clean their hands before handling food. Normally, heaters modeled out of low gauge iron sheet are used for small and informal outlets. These are cylindrical containers with charcoal burners built inside the water holding cavity and a tap attached for accessing the hot water. They are small in capacity, corrode easily hence a short service life. They run on expensive charcoal and are not insulated hence lose much heat. The other alternative used is heating the water using gas, electricity or charcoal boilers. These are expensive and may be inconvenient for low income earners.

1.3 Objectives

1.3.1 Main Objective

The general objective wasto design, fabricate and characterize a prototype ICS solar water heater for use as a hand washing cistern.

1.3.2 Specific objectives

The specific objectives were;

1. To fabricate a batch solar water heater for hand washing that uses baffles to regulate temperatures inside the tank.
2. To characterize a solar collector made of plastic and steel, and compare performance with the collector having a glass cover, a plastic cover and with no cover at all.
3. To compare performance of the batch solar water heater collector at different horizontal orientations and different tilt angles.

1.4 Research Questions

The study endeavored to answer the following questions;

1. Can baffles be used to regulate temperature distribution in a solar batch heater's collector tank?
2. What are the performance differences of such a collector relative to different horizontal orientations and different collector tilt angles, in a relatively clear sky day?
3. Given the relatively small size of batch collector required, can solar provide an alternative fuel to replace charcoal and wood for use in a hand washing cistern?

1.5 Justification

To improve hygiene and reduce incidence of communicable diseases spread through dirty hands. It will also help in the reduction of charcoal use and consequent destruction of trees through replacement of charcoal heaters with a sustainable solution, for provision of hot water. It is could provide a business opportunity for manufacturers and resellers of the solar cistern, hence, provide jobs and income.

1.6 Scope

The scope of the study was limited to batch water heaters otherwise called integrated collector heaters, operating in the range of not more than 70° centigrade with a volume of less than 40 liters, for application in a tropical climate. The test location wasRuiru/Juja in central Kenya at latitude of-1.143°, and alongitude of -36.969°. Altitude was 458 m above sea level.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

Solar radiation is electromagnetic radiation in the range 0.28 µm to 3.0 µm wavelength ranges. The amount of incident energy per unit area per day depends on latitude, local climate, season of the year and inclination of the collecting surface in the direction of the sun. Solar energy is an adequate solution to the energy problems faced by the world. For inhabited areas, this flux varies from about 3 MJm^{-2} to $30MJm^{-2}$ per day, depending on place, time and weather (Twidelland Weir, 2006). Solar energy collection methods dates all the way back to 1767, when Horace de Saussure, a Swiss scientist, built the world's first solar collector (Berinstein, 2001). From then, the industry has grown and developed. Renewable energy which had been technologically immature and financially expensive became a serious force in the U.S. scene following the international oil embargo of 1973 (Berinstein, 2001)

In solar thermal technologies, a number of different technical applications exist. Besides space heating, water heating or industrial processes, solar thermal systems can be used for cooling applications or electricity generation with solar thermal power plants. The main usage areas are solar swimming pool heating, solar domestic water heating, solar low-temperature heat for space heating in buildings, solar process heat, and solar thermal electricity generation (Quaschning, 2005). Solar radiation can be directly converted into heat. Many different kinds of equipment are available for this conversion. Flat plate collectors and batch solar heaters are an example of such implements. If widely adopted, they can be used to help lessen the impact of domestic and hospitality sectors on the environment. Flat plate collectors have been in service for a long time without any significant changes in their design and operational principles (Duffie and Beckman, 1991). A simple flat plate collector consists of an absorber plate in an insulated box covered with transparent sheets. The most important part of the collector is the absorber that converts the solar energy to heat. An absorber plate performs three functions; convert the maximum possible amount of solar irradiance into heat, transfers this heat into the working fluid with minimum heat loss and prevents re-radiationof heat back to the surroundings (Wazwaz, 2002). The collector is assembled in a housing which is insulated on all the sides to prevent heat losses. Major heat losses are due to the temperature difference between the absorber and ambient air resulting inconvection and radiation losses (Muneer, 1985).

The simplest solar water heater (SWH) is the integrated collector storage (ICS), which functionally is an absorber and storage unit in one, also referred to as a batch heater. The ICS heaters are a popular, inexpensive and a maintenance-free means of solar water heating. These heaters have been in use for a relatively longer time compared to the modern day, more sophisticated counterparts. This is because of simplicity in design and lower cost of construction. The earliest evidence of their deployment dates back to the late 19th century, when they were being used in farms and ranches in Texas, USA (Smyth *et al*., 2004).

The angle may incorporate a seasonal bias in the tilt. Inclination of the ICS collector induces variation in the stratification profile (temperature variation along the depth and length of the heater). This variation alters the heat gain and loss characteristics of the heater. The main disadvantage of the ICS units is the greater thermal losses of the stored water tank as compared to the corresponding thermal losses of the water tank in Flat Plate Thermosiphonic Units (FPTU), (Laughton, 2010). This is related to the fact that a large part of the storage tank surface is exposed to ambience, for the absorption of solar radiation. However, this can be mitigated by use of suitable insulation.

Radiation is considered as direct, diffuse and global radiation (Kaltschimitt *et al*, 2007). Direct radiation is the radiation incident on a particular spot, having travelled a straight path from the sun. Diffuse radiation is the radiation resulting from diffusion in the atmosphere and thus indirectly reaching a particular spot on the earth's surface. The sum of direct (beam) radiation and diffuse radiation adds up to the total radiation on a receiving surface (Duffieand Beckman, 1991). Diffuse radiation consists of the radiation diffused in the atmosphere, the atmospheric counter radiation, and the radiation reflected by the neighborhood. The direct radiation incident on a tilted surface is determined by its incident angle. Batch heaters and flat plate collectors use direct and indirect beams while CPC (Compound Parabolic Concentrator) utilizes the direct beam only because only thedirect beamcan be focused. The main reason of using concentrating collectors is to obtain higher temperatures (Laughton, 2010).

2.2 Solar Collector Energy Gain

If I is the intensity of solar radiation in W/m^2 , incident on the aperture plane of the solar collector having a collector surface area of A in m^2, and the rate of useful energy extracted by the collector is Q_u (under steady state conditions),then the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through the collector as shown in equation 2.1.

$$Q_u = mC_p(T_O - T_i) \quad \text{.......} \quad (2.1)$$

Where, m is mass flow rate of fluid through the collector, in kg/s, C_p, specific heat of water, $T_o$and T_i, the outlet and inlet temperatures respectively. A quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature is the collector heat removal factor $F_{R.}$

$$F_R = \frac{mC_p(T_O - T_i)}{A[I_{\tau\alpha} - U_L(T_i - T_a)]} \quad \text{.......} \quad (2.2)$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. The actual useful energy gain Q_u, is found by multiplying the collector heat removal factor F_R by the maximum possible useful energy gain hence;

$$Q_U = F_R A[I_{\tau\alpha} - U_L(T_i - T_a)] \quad \text{.......} \quad (2.3)$$

Where $U_L$is the overall heat loss coefficient, τ, the transmittance of the cover, α, the absorbance of the plate and $I\tau\alpha$ the fraction of irradiance converted to heat, $\tau\alpha$ is the transmittance absorbance product.

Equation 2.3is the "Hottel-Whillier-Bliss equation" (Twidell and Weir, 2006). A measure of a flat plate collector performance is then the collector efficiency η, defined as the ratio of the useful energy gain Qu, to the incident solar energy, I, over a particular time period and can be found from equation 2.4.

$$\eta = F_R\tau\alpha - F_RU_L\left[\frac{T_i - T_a}{I}\right] \qquad (2.4)$$

For other types of collectors other than the flat plate, a variation of these basic equations is made depending on characteristics of the collector being considered. For a collector under steady state with one cover, the collector performance graph in figure 2.1 applies.

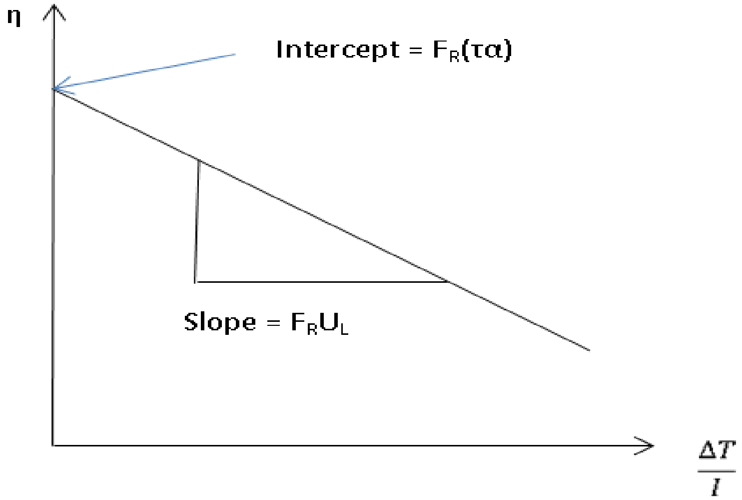

Figure 2.1: Collector performance graph(Soteris, 2009)

The incident angle of the solar radiation is important because the ratio of refracted to reflected intensities in the transparent cover, depends on the incident angle. The incident angle modifier is defined as;

$$K_{\tau\alpha} = \frac{\tau\alpha}{(\tau\alpha)n} \qquad (2.5)$$

Where $K_{\tau\alpha}$ is the incidence angle modifier, and n is the number of covers (Soteris, 2009). To characterize the performance of any solar collector analytically, a model equation can be used to simulate these quantities by manually working out the values, or by use of industry standard software tools to simulate the values. Experimental methods can also be used to characterize the performance of solar collectors as is the case in this study.

2.3 Solar radiation geometry

2.3.1 Solar declination Angle

The Solar declination∂, is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given in equation2.6(Twidell and Weir).

$$\partial = 23.45 \sin\left(2\pi \frac{(284+n)}{(365)}\right) \qquad (2.6)$$

Where n is the day of year (n =1 for January 1, n =32 for February 1, and so on). Solar declination varies between -23.45° on December 21 and +23.45° on June 21.

2.3.2 Solar hour angle and sunset hour angle

The solar hour angle is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15° per hour from solar noon. The sunset hour angle ω_s is the solar hour angle corresponding to the time when the sun sets (Soteris, 2009).

2.3.3 Solar Azimuth Angle

The solar azimuth angle, z is the angle of the suns rays measured in the horizontal plane due true south from the Northern Hemisphere or due north fom the Southern Hemisphere, westward being positive. The mathmatical expression for the solar azimuth angle is giveninSoteris(2009)asshown in the equation 2.7.

$$Sin(z) = \frac{Cos(\delta)Sin(h)}{Cos(\alpha)} \ldots\ldots (2.7)$$

Where δ is the Solar declination angle and h the solar hour.

2.3.4 Incidence Angle

The solar incidence angle, θ is the angle between the suns rays and the normal on a surface. For a horizontal plane, the incidence angle, θ and zenith angle, Φ, are the same. An extensive treatment of the angle of incidence is given by Kreith and Kreider (1978) or Duffie and Beckman (1991) indicated in figure 2.2.

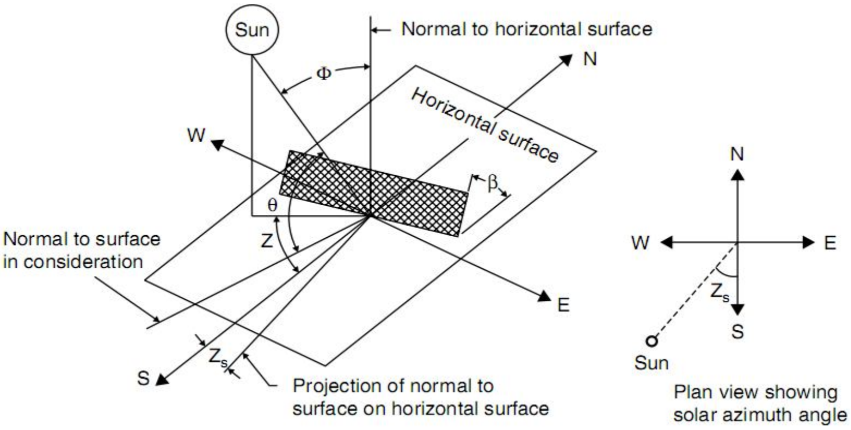

Figure 2.2: Solar Angles (Soteris, 2009)

2.4 Solar radiation measurement

2.4.1 Pyrheliometer

A pyrheliometer is the instrument used for measurement of direct beam solar irradiance (Duffie and Beckman, 1991). Withinits application, the sunlight beam enters the through a window and is directed onto a thermopile which converts heat to an electrical millivolt signal that can be recorded. The millivolt signal is then scaled into watts per square meter units. For the total irradiance, a pyranometeris used to measure solar irradiance on a planar surface (Duffie and Beckman, 1991).

2.4.2 Pyranometer

A pyranometer is an instrument that measures the total amount of sunlight reaching a horizontal plane on Earth's surface, from a field of view of 180°. In irradiance measurements, beam radiation is known to vary with the cosine of the angle of incidence. This quantity is called "insolation." It is typically measured in metric units of watts per square meter (W/m^2).

There are two kinds of pyranometer. The expensive kind uses a collection of thermocouples, called a thermopile that generates a small voltage difference when the two junctions of the thermocouple are at different temperatures. A much less expensive kind uses small silicon-based photo detectors equivalent to very small solar cells.

These less expensive detectors do not respond uniformly to input across the solar spectrum. Despite their limitations, they are widely used for agricultural and environmental monitoring and other applications when very high absolute radiometric accuracy is not required. Calorimetric methods can also be used to estimate the amount of solar radiation available at a location.

2.4.3 Calorimetric Methods of Estimating Solar Irradiance

From basic calorimetric theory, the irradiance of the solar beam can be measured using the formula;

$$\alpha\tau AI = mC\frac{\Delta\theta}{\Delta t} \quad \text{.......} \quad (2.8)$$

The method assumes the absorber material is a black body. The calorimeter is inserted inside the collector at the level of the absorber and the change in time $\Delta t(s)$, required for the temperature to rise by $\Delta\Theta$ (ºC), are noted. Here, C is the specific heat of water in the calorimeter, m the mass of water (kg), and A the collector aperture, while I is the solar beam irradiance on a horizontal surface.

This formulae applies equally well to the collector system and is used to estimate the area of the absorber required by the ICS collector for the specific volume of water required at a certain output temperature. Usedwhen designing a collector.

2.5 Collector Insulation

2.5.1 Side insulation

Solar energy is an intermittent resource; hence, insulating materials must play a vital role to retain the solar heat for the desired storage period. To retain the hot water heated by solar energy up to the desired period, fiberglass wool is generally used as insulating material in the storage system (Chaurasia P.B. L, 1991).

A low cost material, like sawdust is also possible to use. Suchsawdust insulation was tested in a hot water storage system its performancecompared with the fiberglass wool storage system under similar conditions (Chaurasia P.B. L, 1991). From this study, it was observed that the sawdust storage system gave comparableperformance in retaining the solar heated hot water up to the following evening. The solar water heating efficiency was found to be in the range of 46.9%-47.1% (fiberglass wool storage system) compared to 46.0%-46.4% (sawdust storage system).

2.5.2 Glazing and the Transmittance Absorbance product

Only part of the incident solar irradiation usefully reaches the absorber. The higher this is, the more efficient the collector. The collector cover allows radiation to pass straight through to the absorber, but at the same time must reducethe amount ofremittance or heat loss back from the absorber. In some very hot climates, glazing may not be needed.

Glass covers have the advantage of durability and ease of recycling, but tend to be heavy and can sometimes crack when impacted. Plastic covers have the advantage of lower weight, but can suffer from thermal and ultraviolet degradation with time. The plastic cover becomes discolored and causes reduced solar radiation transmission.

The ideal glazing material for solar collectors would have the following properties: High temperature capability, transmit light very well and long life when exposed to ultraviolet (UV) and high temperatures. In addition it needs good impact resistance and should be light weight and opaque to long wave infrared (IR). No single glazing material exhibits all of these properties, so picking the best material for glazing is a tradeoff against design criteria.

2.6 Orientation and inclination of collector

Solar collectors should be located in a position where as much radiation as possible will fall on them. The optimum direction for a collector is to face the equator (Twidell and Weir, 2006). The collector bank should be slightly tilted up at the outlet end, to eliminate airlocks and to promote thermosyphon flow. The larger the angle between the incident solar radiation and a line at right angles to the surface, the lower the amount of radiation intercepted by each square meter of surface.A study done by Henderson*et al*., (2007) drew the result that a $5^{\circ}$to 10°increase in the angle of inclination for particular latitude would improve the thermal performance of the heater. In any case the collector is best tilted to at least 10° slope, to aid thermosyphon.

2.7 Cost benefit

Solar water heating systems usually cost more to purchase and install than conventional water heating systems. However, a solar water heater can usually save money in the long run. How much money is saved depends on the amountof hot water required, the system's performance, geographic location and solar resource availability. Factors that may determine uptake of the technology like available financing and other incentives, cost of availablefuels and the cost incurred in other water heating systems all determine the acceptability of the solar water heating system.

A big advantage with solar water heating system is that the sun is free and users are protected from future fuel shortages and price hikes. There are many factors to be considered while evaluating the life cycle cost of a solar water heating system. These factors are: interest rate, inflation rate, unit cost of electricity, operation and maintenance cost and solar water heater service life. All these factors are affected by fluctuations in the economy, government policies, and electricity tariffs.

Considerations that need to be made include comparison and evaluation of capital cost, simple pay back and life cycle costs of solar and other hot water heaters being compared. Also the initial set-up costs and the energy savings available are a factor. The simple payback period is usedin the current study.

2.8 ICS solar collector

In existing literature, there are works on ICS systems with rectangular, cylindrical or other type of water storage tank. Among such works onthe improvement of these ICS systems is Schmidt andGoetzberger(1990), who suggest the use of transparent insulating materials (TIM) over the absorbing surface, Mason and Davidson (1995), who propose the use of selective absorbing surface within evacuated tube, while Kaptan and Kilic (1996), and Smyth *et al*., (1999) adopt the use of tubular absorber with a baffle plate placed inside them and the use of a vessel with inner sleeves, respectively. Tripanagnostopoulos and Yianoulis (1992) suggested the use of inverted absorbing surface to suppress the thermal losses of the ICS systems approaching the thermal losses of the FPTU units. In a paper by Smyth *et al.*, (2006), the most representative works on this subject was presented.

The earliest solar water heater was a batch heater achieved by placing under the sun, a black painted metal tank full of water to absorb solar energy. The disadvantage was as the sun went down, the tank rapidly lost its heat because it had no insulation (Smith, 1995).

2.8.1 Bifacial Collector

A bifacial collector shown in figure 2.3 incorporates two stationary concentrators with a flat plate absorber mounted above them (Goetzberger *et al.*, 1991). The design achieved higher efficiencies than other flat plate collectors under low irradiation condition. A collector design was presented for domestic solar water heating (Groenhout *et al.*, 2000). A double sided absorber with low emissivity and a selective surface which was coupled with high reflectance stationary concentrators was used. This reduced the radiative and conductive losses through the back of the collector. The main source of heat loss in this design is through the glass cover.

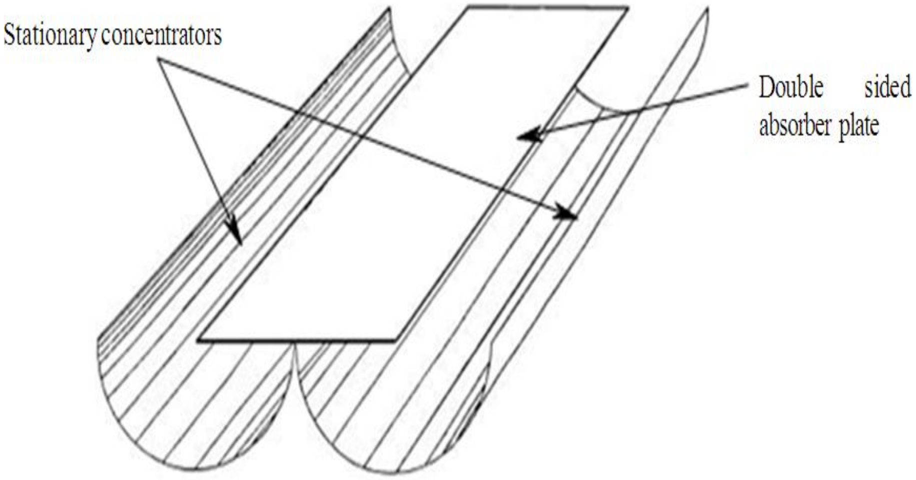

Figure 2.3: Bifacial collector (Goetzberger et al., 1991)

2.8.2 Reverse solar collector

The reverse flat plate collector shown in Figure 2.4 has an inverted absorber plate with a stationary concentrating reflector beneath (Kienzlen *et al.*, 1988).

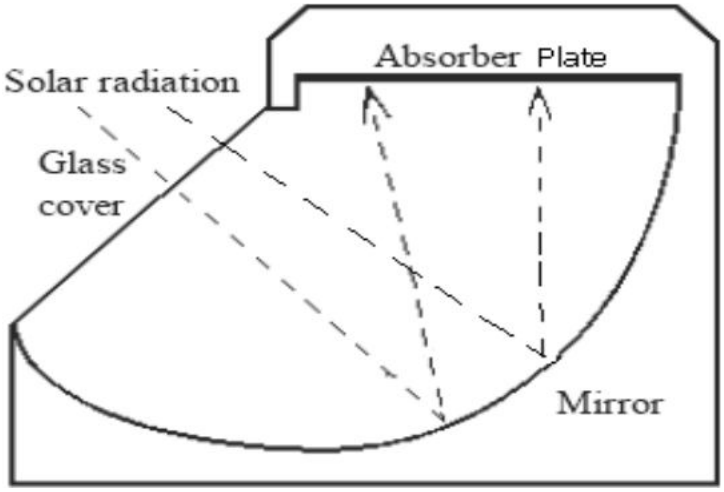

Figure 2.4: Reverse Collector(Kienzlen et al., 1988)

This design reduces considerably the convective heat losses, but there are still heat loss paths through the insulation above the collector and the conduction of heat through the air cavity.

The design allows modifications on the shape of the concentrating mirror. The drawback of this collector is its large size resulting in difficulties moving it or mounting it on a typical roof.

2.8.3 Triangular storage solar collector

A triangular built-in-storage solar water heater, as seen in figure 2.5, has been studied under winter conditions.

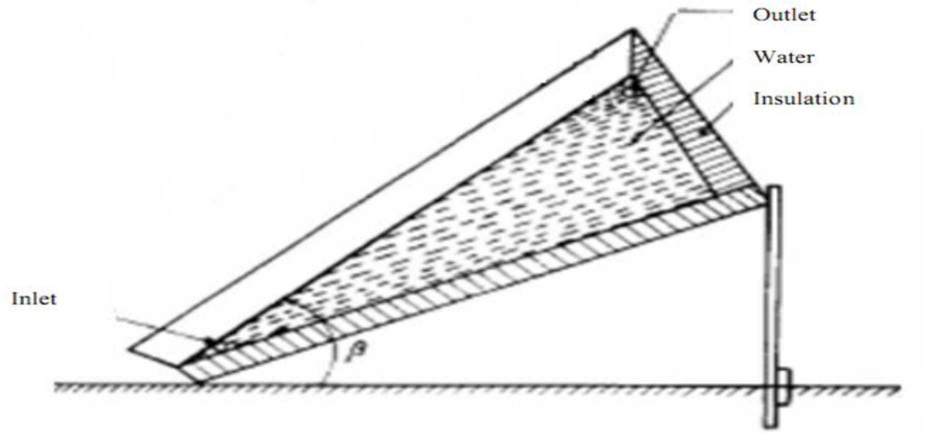

Figure 2.5: Triangular storage (Kaushik *et al.*, 1994)

A comparative study of the triangular water heater with a rectangular one was done(Kaushik *et al*., 1994).The triangular system resulted in higher solar gain and enhanced natural convection, leading to a higher water temperature.

2.8.4 Inverted absorber solar collector

An inverted absorber 'Integrated Collector Storage Solar Water Heater' ICSSWH was mountedby Smyth *et al.*, (2005) in the tertiary cavity of a compound parabolic concentrator. It had secondary cylindrical reflector using several types of transparent baffles at different locations within the collector cavity. After experimental investigation, it was concluded that the collector performance increased by using transparent glass baffles in the collector cavity (Smyth *et al.*, 2005). Employing full baffles or baffles located at the wrong position resulted in unnecessary surfaces at which extra reflections and absorption of incident radiation occurred.This cancelled any thermal benefits of reduced fluid motion.

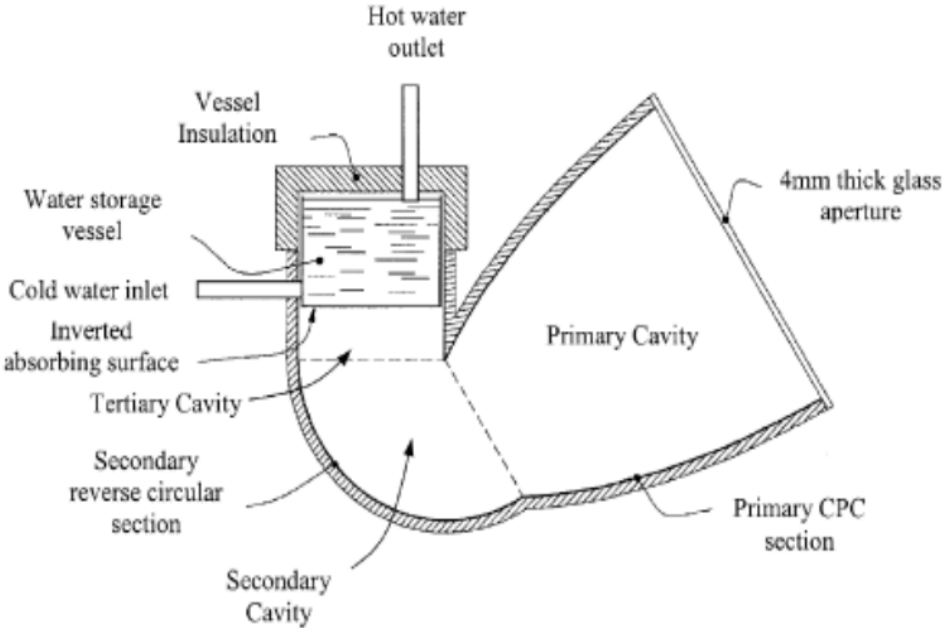

Figure 2.6: Inverted absorber (Smyth *et al.*, 2005)

2.9 Collector efficiencies

To summarize performance for the various types of collectors, table 2.9.1 (Grigorios, 2009) is inserted.

Table 2.1: Typical collector types and efficiencies (Grigorios, 2009)

Collector Types	Operational Collection Efficiency (%)
Collector with internal fins (Theoretical)	60 - 72
Bifacial Type Collectors	50 - 68
Intergraded solar systems (ICSSWH)	46 - 63
Plastic Collectors	42 - 52
Tar Collector	40 - 50
Conventional Collector	40 - 46
Cylindrical Collectors	38 -42

The efficiency ranges depended on the ambient temperatures and the time of the day that the experiments took place.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Introduction

This study is a structured approach achieved through an experiment. The structured approach to inquiry, usually, classified as quantitative research, is the best method of analysis as indicated by Dawson (2002). This is the recommendation applied in this study. MINITAB® statistical software, Release 14.1, was used for analyzing datadue to its ease of handling statistical data. It was also available and has no learning curve.

The prototype used in this study was based on the triangular collector (figure 2.5). In a study of the triangular storage system Kaushik *et al*., (1994) found out that the design resulted in higher solar gain and enhanced natural convection, leading to a higher water temperature. Due to the need for enhanced convection required for the prototype in this study, the triangular design was suitable. The prototype consist an absorber plate made out of a 1mm sheet of galvanized steel treated with black paint.

A high iron glass plate acted as a cover. This was used to prevent convective heat losses from the absorber plate and prevent infrared radiation from the plate escaping to the atmosphere. The collector tank was cut out of a PVC plastic container, the outside of which was covered with aluminum foil and further insulated with glass wool. This was to cut down heat loss by conduction from the sides of the container.

A suitable stand was made in such a way that allowed the absorber to be correctly inclined to the horizontal for inclination tests. The prototypehad no sun tracking capability. Removing heat from the collector plate was achieved through the direct contact of the plate with the water in the collector storage. Good thermal contact between the water and the plate was ensured by making sure that there was no air trapped at the top of the collector.A tiny air vent was provided at the highest point on the absorber.

The design selection criteria for basing the heater on an ICS collector was mainly simplicity of construction and the least cost due to relatively fewer materials required. The potential disadvantage for the ICS collector used in this study was the high losses of heat and the difficulty of tapping off the hot water from the top of the collector. The loses in this study were minimized by applying glass wool insulation on the collector body. Also characteristics of the sites where it will be located, for example camping sites, were a consideration. One such consideration is that there is no piped water in such places, meaning pressure from cold water source cannot be used to push out the hot water from the collector top. Henceit was also not possible to use a tempering device to mix with the cold water, if the water became too hot.These challengeswere taken care of by use of baffles inside the tank to mix the tank contents and provide hot water from the bottom. A slightly larger tank for the absorber area installedensured that the water never became too hot to require cooling before use.

3.2 Fabrication

3.2.1 Choice of Design

All of the improved collectors in explained in Section 2.8 have an enhanced performance, but at an increased cost, when compared to the traditional flat collectorsSmyth *et al.*, (2006). This was one of the reasons why they were not preferred, except for the triangular design. The other reason for not using these designs to implement the product of this study was that the size of the collector was inherently big, due to their working principle. They are also complex to fabricate.

3.2.2 Baseline data used in fabrication

To estimate the size of the collector, baseline data in appendix B.2 was used as well as equation 2.4. The volume of water required was estimated for a typical food outlet handling about 60 clients each client may using a maximum of half a liter to wash their hands. A total of 30 liters of hot water was then required. To prevent the water getting too hot for use the volume was overrated by 30 percent. There was flexibility to reduce this volume after pilot tests, in case the water did not attainthe target temperature of 40 °C. The materials used are listed in table B.2. The pilot tests were to check that the cistern had operation integrity, for example not leaking, and that the baseline data used was correct.

3.2.3 Fabrication of the collector

A plastic water container was cut to size using a wood saw as indicated in plate A.1. The total volume of the container was 60 liters. Top part of the container was removed in a slanted cut and 40 liters of water was poured into the bigger of the two pieces. The water line was marked then used to locate the lip of the tank on which the frame and other accessories were mounted by help of heat from a gas torch. Two rectangular frames were then designed from a flat steel bar then welded as required. The frames were used to hold the tank and absorber together in a watertight joint. A finished mounting surface is illustrated in plate A.2, together with the fixtures used to hold down the absorber to the tank.

The inlet and outlet plumbing holes were then made and the attachments on which the pipe will be screwed into, installed. Adhesive was then applied on the outside of this plastic tank and aluminum foil stuck on the outside of tank. On top of this foil, glass wool insulation was applied. The wooden frame that holds the collector tank was then assembled and the collector tank mounted on it using panel screws. The four thermocouples at the bottom of the tank were then fixed at appropriate intervals along the length of the tank, in the middle line, alongthe tank's lengthwise axis.

The frame was then screwed on with the thermocouple wires suitably placed and leading out of the tank. To ensure no leakage, silicone sealant was applied liberally at the seams. The absorber was then cut to size and a breather fashioned at the top edge of the absorber, in form of a tiny hole to release any air that could gettrapped inside the tank when loading water. The absorber was then placed on top of the lower frame with silicon sealant in between. The upper frame was then screwed on top of the absorber to hold it into place and prevent leakage as seen in plate C.3. The frame to hold the glazing was then fixed on top around the absorber edge. The inlet funnel and the water outlet valve were then fixed. The absorber treatment (matt black paint) was applied, keeping the resulting film as thin as possible, using a spray painting gun. The glass top was then fixed to complete the collector top. A stand was then fabricated onto which this cistern and its mount was placed. The cistern was not fixed to its stand to allow for changing the collector inclination angle. The assembly was made in such a way that the cistern can be tilted through 0° to 60° for inclination tests without toppling. Plate 3.1 illustrates this in a typical experimental setup of the cistern.

Plate 3.1: Typical experimental setup for the ICS cistern

3.2.4 Thermocouple sensors

High purity type-k thermocouple sensor wire was used to fabricate the sensors. Nine pieces of one meter length of this wire were stripped at both ends. On one end a micro-connector for type K- thermocouple was attached and the other end was twisted for a length of about 4mm to make the sensing tip which was then covered by an open ended rubber sleeve. All the sensors were then verified by measuring the ice-point, at a temperature of 0 °C. The ice-point was prepared by use of crushed ice mixed with water and placed in a heat-insulated dish.

Two absorbers were fabricated. One was plain and the other was finned (baffled). The plain collector was made by cutting out of a galvanized sheet an area equivalent to the collector aperture (47 mm x 71 mm). The finished absorber had an effective absorber area of (39 mm x 66 mm). One surface was sprayed with black lacquer very thinly applied. It was then perforated to make securing holes. To make the finned collector, a similar plain absorber had fins attached to it in the pattern illustrated in figure 3.1.

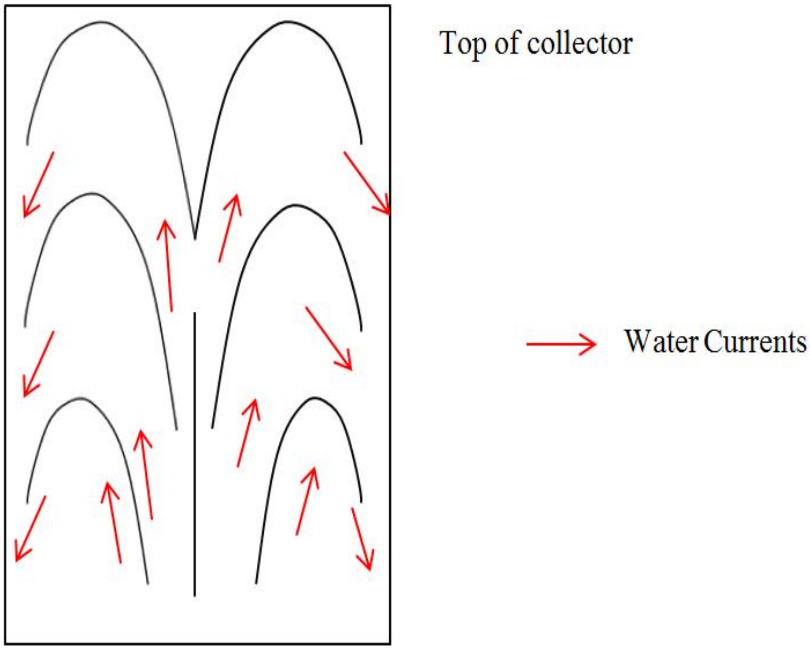

Figure 3.1: Layout of baffles (or fins) on the collector

A photo of the actual finned collector is in plate C.4.The size, pattern, and layout of the fins on the absorber plate was designed with the sole aim to useconvection currents in the tank to mix the upper and lower layers of the tank contents into an equal temperature.

Two types of covers were prepared. One made of high iron float glass cut out of a sheet of 4mm thickness glass with an area equivalent to the collector absorber mounting area. The other having the same dimensions was cut out of 0.5mm thickness Vinyl material. A rubber gasket 22 cm x 2 cm was then attached round the glass circumference. This gasket together with the fixing adhesive gave a separation of about of 2.5 cm between the absorber and cover.

The other cover was made from clear plastic stretched on a 2.5 cm square rubber frame with dimensions equal to those of the other gasket above.

The main insulation at the top was provided by the top cover. The underside of the collector was insulated by first using an aluminum foil with the shiny side facing the tank, and gluing it on. A layer of glass wool of about 4 cm thick was installed on this foil by gluing the wool on top of the foil. Sack material was then used to cover the top of the glass wool insulation for protection and to keep the fiber in place.

Sampling was performed by taking measurement of temperature and irradiance at fixed intervals,every 10 minutes, for the duration of a test. Experiments started at 8.00 am and ended at 3.30 pm. The data used was collected up to3.30 pmdaily, because this was just after the highest temperature was attained by the cistern in most days. Inclination and Orientation measurements were done each on its own day. The volume of the tank, transmittance of the covers and the area of the absorber were measured only once during fabrication. The temperature sampling thermocouples were fixed at eight different positions inside the heater tank as illustrated in figure 3.2.

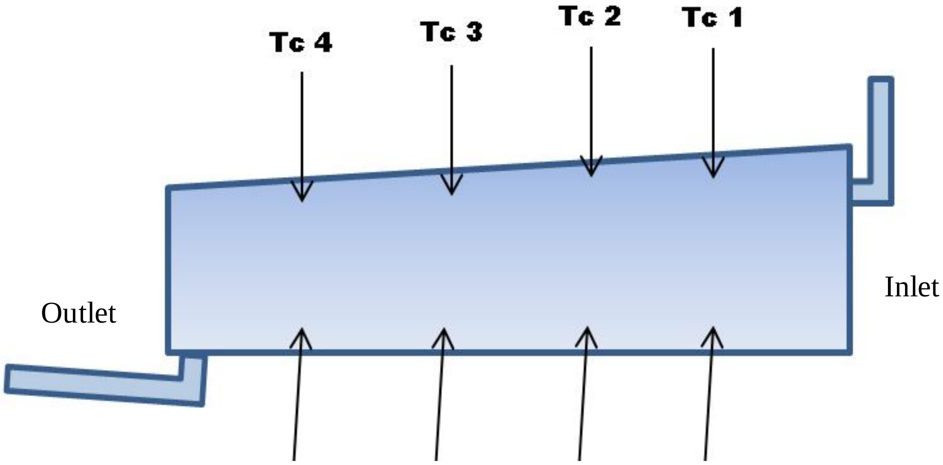

Figure 3.2: Thermocouple sensor placement in the tank.

The thermocouple sensors were then connected to a laptop through a Picolog TC-08 temperature logger. A solar irradiance meter (Seaward solar survey 200) that can also measure inclination angle of a surface, the ambient air temperature and the compass orientation as well was used to set up the cistern's inclination and orientation angles.

3.3Measured parameters

All tests started with an empty tank which was loaded every morning and all measurements started at around 8.00 pm and ended at 3.30 pm. The following parameters were measured as indicated in each test.

The electrical connections between the computer, logger and cistern are shown in figure 3.3. Temperature was measured at two levels inside the tank, 1 cm from the absorber surface using 4 thermocouples spaced equally and mid-way along the length of the absorber. Similarly below the upper set, another set of

4 thermocouples were installed at the bottom of the tank. The placement of the sensors and electrical connections is illustrated in figure 3.3.

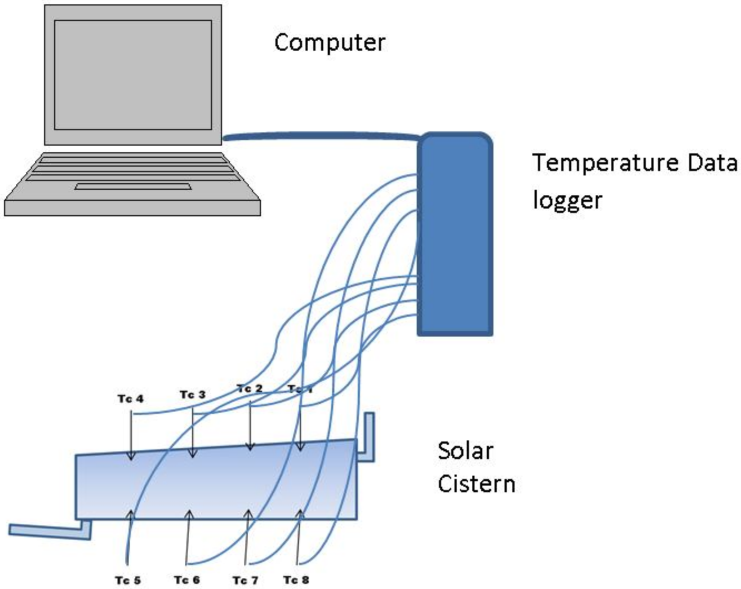

Figure 3.3: Data logger electrical connections

The sensors were then read off using the 8 input TC-08 data logger attached to a laptop.The ambient temperature was logged in through the pyranometer ambient temperature sensor. All temperatures were measured in degrees centigrade.

Solar irradiance was measured directly, at the absorber inclination, using the solar survey 200 pyranometer which saves the readings internally as they are sampled. This implies that the irradiance data couldthen be used without the incident angle being taken into account. The temperature logger and the irradiance meter had time of day clocks that were synchronized and the two instruments were started simultaneously at the beginning of the experiment.

Irradiance was measured in watts per square meter. The Irradiance meter required no full time connection to the computer since it had its own internal memory which had to be downloaded at the end of the experiment.

Solar survey 200 was used to set the inclination. The datum was the top of the collector and measurement were done in angular degrees from the horizontal position. The horizontal position was verified using a spirit level on top of the absorber.

Collector orientation was set using the Solar Survey 200 instrument. The datum was the center line at the top of the collector (lengthwise) aligned to the desired compass direction and measured in angular units of degrees. All angles were calculated from the magnetic North and verified using a magnetic compass.

Time of daywas measured through the internal clock inside the TC-08 and the computer. The recording was in time of day units.

Transmittance is a ratio of the radiation passing through when there is a cover, to the radiation passing through when there is no cover. It varies as a function of the optical properties of a particular cover and with the angle of inclination. For common cover materials, the values can be obtained from data books. The value can also be estimated by measurements from first principles as explained above

The tank volume was measured by repeatedly emptying the water from a fully loaded tank into a calibrated jug and calculating the cumulative volume in liters. The mass of the load was then calculated by first principles using the density of water.

Area of the absorber was estimated by measuring the absorber length and breadth of the rectangular absorber, using a steel measuring tape, then using the area formulae. Location was established using a GPS device

To answer the research questions, the following experiments were conducted; Inclination test was done withorientation of the collector higher side set facing North, a glass cover and finned absorber were fitted. The experiment was conducted at inclination angles of 0° (Horizontal), 15°, 30°, 45°, 60°.

Orientation test was done with inclination of the collector at 30°; a glass cover and finned absorber were fitted.Collector was tested facing E, NE, N, NW, W.

Covers test were done withno cover, plastic cover and with glass cover. For this test, the inclination of the collector was 30° and orientation of the collector higher side was set facing north.

Adequate data for stratification analysis was automatically acquired all the time as the other tests were being conducted.

3.4Procedure

Step by step procedure of how tests in section 3.5 were conducted, are given in this section. All tests were done at Latitude: -1° 07' 12" S. Longitude: -36° 58' 10" E. Location was by GPS.

3.4.1 Set up for sensors and data loggers

The thermocouples were fixed at eight different positions inside the heater tank as indicated in figure 3.1 and were monitored through a Picolog TC-08 temperature logger and a computer. A solar irradiance meter was used to monitor the ambient air temperature and the solar intensity and placed beside the absorber. The ambient temperature sensor was placed below the stand where there was no direct sunlight, while the solar sensor was placed directly in the suns beam, alongside the absorber and at the level and inclination angle of the absorber.

3..4.2 Inclination Angles Test

A glass cover was fitted to the cistern. The cistern was then oriented to face north with the absorber set at a horizontal level (0°) using the solar survey 200 compass orientation and surface inclination functions. A standard spirit level was used to confirm the horizontal position while at the same time verifying the datum of the solar survey 200. Data was recorded from 8.00 am to 3.30 pm, with the data loggers sampling at a frequency of 10 minutes. Data recorded was then saved in a computer file at the end of each day. The above procedure was then repeated in consecutive days with the inclination settings of 15°, 30°, 45°and 60°, each configuration’s results were taken each on its own day. The angular measurement is as illustrated in figure 3.4.

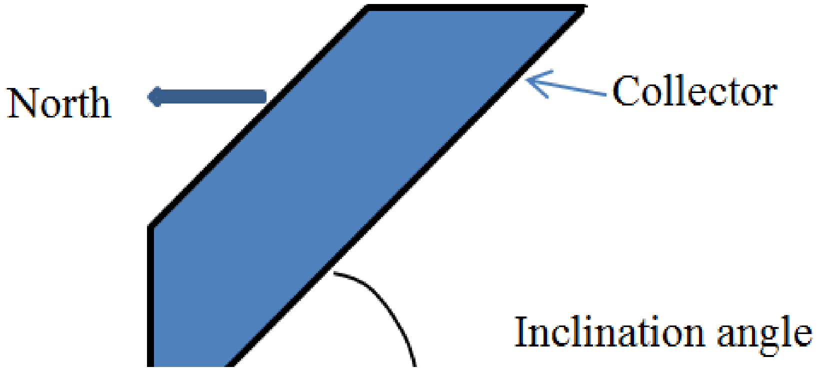

Figure 3.4: **Setting the inclination angle of the collector**

3.4.3 Orientation Angles Test

A Glass Cover was fitted to the cistern. The cistern was then oriented to face East with the absorber set at an inclination angle of 30° using the solar survey 200 orientations and inclination function. Data was taken from 8.00 am to 3.30 pm with the data logging sampling at a frequency of 10 minutes. The above procedure was then repeated in consecutive days with the higher end of the absorber facing E, NE, N, NW and W (figure 3.5) consecutively, each configuration’s results taken on its own day.

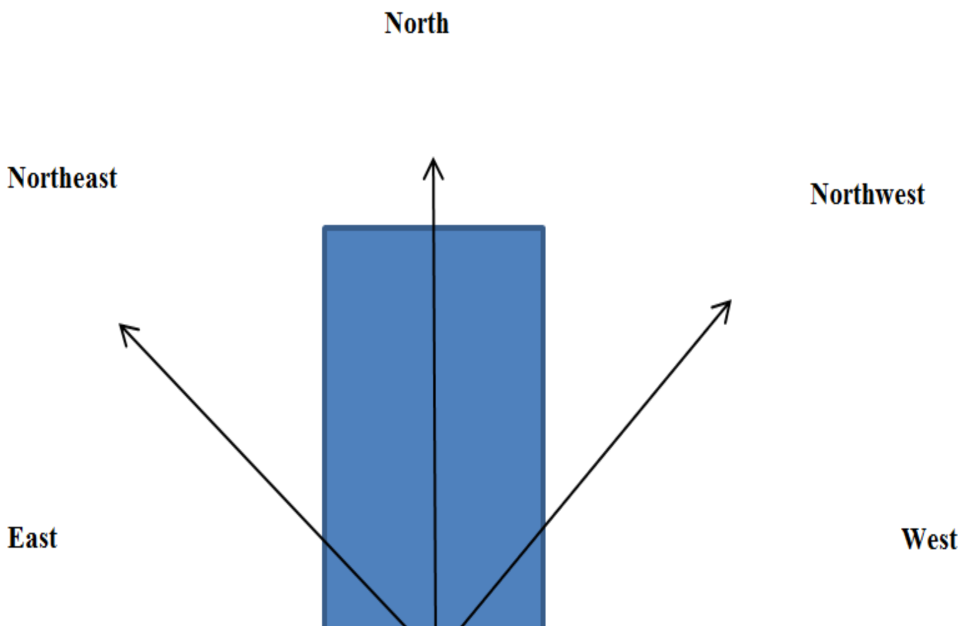

Figure 3.5: **Orientation angles of the collector**

3.4.4 Covers Test

With no cover fitted to the cistern, the absorber was set at an inclination angle of 30° and orientation facing north, using the solar survey 200 orientation and inclination functions. Data was taken over a whole day from 8.00 am to 3.30 pm with the data logging sampling at a frequency of 10 minutes. The procedure was repeated in consecutive days with the cistern fitted with a plastic cover and a glass cover in that order, each configuration's results taken on its own day.

3.4.5Absorbers Test

To check for effect of fins/baffles connected to the absorber, the following was done. Two absorbers were made, one plain and the other with fins. The pattern of the fins was made such that heat from the absorber will flow into the inner depths of the tank through these fins and also that they disrupt convective currents in the tank, hence mixing up the water and reducing stratification. The dimensions and location of the fins was not optimized. The pattern of the fins as applied in this study is as previously shown in figure 3.1.

For this test a glass cover and a plain absorber were fitted to the cistern. The collector was then set at an inclination angle of 30° and with the higher side of the collector facing north. Data was recorded from 8.00 am to 3.30 pm with the data loggers sampling at a frequency of 10 minutes. Data collected was then saved in a computer file.

The above procedure was repeated in a consecutive day with the cistern fitted with a finned absorber.

3.4.6 Cover Transmissivity

Transmissivity is an indicator of how much solar energy is passing through a cover compared to what would have passed if there was no cover.

For measuring the transmissivity of the glass and the clear plastic material used as covers, the following was done. The experiment was timed to take place at solar noon, on a clear sunny day. The sun was used as the radiation source that would be transmitted through the materials under test. The setup of the apparatus was as shown in figure 3.6.

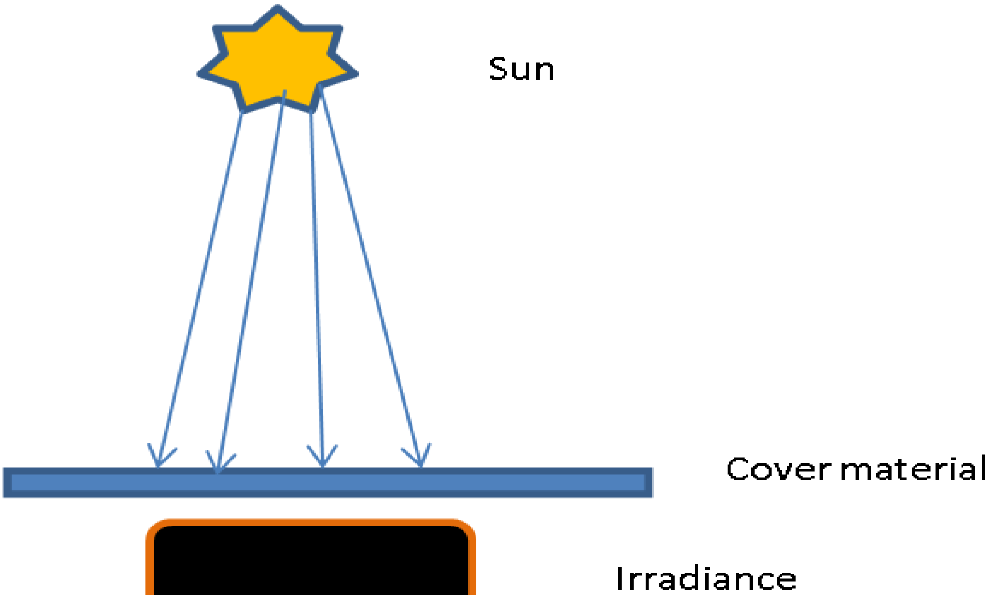

Figure 3.6: Measuring Transmissivity directly using the sun as a source

The solar survey 200 meter was placed on a horizontal surface and this position verified by use of a spirit level. The reading with the no material on top was made and recorded. The material whose transmissivitywas being estimated was placed in a horizontal plane 2 cm above the irradiance meter, and the plane verified. An irradiance reading in watts per square meter was read and recorded. Same procedure was repeated with plastic material stretched on a wooden frame and again with no cover on top.

The ratio of the reading with the material on top and the reading with no material was calculated as the transmittance with the beam angle of 90° to the receiving surface, for each of the materials.

3.4.7 Collector efficiency

To measure the collector efficiency, the collector was set at the most optimum angles of inclination and orientation with a glass cover and finned absorber. The optimum angle was estimated experimentally as 60° to the horizontal. The water was then loaded at 10.45 am and data logging started at 11.00 am to 1.00 pm. The irradiance and temperature data was used to estimate the efficiency of the collector using standard equations.

In this section, the refined data from all the tests in the study is presented. Tc a is the ambient temperature, Tc 1 to Tc 4 are temperatures of the sensors near the absorber and Tc 5 to Tc 8 are temperatures of the sensors near the bottom of the tank. Irradiance data was measured in W/m^2 at particular inclinations and orientations of the absorber, while time of day was generated by the logging equipment. Temperatures were measured with a resolution of 0.01°C, but rounded off to the nearest degree.Irradiance was at a resolution of 1 W/m^2, while time was measured at a resolution of 1 second.

The total volume of the water in the tank was found to be equal to 38 liters. This multiplied by the density gave the mass of water as equal to 38 kg.

The area of the absorber was calculated at two levels;thecollector aperture area, Ac was equal to 0.3266 m^2 while the effective absorber area, A was equal to 0.2442 m^2.

The position coordinates were measured as using a GPS receiver and found to be latitude -1.143°,while longitude was -36.969°.

The readings were recorded at these three instances; with the plastic material, with the glass material and with nothing above the solar sensor at a beam to surface of 90°(solar noon).

All the recorded data for collector with various covers was done at a collector inclination of30°, the higher side of the collector facing north.In all temperature graphs the following legend is used;

Tc a is the ambient temperature

Tc 1-Tc 4 is mean temperatures of the sensors near the absorber

Tc 5-Tc 8 is mean temperatures of the sensors near the bottom of the tank

Tc1-Tc 8 is meantemperatures of the all eight sensors inside the tank

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1Various covers

Table 4.1: Irradiance readings with various materials on top

Angle	Reading in W/m^2
No material on top	965
With glass material	820
With plastic material	888

Based on data in table4.1, the following were the calculated transmittance; plastic material was calculated to 0.92 while glass material was 0.85.

4.1.1 Collector with No Cover

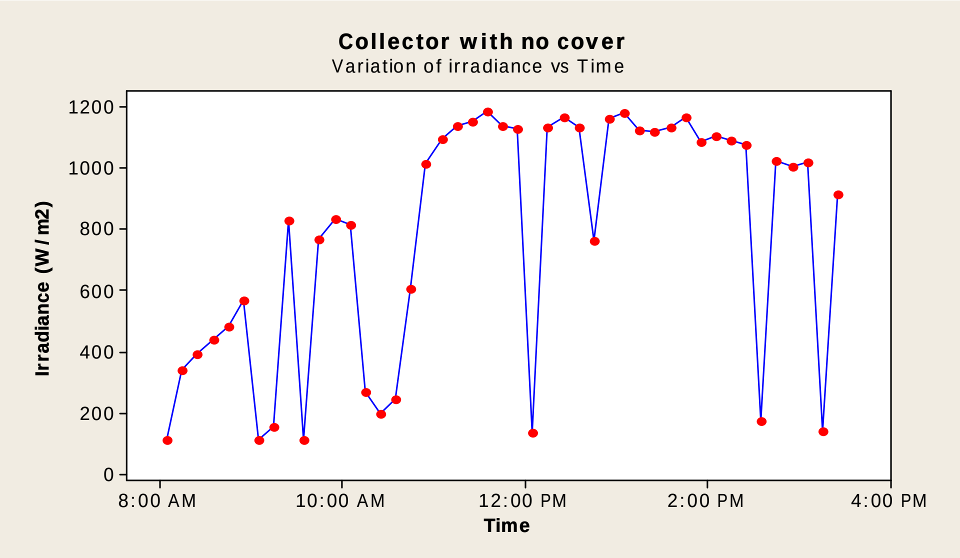

Figure 4.1: Irradiance variation with no cover on collector

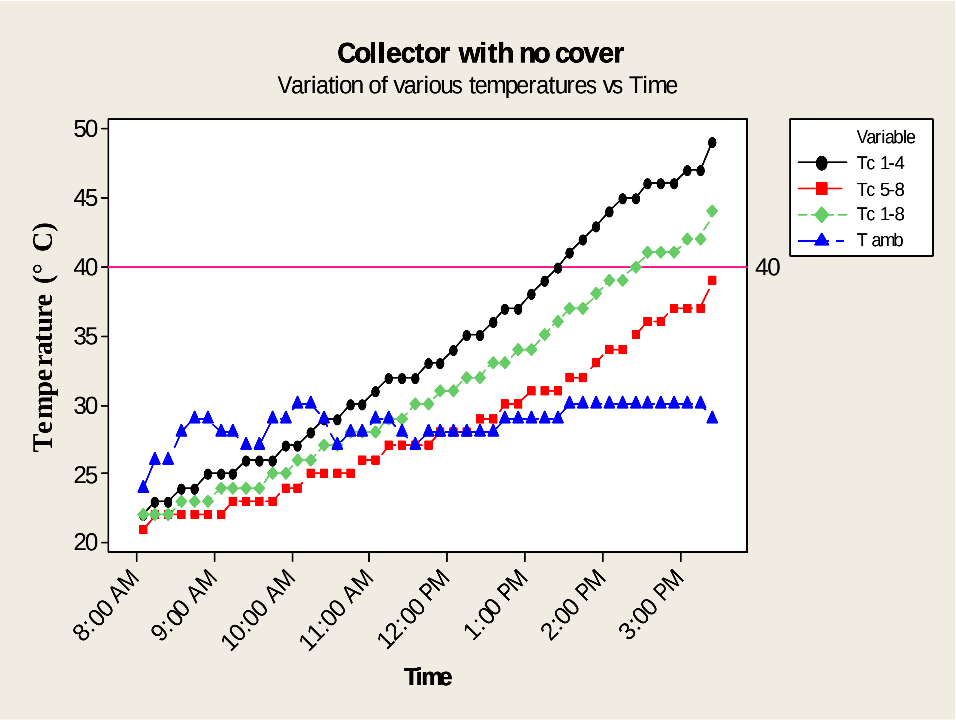

Figure 4.2: Temperature variation with no cover on collector

4.1.2 Collector with plastic cover

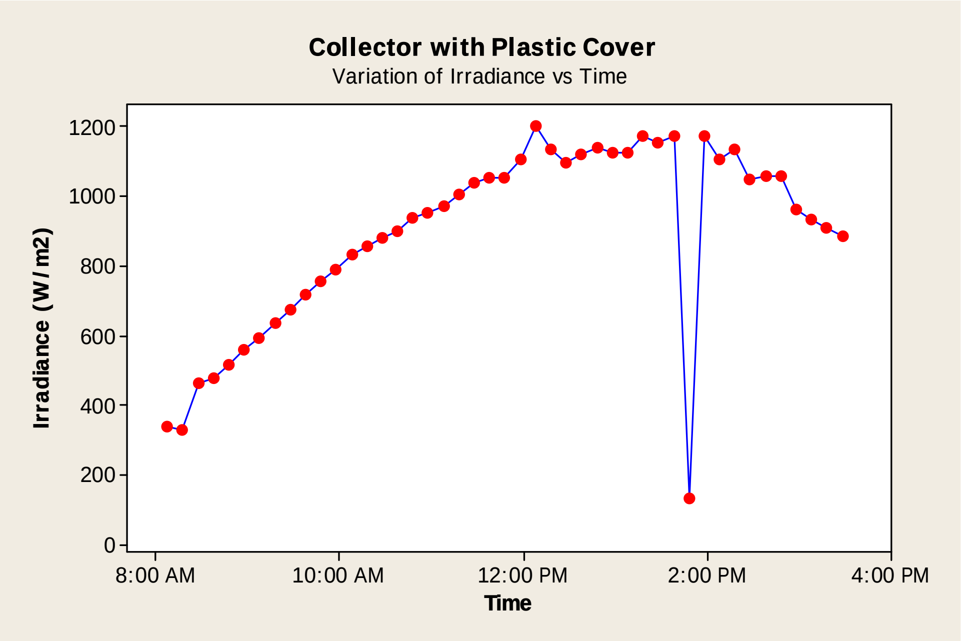

Figure 4.3: Irradiance variation with plastic cover on collector

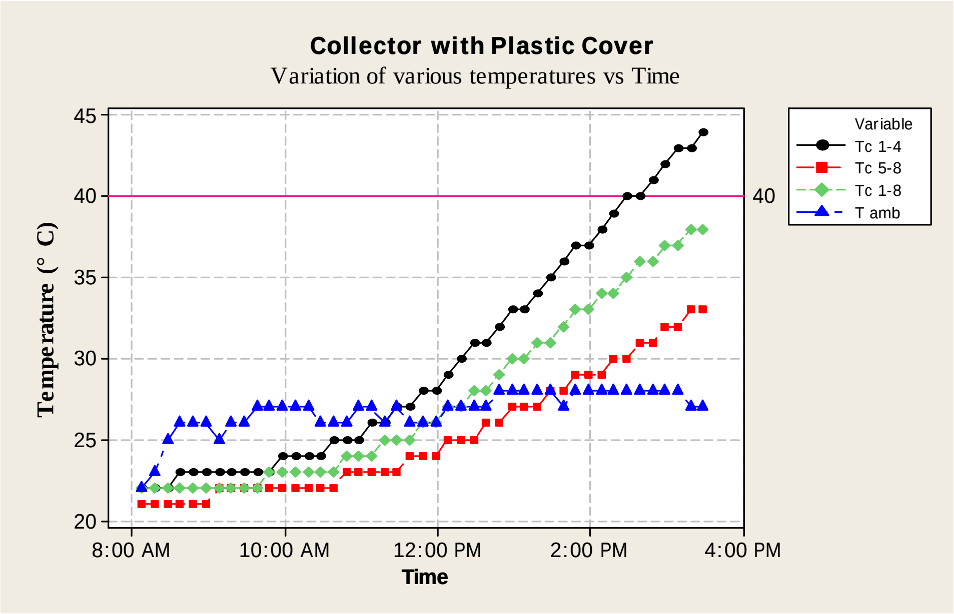

Figure 4.4: **Temperaturevariation with Plastic coveron collector**

4.1.3Collector with glass cover

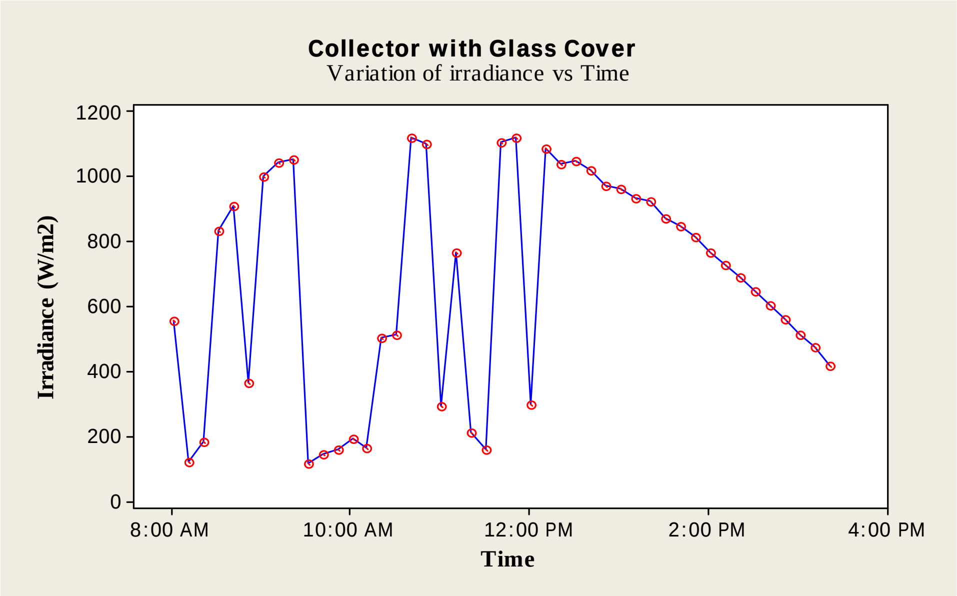

Figure 4.5: **Irradiance variation with Glass Cover on collector**

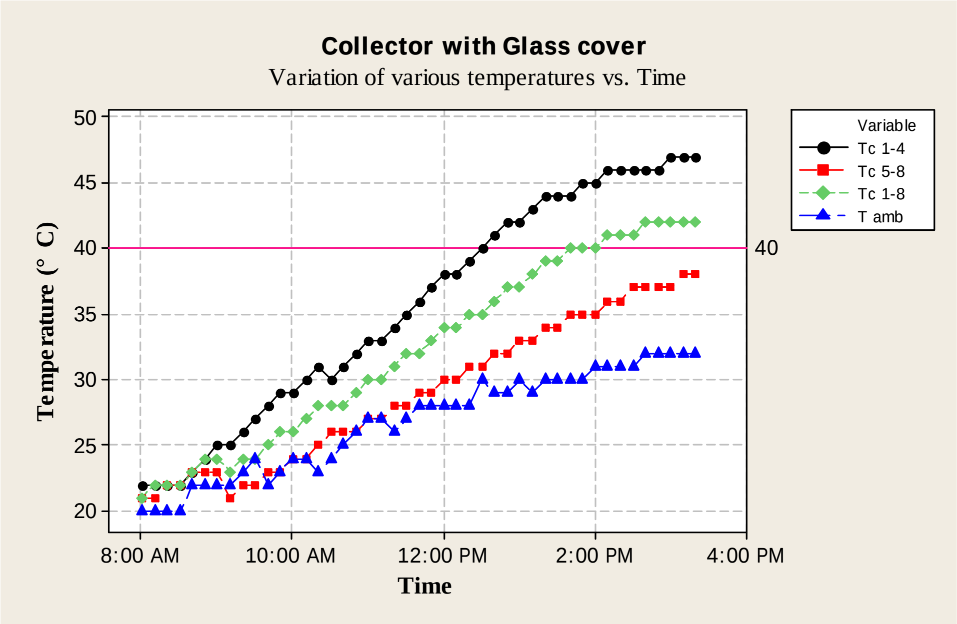

Figure 4.6: Temperatures variation with Glass Cover on collector

There are no marked variances in the stratification of temperatures at the top and bottom levels of the collector with various covers installed as can be seen in figures 4.2, 4.4and 4.6. In figure 4.2, the collector mean temperature was equal 40 °C at 2.25 pm. The mean irradiance during the test form 8.00am to 3.30 pm was calculated as 905.7 W/m^2. This was much lower than the mean irradiance of with plastic cover 1017W/m^2 (figure 4.3), where the collector mean temperature did not manage to hit the target of 40 °Cat a mean irradiance 1017W/m^2 as recorded figure 4.4. This may suggest that perhaps the losses due to transmittance (calculated as 0.92 in section 4.4) combined with increased reflective losses at that angle, may have contributed to the lower performance. The glass cover performed the best, and the reason is because even though the glass cover had the least transmittance at 0.85, it provided best insulation against losses to the atmosphere.

4.2Performance with various collector orientations

These tests were done with a glass cover with a collector inclination of 30°

4.2.1 Collector facing east

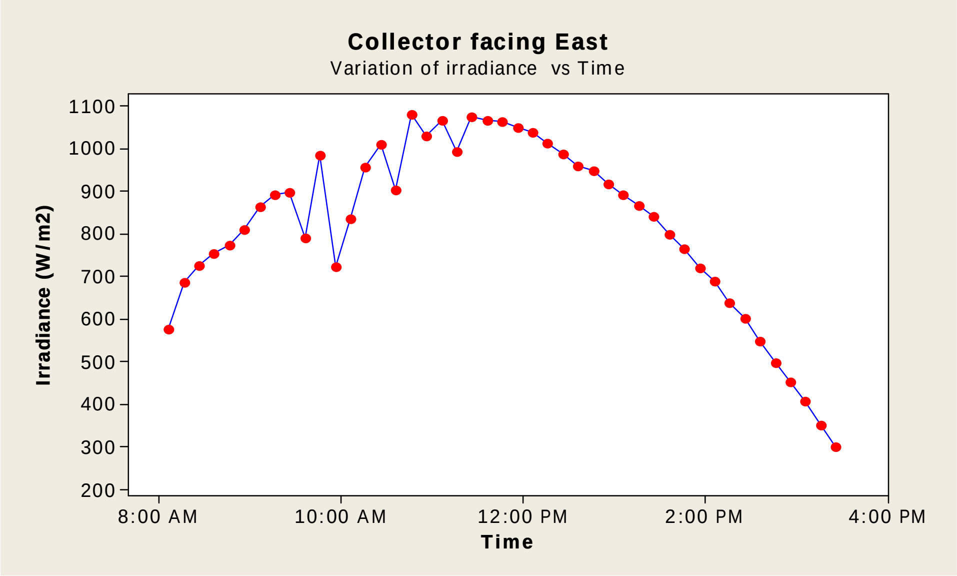

Figure 4.7: **Irradiance variation with collector facing East**

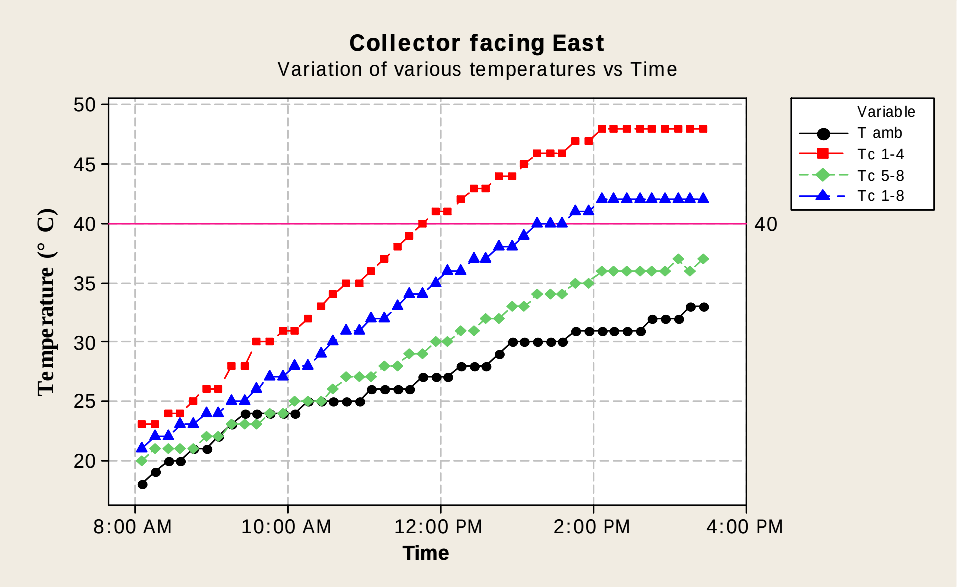

Figure 4.8: **Temperature variation with collector facing East**

4.2.2 Collector facing Northeast

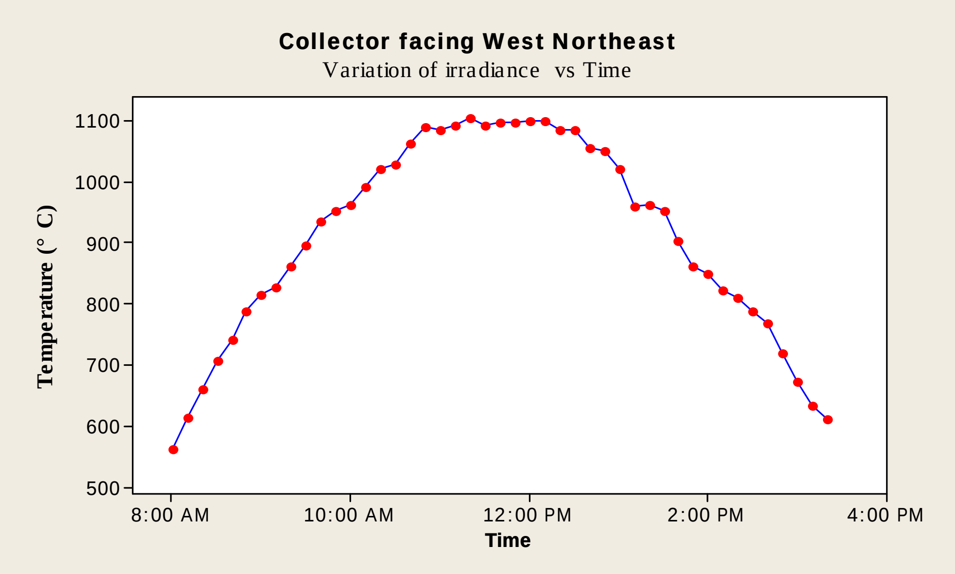

Figure 4.9: Irradiance variation with Collector facing Northeast

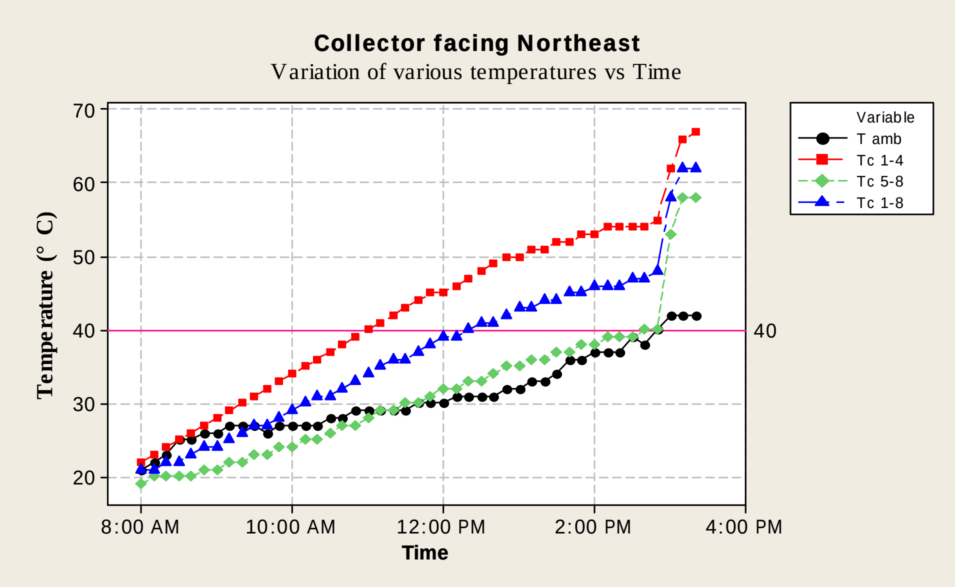

Figure 4.10: Temperatures variation with collector facing Northeast

4.2.3 Collector facing Northwest

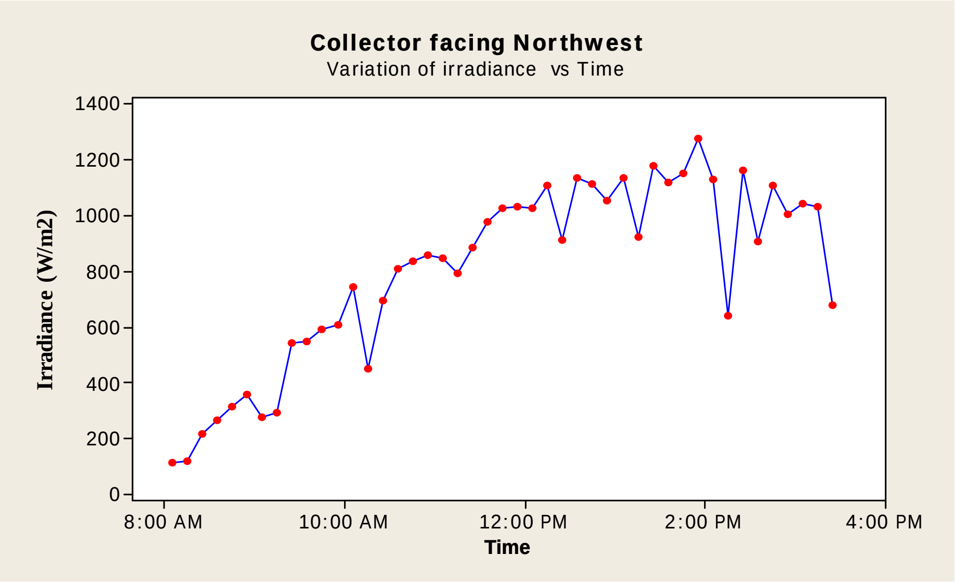

Figure4.11: Irradiance variation with collector facing Northwest

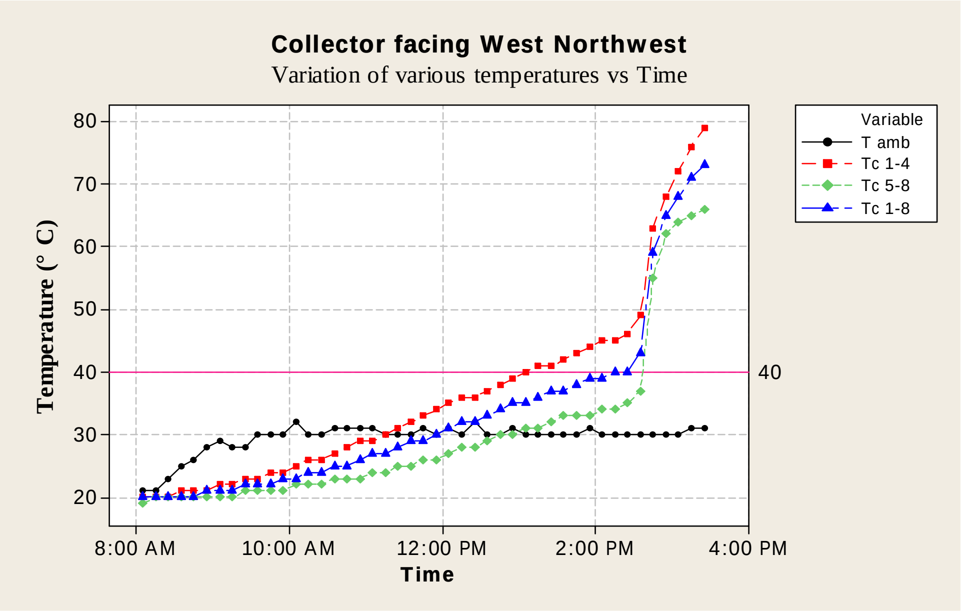

Figure 4.12: Temperature variation withcollector facing Northwest

4.2.4 Collector facing North

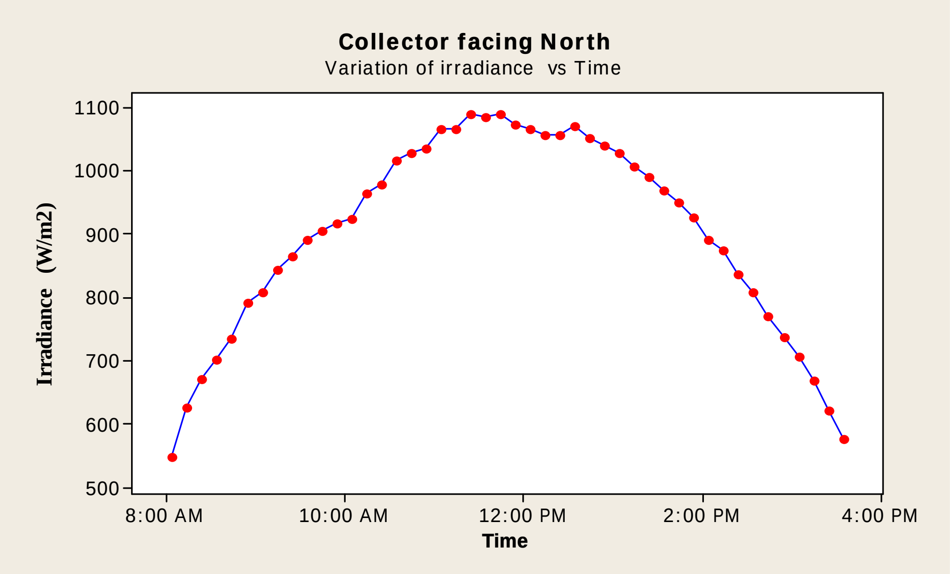

Figure 4.13: Irradiance variation with Collector facing North

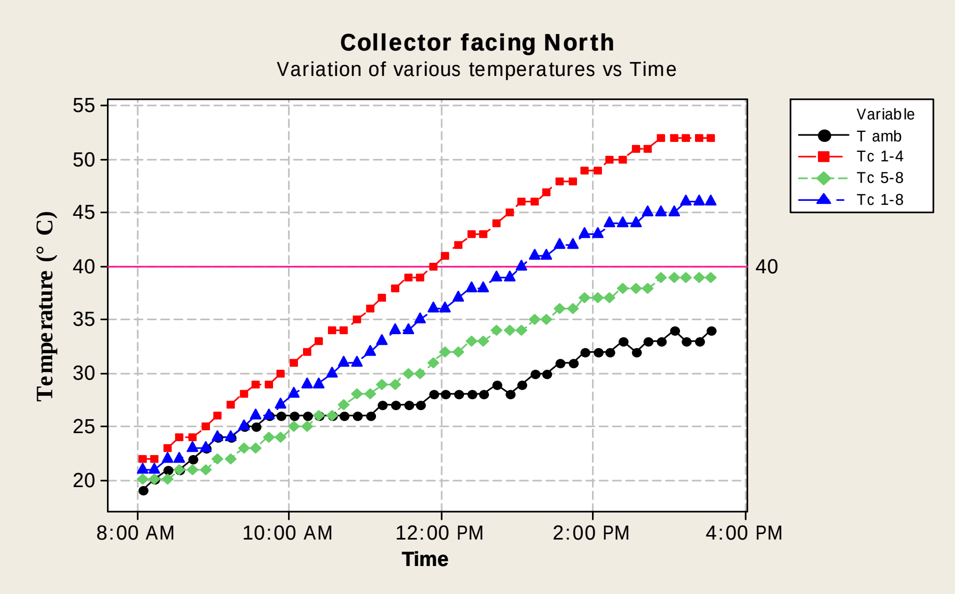

Figure 4.14: Temperature variation with collector facing North

4.2.5 Collector facing West

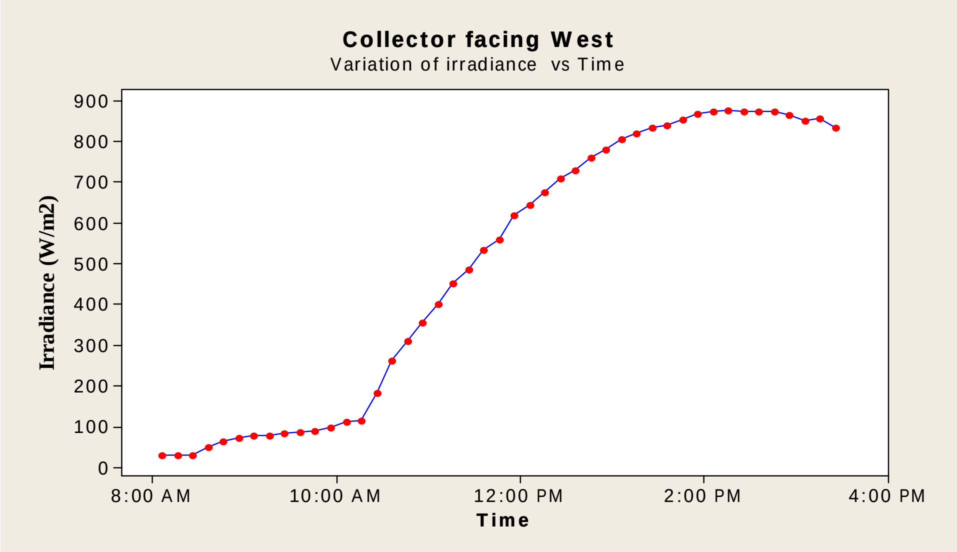

Figure 4.15: Irradiance variation with collector facing West

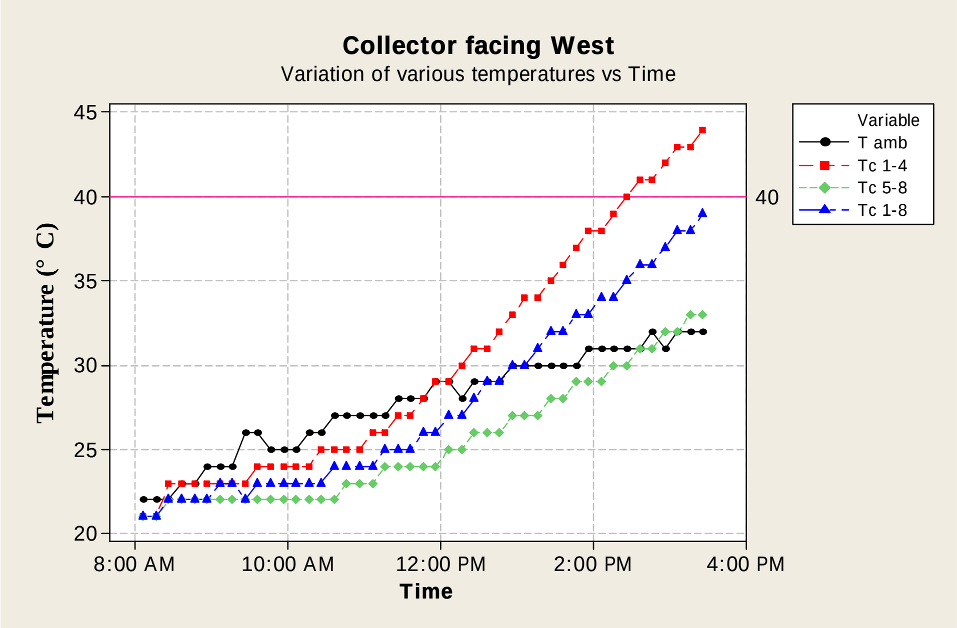

Figure 4.16: Temperature variation with collector facing West

4.3Performance at various collector Inclinations

These tests were done with Glass Cover, with the collector higher side facing north.

4.3.1 Tests for 0° Inclination

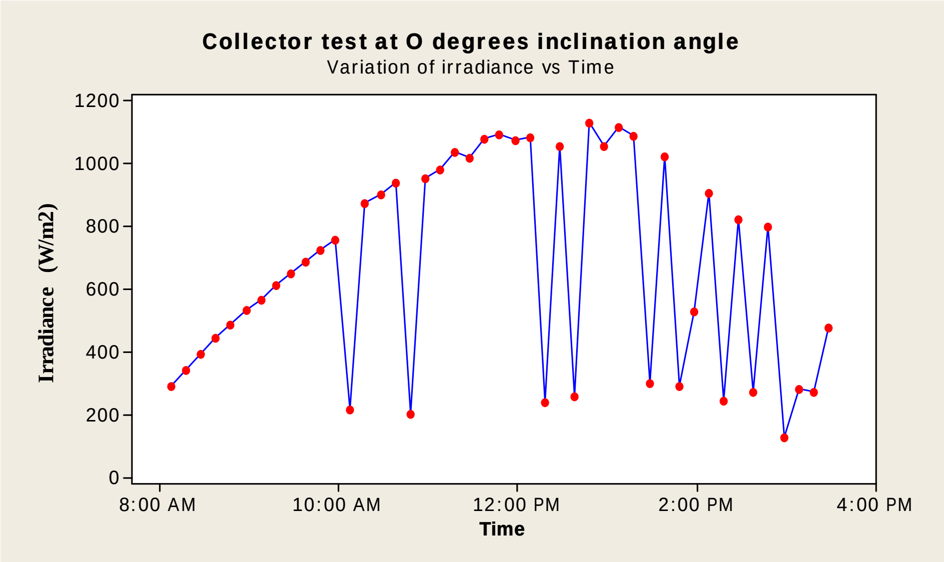

Figure 4.17: Irradiance variationat 0°collector inclination

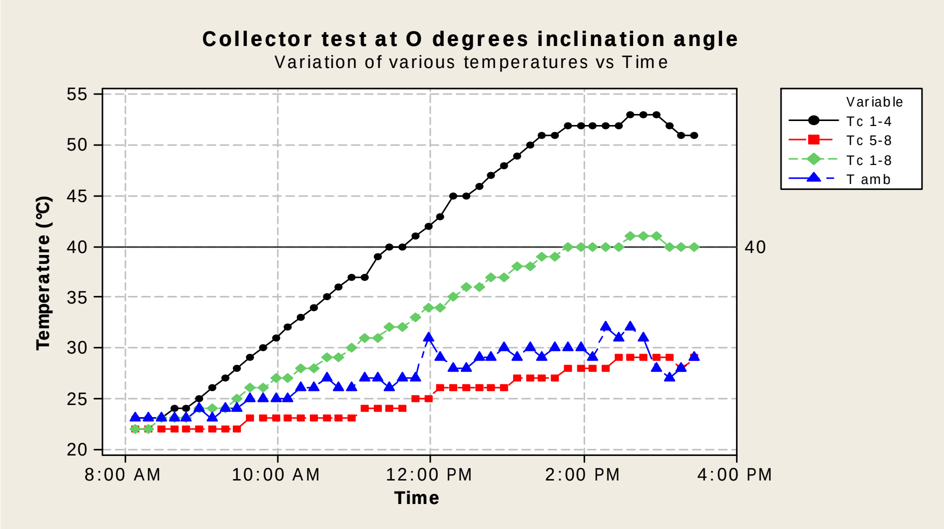

Figure 4.18: Temperature variation at 0°collector inclination

4.3.2 At 15°Collector Inclination

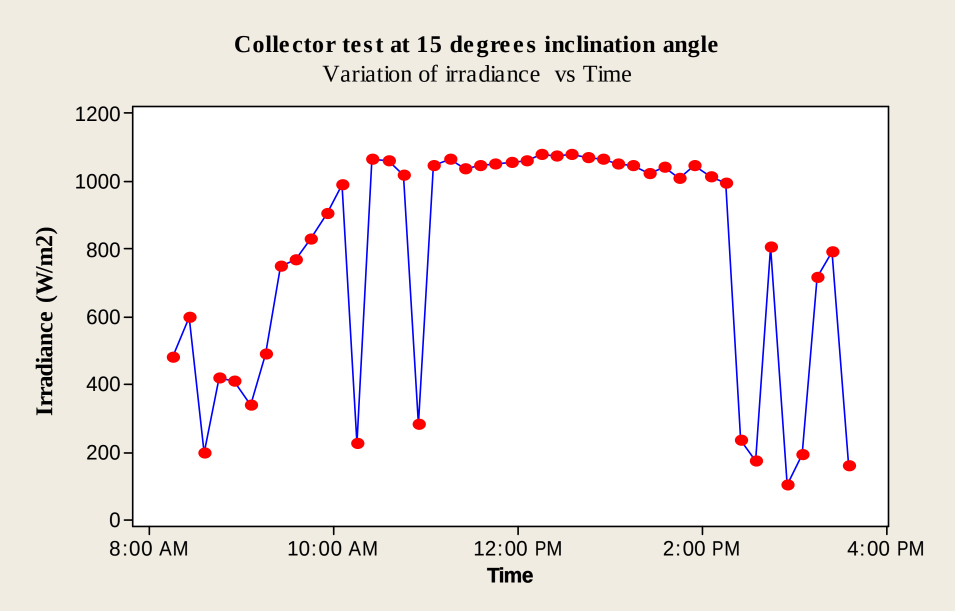

Figure 4.19: **Irradiance variation at 15°collector inclination**

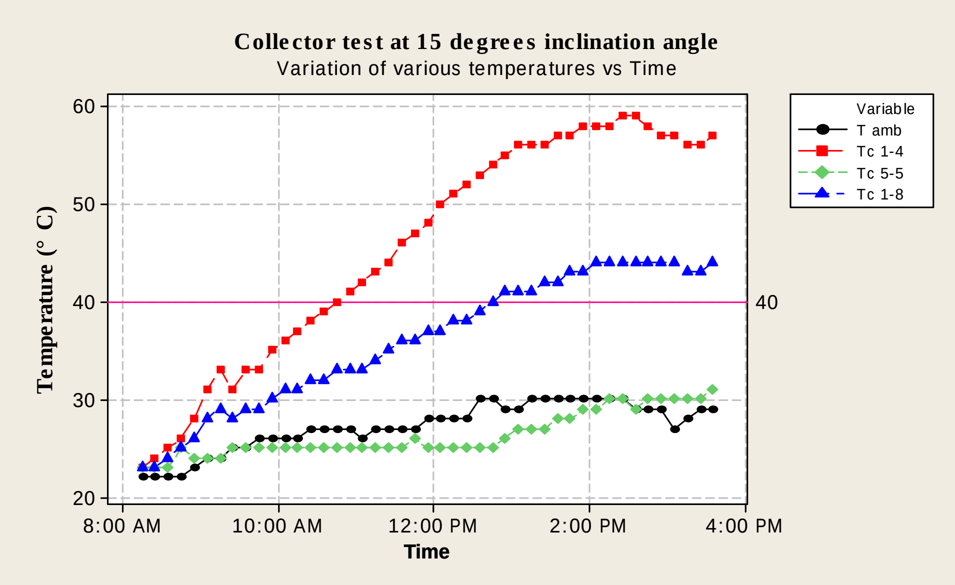

Figure 4.20: **Temperatures variation at 15° collector inclination**

4.3.3 At 30° Inclination

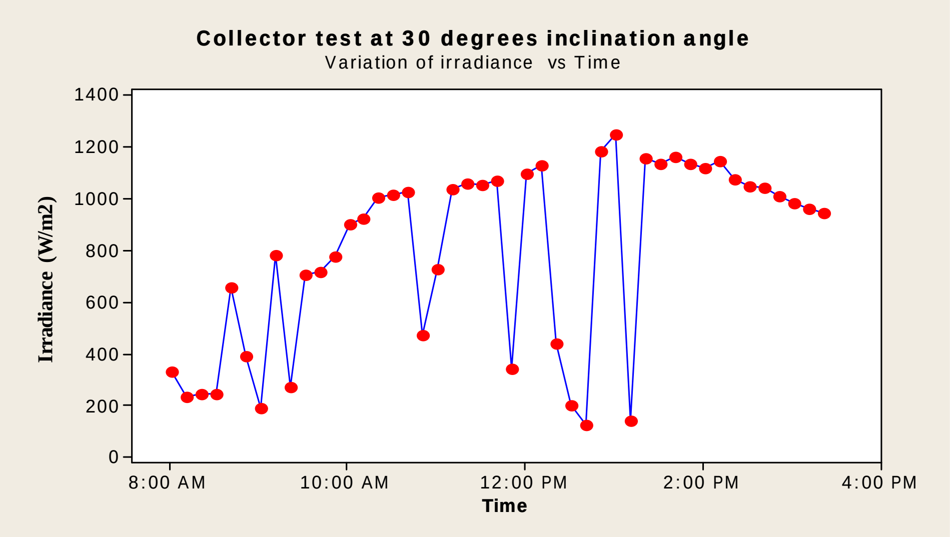

Figure 4.21: Irradiance variation at 30°collector inclination

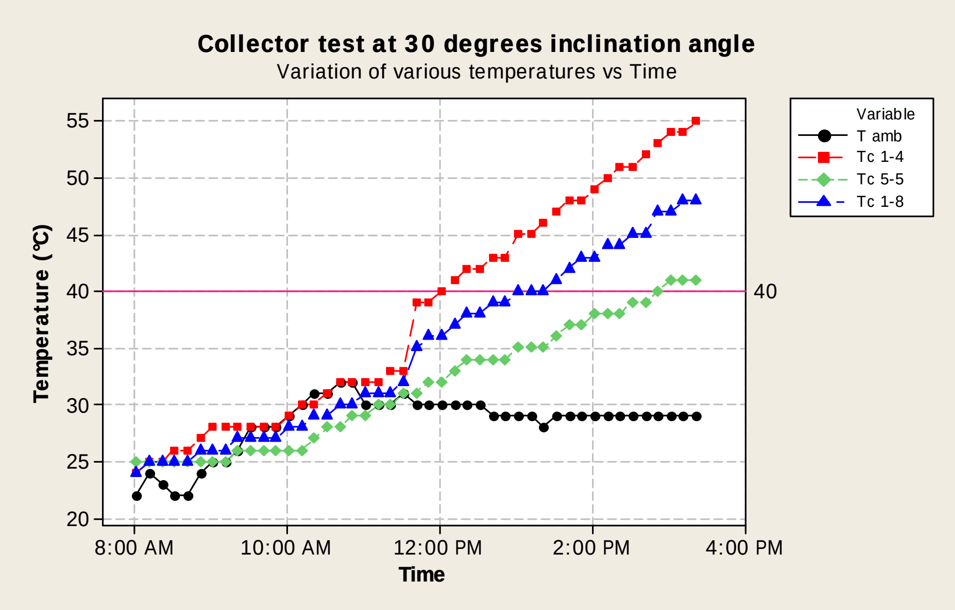

Figure 4.22: Temperaturevariation at 30°collector inclination

4.3.4 At 45° Inclination

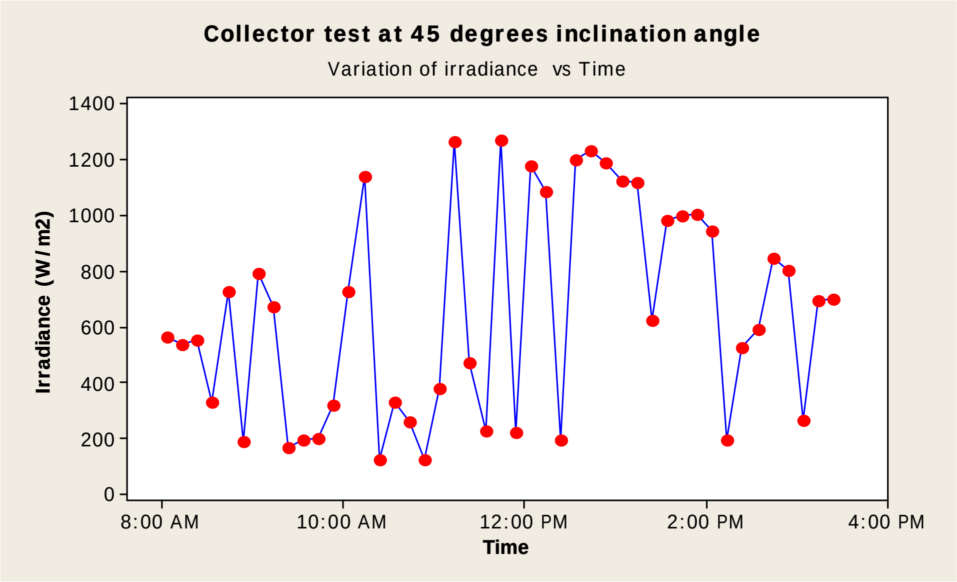

Figure 4.23: Irradiance variation 45°Collector inclination

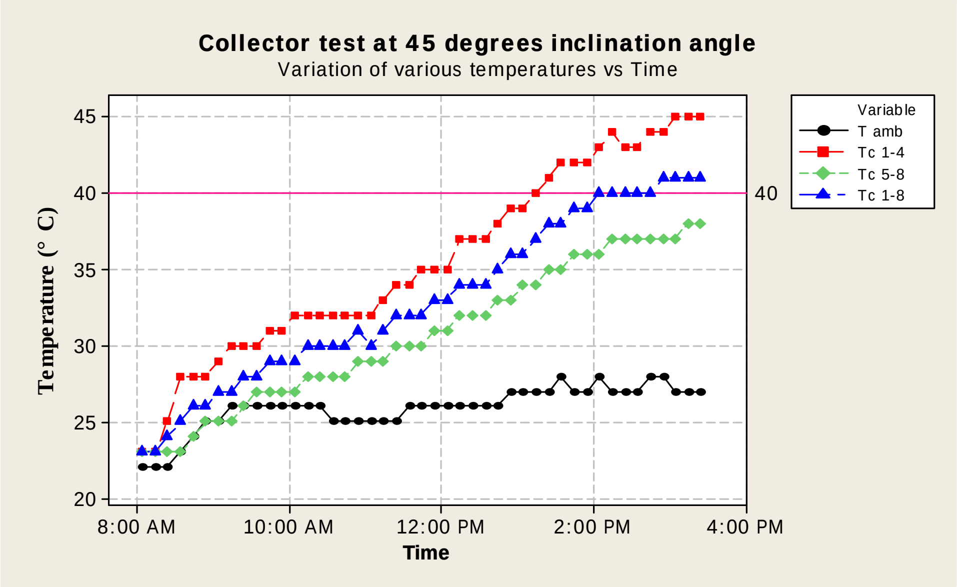

Figure 4.24: Temperature variation at 45°collector inclination

4.3.5 At 60° Inclination

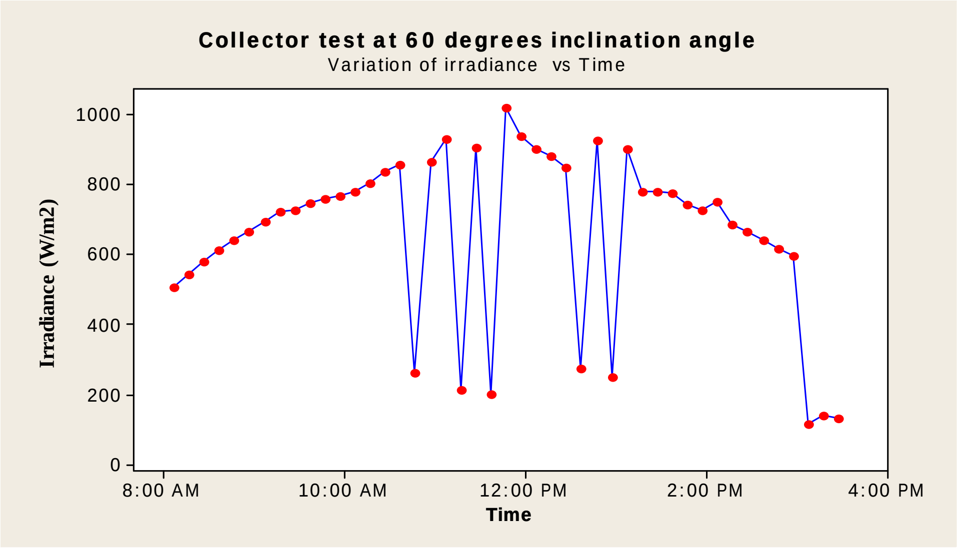

Figure 4.25: **Irradiance variation at 60°Collector inclination**

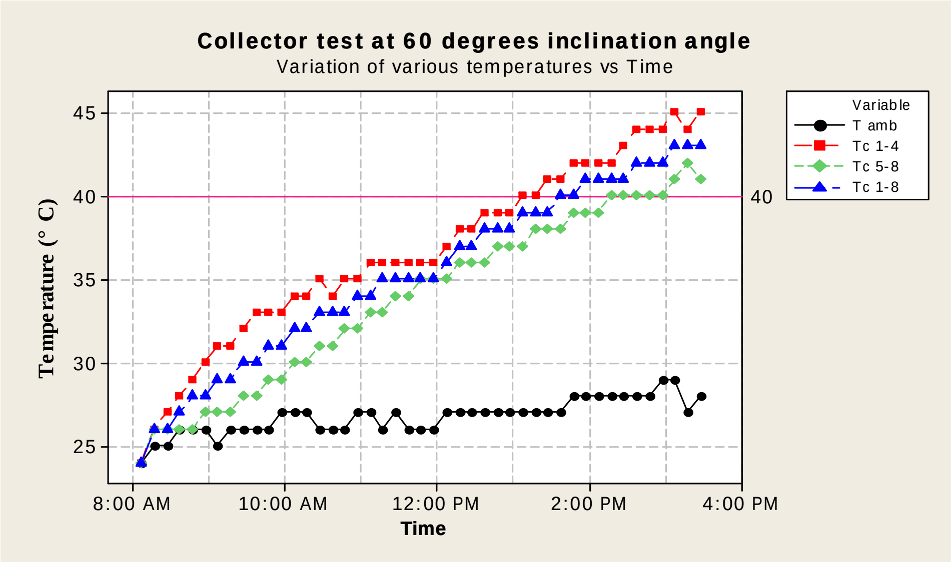

Figure 4.26: **Temperature variationat 60°collector inclination**

4.4Analysis of absorbers

4.4.1 Plain (non-finned) collector

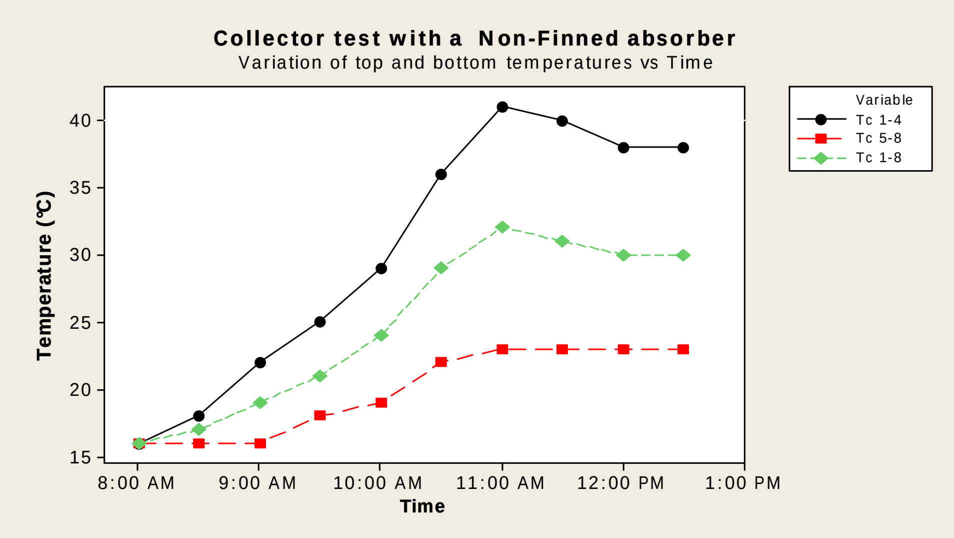

Figure 4.27: Temperature variation witha plain absorber

4.4.2Finned collector

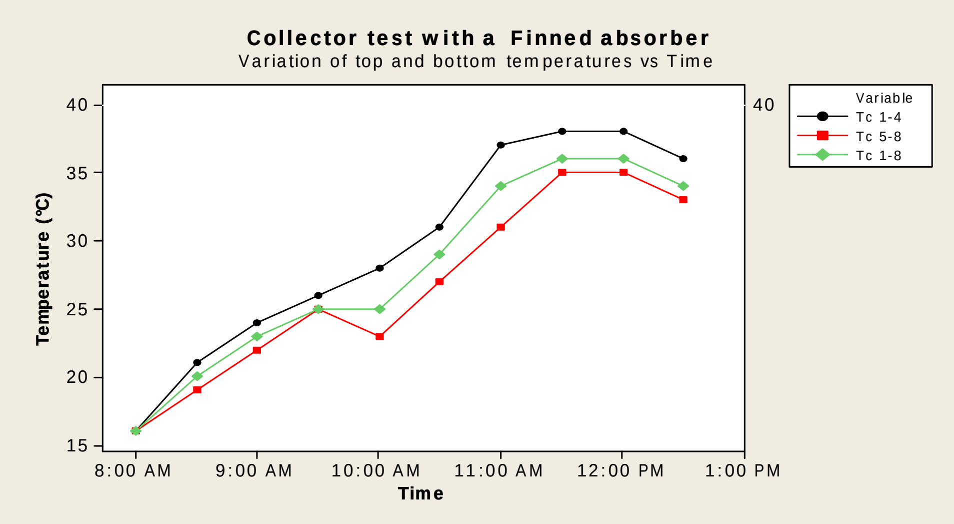

Figure 4.28: Temperature variation with a finned absorber

4.4Summary of collector performance

Table 4.2 indicates the time taken by the collector to hit target temperature of 40 °C with the various cover materials. The minimum and maximum temperatures recorded in the collector during the test are also indicated.

Table 4.2: Summary of tests with different covers

Cover Type	**Time to reach Target temperature (40 °C)**	**Minimum Collector Temperature (°C)**	**Maximum Collector Temperature (°C)**	**ΔT**
Plastic cover	1.48 pm	37	29	8
Glass cover	1.41 pm	44	35	9
No cover	3.28 pm*	38	22	16

***this configuration did not manage to attain the target temperature but these are the conditions at the end of the experiment.**

Table 4.3 indicates the inclination angles used, the time the target temperature was reached and the average temperatures at the top and bottom of the collector. The positive difference between the two temperatures was the recorded stratification at that inclination.

Table 4.3: Summary of tests at various inclinations

Inclination	**Time to reach Target temperature (40 °C)**	**Top of Collector Temperature (Tc 1-4) (°C)**	**Bottom of Collector Temperature (Tc 5-8) (°C)**	**Stratification °C**
0°	1.48 pm	52	28	24
15°	12.45 pm	54	25	29
30°	1.01 pm	45	35	10
45°	2.04 pm	43	36	7
60°	1.37 pm	41	38	3

Table 4.4 indicates the orientation angles used, the time to the target temperature and the average temperatures at the top and bottom of the collector. The positive difference between the two temperatures was the recorded stratification at that orientation angle.

Table 4.4: Summary of tests at various orientations

Orientation Angle	Time to reach Target temperature (40 °C)	Top of Collector Temperature (Tc 1-4) (°C)	Bottom of Collector Temperature (Tc 5-8) (°C)	Stratification °C
E	1.16 pm	46	34	12
NE	12.20 pm	47	33	14
N	1.04 pm	46	34	12
NW	2.15 pm	45	34	11
W	3.26 pm	44	33	11

Table 4.5 indicates the types of covers used and the average temperatures at the top and bottom of the collector. The positive difference between the two temperatures was the recorded stratification for the specific absorber design. NE direction gave the highest maximum temperature,

Table 4.5: Summary of Different absorbers

Design of Absorber	Top of Collector Temperature (Tc 1-4) (°C)	Bottom of Collector Temperature (Tc 5-8) (°C)	Stratification °C
Finned collector	36	33	3
Non-finned collector	38	23	15

4.5Collector efficiency estimation

The efficiency was estimated by taking the area under the curve in figure 4.29 as the total aggregated energy required to raise the average temperature of the water from 23 °C to 33 °C between 11.05 pm to 1.05 pm as indicated in table 4.6. The efficiency was estimated to be 20.3 %.

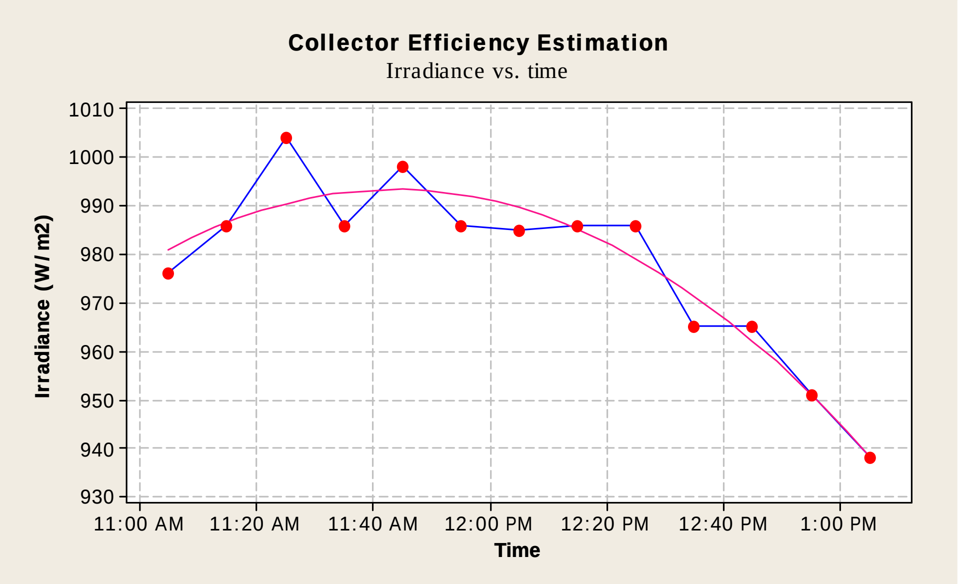

Figure 4.29: Variation of Irradiance with Time of day

Table 4.6 indicates irradiance readings at various times and the prevailing ambient temperature at that instant together with the collector mean temperature.

Table 4.6: Efficiency calculation data

Time	Irradiance	T ambient	Tc 1-8
11:05 AM	976	27	23
11:15 AM	986	27	25
11:25 AM	1004	27	26
11:35 AM	986	28	26
11:45 AM	998	28	27
11:55 AM	986	28	28
12:05 PM	985	28	29
12:15 PM	986	29	30
12:25 PM	986	29	31
12:35 PM	965	30	32
12:45 PM	965	30	32
12:55 PM	951	30	33
1:05 PM	938	31	34

4.6 Comparison of costs

Table 4.7 indicates the costs of purchase for a charcoal cistern, the costs of running such a cistern for one year and estimated costs of maintenance. The total for all these costs is KES 45,500.

Table 4.7: Charcoal heater costs for one year

Costs	Amounts (KES)	Total (KES)
Purchase	2000	2,000
Charcoal one year	60 x 2 x 30	43,200
Repair	300	300
TOTAL		45,500

In table 4.8 the total costs for fabricating, maintenance and running costs have been aggregated to a total of KES 9,100.

Table 4.8: ICS collector Costs for one year

No	Item	Amount (KES)
1	Plastic Tankand insulation	2000
2	Wooden Frame And Stand	1,000
3	Absorber Material And Fabrication	1,800
4	Rubber Gaskets	600
5	Glues	900
6	Nails, Screws And Fixtures	400
7	Glass Cover	400
8	Labor	2,000

	Sub total	8,100
	Running costs per year	
9	Fuel	0
10	Repair/maintenance	1,000
	Grand total	10,100

4.7 Discussion

4.7.1 Orientations

From the above data it evident that some positions are better than others. With the collector facing east, the collector receives its peak irradiance in the morning accumulating a mean irradiance of 829 W/m^2 as seen in figure 4.7 for the period of the test.The overall collector temperature attained the target 40°Cat 1.16 pm as illustrated in figure 4.8.

In the northeast direction, the mean radiation was 970 W/m^2(figure 4.9) with the collector hitting the target 40°C quite late at 2.15 pm(figure 4.10). This suggests if the hot water is required at lunchtime (by 1.00 pm) then this orientation is not suitable. This time is improved with the north orientation with a mean irradiance of 945 W/m^2(figure 4.13) where the target 40°C occurred at 1.04 pm (figure 4.14). The maximum of that day leveled off at 53°C.

In the northwest direction, the irradiance peaked in the afternoon (figure 4.11), with the collector hitting the target 40°C quite late past 2 pm (figure 4.12). Overall the performance at this orientation is poor.An interesting phenomenon that was observed occurs whenever the irradiance starts dropping immediately after a spell of high intensity. The observation is that all the temperatures being monitored start rising sharply to high levels as happens at 3.00 pm in figure 4.10. The same observation is evident at 3.00 pm in figure 4.12 and at 11.30 am in figure 4.22 although not as marked as in the first two cases.

The worst case observed with the collector facing west. The irradiance was at a mean of 668 W/m^2 illustrated in figure 4.15 where it is observed that the morning irradiance up to 10.30 pm was very low. The irradiance peaked at around 2.00 pm with the result that the target temperature was never attained by 3.30 pm when the experiment stopped as illustrated in figure 4.16.

The difference in stratification of temperatures between top and bottom inside the collector did not improve with all the different orientations, so all positions were equal on this basis. But the north east and the north orientations in that order, achieved the best times to hit the target temperature.

4.7.2 Inclinations

In the case of 0° inclination at a mean irradiance of 673 W/m^2 (figure 4.17), the maximum mean temperature reached with all sensors taken into account was 40.9 °C as indicated in figure 4.18. The target temperature was hit at 2.18 pm at which time the mean for all the sensors was 40°C the top sensors averaging 40°C and the bottom sensors averaging 28°C. It was noticed that at this inclination position there was heavy stratification with the bottom water being at almost ambient. This is also an indication that thermosyphon action was not very active hence the mixing baffles were useless. It also meant that the action of the baffles to even out the temperature in the tank relied more on thermosyphon action than on conducting heat from the absorber into the lower layers of the tank contents.

In the case of 15° inclination at a mean irradiance of 779 W/m^2 (Figure 4.19), the maximum mean temperature reached with all sensors taken into account was 43.8°C as indicated in figure 4.20. The target temperature was hit at 12.55 pm at which time the mean for all the sensors was 40.6°C the top sensors averaging 40°C and the bottom sensors averaging 28°C. It was noticed that at this inclination position there still was heavy stratification with the bottom water temperature measuring near ambient. This is an indication that thermosyphon action was still not very active.

In the case of 30° inclination at a mean irradiance of 792 W/m^2 (figure 4.21), the maximum mean temperature reached with all sensors taken into account was48.0°C as indicated in figure 4.22. The target temperature was hit at 1.21 pm at which time the mean for all the sensors was 40.4°C the top sensors averaging 45.5°C and the bottom sensors averaging 35.2°C. It was noticed that at this inclination position stratification had reduced by a large margin with the bottom water and the top water temperature being quite close to each other up until 11.00 am when the graphs started diverging though not to the extent of the previous two cases (0° and 15°) (figures 4.18, 4.20). This is also an indication that thermosyphon action had kicked in by creating convective currents in the tank. The reason for the sudden diverging of the graphs was because the collector had just experienced a long spell of steady irradiance just after a low fluctuating irradiance in the morning.

In the case of 45° inclination at a mean irradiance of 650 W/m^2 (Figure 4.23), the maximum mean temperature reached with all sensors taken into account was 41.3°C as indicated in figure 4.24. The target temperature was hit at 1.54 pm at which time the mean for all the sensors was 39.1°C the top sensors averaging 42.2°C and the bottom sensors averaging 36.0°C. It was noticed that at this inclination position stratification had reduced and the uniformity of temperatures inside the tank was much better than all the previous cases of 0° 15° and 30° (Figure 4.12). This is also an indication that thermosyphon action had improved. All the curves in figure 4.12 were moving steadily upwards, near each other and almost in a parallel path. Considering the relatively lower irradiance on this day that was also very intermittent (Figure 4.10), this position seems very suitable for operating the cistern. It is noted that at this position, optical losses because of the glass cover are much higher than all the previous cases (0°, 15° and 30°) hence contributing to lower irradiance incident on the absorber.

In the case of 60° inclination at a mean irradiance of 659 W/m^2 (Figure 4.25), the maximum mean temperature reached with all sensors taken into account was 43.3°C as indicated in figure 4.26. The target temperature was hit at 1.37 pm at which time the mean for all the sensors was 39.6°C the top sensors averaging 41.0°C and the bottom sensors averaging 39.6°C. It was noticed that at this inclination position uniformity of temperatures inside the tank was much better than all the previous cases (0°, 15° and 30°) but not as good as inclination angle of 45°. All the graphs in figure 4.26 were moving steadily upwards, with the top sensors being nearer the collector mean temperature curve. All the graphs were however still moving parallel to each other. The irradiance on this day was still relatively lower but much more constant than the previous day (Figure 4.24). Still this position was not as effective as 45° inclination. It is noted that at this position, optical losses because of the glass cover are even higher than all the previous cases (0°, 15°, 30° and 45°) hence contributing to lower irradiance incident on the absorber. The summaries of these inclination positions are tabulated in table 4.2.Results in table 4.2 indicates that the collector attained the highest mean temperature (52°C) at an inclination of 50°, hitting the target temperature earliest (1.01 pm) compared to all other inclination angles.

4.7.3 Absorbers

The behavior of the collector with a plain absorber is shown in figure 4.27. It is noted that the difference in temperatures between the mean top four sensors (Tc 1-4) and the mean of four bottom sensors (Tc 5-8) increases with time and when the temperature evens out, this big temperature stratification difference remains. Both of these mean temperatures maintain the same widening distance from the overall collector mean temperature (Tc 1-8).

The behavior of the collector with a plain absorber shown in figure 4.27indicates that the difference in temperatures between the mean top four sensors (Tc 1-4) and the mean of four bottom sensors (Tc 5-8) diverges out and the divergence increases with time. On the other hand the behavior of the collector with a finned absorber shown in figure 4.28 indicates that the difference in temperatures between the mean top four sensors (Tc 1-4) and the mean of four bottom sensors (Tc 5-8) does not increase with time and is much smaller compared to results of the plain collector. Both of these mean temperatures with the finned collector maintain an almost parallel distance between them and the overall collector mean temperature (Tc 1-8).

The stratification was analyzed by comparing the mean of temperatures at the top (Tc 1-4) near the absorber and at the mean of temperatures at the bottom (Tc 5-8), of the collector. The collector temperature which is compared with the target temperature is the mean temperature of all the 8 sensors in the tank (Tc 1-8). Tables 4.2 to 4.4 summarize the various configurations, the time they take to attain the target temperature of 40°C.

The summary in table 4.2 indicates the effect of the different types of collector covers on stratification. The glass cover and the plastic cover had almost the same stratification. The 'no cover' configuration did not manage to hit the target temperature by the time the experiment ended at 3:28 pm which indicated heavy losses due to convection and radiation. Table 4.2 summarizes the effect of various collector inclinations on the stratification temperatures. The stratification is highest at 0°inclination angle calculated at 24°C, 29°C at a 15° inclination angle, 10°C at a 30° inclination angle, 7°C at 45° inclination angles and only 3°C at a 60° inclination angle. The general trend is therefore that the stratification temperature increase inversely with increasing inclination angles as shown in the graph.

Table 4.4 summarizes the effect various collector orientations on stratification. For all the directions from east to west, the stratification temperatures range between 11°C and 14°C, a range of a mere 3°C. From this result all the orientations can be considered equal as far as their effect on stratification is concerned. However the stratification difference is more pronounced in Table 4.5 that summarizes the effect of the two types of absorbers on stratification. The finned absorber has the smallest stratification temperature at 3°C and the non-finned absorber has a stratification temperature of 15°C. The finned absorber therefore is much more superior in the aspect of controlling stratification.

From the above it is seen that stratification temperature can be controlled by using inclination angles. The higher the inclination angle, the lower the stratification temperature achieved. Barriers were used to interrupt the convection currents inside the collector tank to mix up the water layers and reduce stratification. A strong thermosyphon action was beneficial in this function. Thermosyphon action got stronger with increasing inclination angles therefore the best angle to apply is inclination angles of 45°to 60°. This is best done with a finned absorber fitted to the collector.

The plain absorber (with no fins or baffles) was observed to have a widening difference between the mean of the four top temperatures and the mean of the bottom four temperatures with time. The reason was that as the insolation increased with time, it initiated stronger convection currents that arose from the heated water becoming lighter and floating to the top of the tank. On the other hand, the fins on the absorber in the second case prevented this pile up of hot water at the top of the collector by utilizing the currents caused by thermosyphon to churn and mix up the layers into an even temperature.

As a physical confirmation of the action of the baffles, the finned absorber had the smallest stratification temperature difference recorded as 3°C at the highest collector inclination. At this steepest inclination angle, thermosyphon action is expected to be strongest. On the other hand, the non-finned absorber had a stratification temperature difference of 15°C under the same physical conditions. These results indicate that steeper inclination angles produce better mixing, confirming that steeper inclination angles produce stronger thermosyphon currents. Stratification at the horizontal position is about 5° less than at 15°inclination. This is because at the horizontal position, convection currents are weaker than at 15°inclination, hence creating less stratification.

Thermosyphon action improves with higher angles of inclination hence these convective currents would be strongest at 60°, a reason why the temperatures are almost equal at the top and bottom of the tank at this setting. This confirms that convection is affected by the angle of inclination of the plate. However with a 60° inclination, more optical losses occur due the cosine loss in the beam component as the collector is tilted from the horizontal. Collector inclination of 45° is an acceptable angle as optical losses are unlikely to prevent attaining of the target temperatures. The baffles fixed to the underside of the collector also aided in improving heat penetration to the lower parts of the tank by conduction and convection.

From the results, it is evident that stratification temperature difference can be controlled by selecting inclinations angles and by adding mixing baffles inside the water tank. Higher inclination angles resulted in better mixing of the water in the tank due to stronger currents. A strong thermosyphon action has proved beneficial for this mixing. From results, the best angle to use in this respect is inclination angles of 45° to 60° with a finned absorber collector and a glass cover.

On costs, the charcoal heater consumes 2 kg of charcoal in two lots per day each 2 kg tin selling at 60 shillings. The acquisition and running costs for one year is KES 45,500 as tabulated in figure 4.7. The acquisition and running costs for the solar heater for one year is KES 10,100 as tabulated in table 4.8. The annual costs for the charcoal cistern is therefore able to acquire and run at least four of the ICS cisterns for one year.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMENDATIONS

The batch solar water heater was fabricated using available local materials. It was sufficiently portable, and effective as a solar water heater for provision of hot water for hand washing.

From results it was demonstrated that it is possible to uses baffles to regulate temperatures inside the collector tank.

The collector behavior was characterized using data generated in various configurations of the cistern.

The results indicate that the optimum inclination angle for best mixing of the collector load is 60°C, see Table 4.3, the most effective cover was glass one, see Table 4.2, the best orientation was NE (Northeast), seeTable 4.4, and the best absorber was the finned one as indicated in Table 4.4.

The fabricated cistern was found to be a viable replacement for the charcoal heater in aspects of portability, cost of fabrication and running costs.

5.1Conclusions

The study demonstrated that by using baffles inside the tank and taking advantage of naturally occurring thermo currents, it was possible to regulate the water temperature inside the collector hence answering the first research question and satisfying the first objective.

The second and third research questions were answered by testing the collector at different positions and with different types of covers and was data generated which lead to a conclusion that of the tested covers, glass was best, Northeast orientation the most suitable and that 60° inclination gave the most optimum temperature regulation. The available data was also used to characterizethe behavior of the collector and the collector efficiency was found to be 20.3%.

By comparing the acquisition costs and operational costs for one year, the solar collector was found to be a viable, portable alternative to replace the charcoal and wood cisterns, for provision of hand washing hot water.

All the objectives of the study were met.

5.2 Recommendations

Further research is required to model the baffles mixingactionin order to optimize their effectiveness and to make it possible to replicate the same effect with other types of fluids.

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APPENDICES

APPENDIX A: SPECIFICATIONS OF INSTRUMENTS

A.1 TC-08 Data Logger

Number of channels	8
Temperature Accuracy	±0.2% of Value + 0.005 ^{O}C
Voltage Accuracy	±0.2% of Value + 10 µV
Overload Protection	±30 V
Voltage Input	±70 mV
Reading rate	10 Hz
Input connectors	Miniature thermocouple
PC connection	USB
Dimensions	201 x 104 x 34

A.2. Solar Survey 200 Multifunction Solar Irradiance

Technical Specifications
Irradiance
Display Range 100 – 1500 W/m-2 or 30 – 500 BTU/hr-ft2 Measurement Range 100 – 1250 W/m-2 or 30 – 400 BTU/hr-ft2 Resolution 1 BTU/hr-ft2 / 1W/m-2
Temperature
Display Range -30°C to +125°C Measurement Ranges -30°C to +125°C Resolution 1°
Compass Bearing
Display Range 0° to 360° Measurement Ranges 0° to 360° Resolution 1°
Inclinometer
Display Range 0° to 90° Measurement Ranges 0° to 90° Resolution 1°

APPENDIX B: TABLES OF QUANTITIES

Table B.1: Baseline dataused to dimension collector

Item	**Quantity**
Latitude	1° 10' 0" South(-1.16667)
Collector Inlet Temperature°C	23
Desired Output temperature°C	40
Specific Heat of water (kJ/kg/l)	4.2
Density Of Water (kg/m^3)	1000
Volume of tank (liters)	38
Ambient temperature (°C)	23
Absorber material	Galvanized Iron sheet
Absorber thickness (mm)	1.0
Average Irradiance in a day (kW/m^2)	800
Efficiency	0.4
High iron glazing thickness (mm)	4.0
High iron glazing transmissibility	0.87
Collector inclination in°	30
Collector Orientation	North
Time to attain 40 °C	8.00 am to 1.00pm

Table B.2: Materials used for the fabrication

Prototype Component	Material	Attaching Accessories
Frame	20’ x 1”x2” wood	Panel screws, wood glue
Case cover	3 ply 4ft x 8ft	Tack nails
Insulation	3kg glass wool, wood shavings	glue
Glazing	17 ½” x 28 ½” 4mm normal window glass	Silicone glue
Gaskets	1” x ½” rubber gasket	Silicone glue, tack nails
Gasket holding frames	9’ x 2” flat bar	Self-tapping screws
Sealing (Caulking)	500 ml silicon glue	Silicone glue
Absorber (2 No’s, one finned, other plain)	17 ½” x 28 ½” Galvanized sheet	Self-tapping screws
Absorber surface treatment	Automobile spray paint 1 can black matt	-
Plumbing pipes	3 ft x ½” plastic	Pipe jointing accessories
Outlet valve	1 x ½” Ball valve	
Inlet Funnel	1 x 6”	
Water holding cavity	60 L water container	Saw, heat gun, for heating to shape
Stand	20 ft x 1”x2” wood	Self-tapping screws, wood glue

Aluminum foil	1.5 m^2	Impact Adhesive
Collector case treatment	Paint 1 L black	Paint brush
Glass wool	3 kg	Impact Adhesive
Sacking	2 m^2	Impact Adhesive
Expanded Polystyrene	1m^2	Impact Adhesive
Water proof coat	2 L	Paint brush
Self-tapping screws	1” x 54 pieces	Flat screw driver
MDF Screws	1 1/2” x 40 pieces	Star screw driver

APPENDIX C: PLATES

Plate C.1: Plastic water container split into size

Plate C.2: Frame fixtures used to hold the absorber

Plate C.3: Treated absorber fixed to the top of the tank collector

Plate C.4: Improved Absorber with a set of fins attached