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Addis Ababa Institute of Technology

School of Graduate

Energy Center

## **Development and Experimental Testing of Thermal Storage System for Solar Parabolic Dish Concentrator**

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*A thesis submitted to the school of graduate studies of Addis Ababa University  
Addis Ababa Institute of Technology in partial fulfillment for the degree of masters  
of Science in Energy technology*

**Addis Ababa Ethiopia**

**May, 2020**

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# Addis Ababa University

## Addis Ababa Institute of Technology

### Energy Center

#### Development and Experimental Testing of Thermal Storage System for Solar Parabolic Dish Concentrator

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# ABSTRACT

Ethiopia is one of the developing countries in the world, about 79.4% of people live in the rural area and 55.7 % live without electricity. Peoples who live in a rural area mostly use firewood for cooking and heating purpose. Renewable energy sources can be used as alternatives to substitute the firewood in rural areas. Parabolic dish solar collector has a relatively bigger aperture area to focus the solar rays in the limited receiver space and delivers high temperatures. This study deals with the development and experimentation of thermal storage system for solar parabolic dish concentrator.

A phase change material, magnesium chloride hexahydrate was used to store the thermal energy since it is easily available in the local market. The heater (receiver) is portable because it can be easily dismantled from the collector. During sunshine it can be used as it is, whereas after sunset the receiver can be easily dismantled from the dish and kept indoor with an insulating vessel to minimize heat loss from the receiver's outer surface. The aperture area of the parabolic dish is  $0.2160 \text{ m}^2$ . The space occupied by the cylindrical phase change material container is  $0.003083 \text{ m}^3$ . The volume of the phase change material is  $0.002853 \text{ m}^3$ . Rod type fins are integrated to enhance heat transfer. To minimize heat loss by convection the storage system has glazing material.

The glazing (cover) minimized the heat loss by 10.1%. The phase change material was heated up to  $119^\circ\text{C}$ . This ensures that the phase change material was completely melted since its melting point was not exceeding  $117^\circ\text{C}$ . One liter of water was heat from  $22^\circ\text{C}$  to  $92^\circ\text{C}$ . The overall efficiency of the concentrator is 75.9 % with the glazing system and 65.9 % without glazing system.

As compared to the reviewed results of other researchers with similar aperture area of box type solar cooker, 400 g of water was heated from  $25^\circ\text{C}$  to  $78^\circ\text{C}$  with in the time of 2 hours. But in this research 1000 g of water was heated from  $22^\circ\text{C}$  to  $92^\circ\text{C}$  with in 2.67 hours. Hence, parabolic dish solar water heater with storage and glazing systems may comfortably be used in rural areas to warm food and boil water.

**Keywords:** Solar energy, solar water heater, parabolic dish type solar water heater, thermal storage and glazing system, performance of water heater.

## A. NOMENCLATURE

Symbol	Description and Units
$Q_c$	Energy collected by the parabolic dish (J)
$Q_{abs}$	Heat Energy received by absorber (J)
$I_s$	Absorbed solar radiation per unit area ( $W/m^2$ )
$T_{amb}$	Ambient temperature ( $^{\circ}C$ )
$T_{abs}$	Absorber temperature ( $^{\circ}C$ )
$C_R$	Concentration ratio
$C_{Rg}$	Geometric concentration ratio
$C_{Rf}$	Flux concentration ratio
$f$	Focal length (m)
$A_a$	Aperture area of the collector ( $m^2$ )
$T_w$	Water temperature ( $^{\circ}C$ )
$T_{pcm}$	Temperature of phase change material ( $^{\circ}C$ )
$\Delta T$	Temperature difference ( $^{\circ}C$ )
$T_p$	Temperature of heating pot ( $^{\circ}C$ )
$T_{gl}$	Temperature of glass ( $^{\circ}C$ )
$D$	Diameter of absorber (m)
$I_a$	Intensity at the aperture ( $W/m^2$ )
$I_{abs}$	Intensity at the absorber ( $W/m^2$ )
$C_{pf}$	Specific heat capacity of fluid (kJ/kg.K)
$Q_u$	Heating power (W)
$T_f$	Final fluid temperature ( $^{\circ}C$ )
$T_i$	Initial fluid temperature ( $^{\circ}C$ )
$D_a$	Aperture diameter of collector (m)

$\Delta t$	Change in time required to achieve final temperature (s)
$m_w$	Mass of water (kg)
$\dot{m}_f$	Mass flow rate of fluid (kg/s)
$n$	mol number of the reactant (mol)
$\Delta H$	Reaction enthalpy (kJ/ mol).
$L$	Latent heat of fusion (kJ/Kg)
$T_m$	Melting temperature ( $^{\circ}\text{C}$ )
$m_{\text{pcm}}$	Mass of PCM (kg)
$C_{\text{ps}}$	Specific heat of the solid phase between $T_i$ and $T_m$ (kJ/kg. K)
$C_{\text{pl}}$	Specific heat of the liquid phase between $T_m$ and $T_f$ (kJ/kg. K)
$A_{\text{abs}}$	Absorber area ( $\text{m}^2$ )
$V_{\text{spcm}}$	Volume of solid phase change material ( $\text{m}^3$ )
$\rho_{\text{spcm}}$	Density of solid phase change material ((kg/ $\text{m}^3$ )
$V_{\text{cyl}}$	Volume of cylinder (Absorber)
$r_{\text{cyl}}$	Radius of cylinder (m)
$h_{\text{cyl}}$	Height of cylinder (m)
$V_p$	Volume of pot (heating vessel) ( $\text{m}^3$ )
$V_w$	Volume of water
$Q_{\text{pcm}}$	Energy stored in the PCM (J)
$Q_{\text{loss}}$	Energy lost by the absorber and pot (J)
$m_R$	Mass of absorber (kg)
$C_R$	Specific heat of absorber (kJ/kg. K)
$U$	Overall heat transfer coefficient between the absorber and heating pot ( $\text{W}/\text{m}^2\text{K}$ )
$Q_P$	Heat received by the heating pot (J)

R	Resistances to heat flow in materials (K/W)
$x$	Wall thickness of absorber (m)
K	Thermal conductivity of the material (W/m·K)
A	Total area of the heat exchanger (m <sup>2</sup> )
$Q_{fa}$	Output energy from the fluid and into the air above the fluid (J)
$h_a$	Heat transfer coefficient of air above fluid in heater (W/m <sup>2</sup> K)
$T_{air}$	Temperature of air (steam) above fluid in heater (°C)
$A_r$	Internal area of absorber (m <sup>2</sup> )
$Nu_L$	Nusselt number based on length
V	Wind velocity (m/s)
$\eta_o$	Optical efficiency (%)
$\eta_{th}$	Thermal efficiency of the collector (%)
$\eta_u$	Overall efficiency (%)
$A_{cf}$	Cross sectional area of fin (m <sup>2</sup> )
$A_{fs}$	Surface area of fin (m <sup>2</sup> )
$T_b$	Base temperature (K)
$T_\infty$	Surface temperature (K)
$Q_f$	Heat transfer rate of fin (W)
$\epsilon_f$	Fin effectiveness (%)

## B. GREEK SYMBOLS

Symbols	Descriptions
$\epsilon$	Emissivity
$\sigma$	Stefan Boltzmann constant
$\rho$	Reflectivity

$\alpha$	Absorptivity
$\theta_i$	Incidence angle
$\delta$	Declination
$\gamma_s$	Surface azimuth angle
$\varphi$	Latitude
$\tau$	Transmittance

### C. SUBSCRIPTS

P	Pot
F	Fluid
f	Final
i	Initial
th	Thermal efficiency
u	Overall efficiency
o	Optical efficiency
Cyl	Cylinder
abs	Absorber
S	Solid
L	Liquid
amb	Ambient
Pcm	Phase change material
W	Water
a	Ambient
Gl	Glazing

### D. ABBREVIATION

PCM	Phase change material
MCHH	Magnesium chloride hexa- hydrate

GHG	Greenhouse gas
SFSC	Single family solar cooker
CPC	Compound Parabolic Collector
PTC	Parabolic Trough Collector
PDR	Parabolic Dish Reflector
SHTES	Sensible heat thermal energy storage
LHTES	Latent heat thermal energy storage
TCTES	Thermochemical thermal energy storage
TES	Thermal energy storage
DNI	Direct normal irradiance

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# CHAPTER ONE

## 1. INTRODUCTION

Ethiopia is one of the developing countries in the world. According to the World Bank report (March 2019), the current population of Ethiopia is more than 110 million. About 79.4% of Ethiopian people live in a rural area. And about 55.7 % of the Ethiopian population live without electricity. This indicates that it needs so much researches to do in rural areas to electrify these peoples. Because only 44.3% of the total population of Ethiopia have access to electricity. Renewable energy prevents dependency on conventional energy sources and even adds to national economies that provide it.

The sun contributes as a huge amount of renewable energy source both as directly and indirectly. Sunlight or solar energy has a variety of features and can be used for heating, cooking and lighting, generating electricity, hot water, solar cooling across homes, commercial property and for industrial use. Solar energy is great for homes, it may be expensive at first, but after installation or commercialization the benefits of solar energy high.

Statistical data show that tropical regions deal with a better solar energy resource than others with high temperate latitudes. The average annual radiation in Europe is around 1000 kWh/m<sup>2</sup>, whereas, in the Middle East the value is about 1800 kWh/m<sup>2</sup>. In the tropical zone, like Ethiopia the average estimated irradiation is to be approximately 2000 kWh/m<sup>2</sup> [1]. This indicates that Ethiopia has a large potential for solar energy.

Cooking is one of the basic intentions that needs electricity or power in large amount because it is day to day activity. Rural population of Ethiopia uses firewood for cooking and water heating purpose. This firewood has prejudice on the females in rural area i.e they went long distances to collect the wood and then carry that by their back. The smoke of the wood fuel also has impacts on their health like eye disease and respiratory problem. So, design and development of efficient solar cooker can solve this problem. There are three types of solar cookers box-type, panel-type and parabolic solar cooker.

The performance evaluation of the three types of the cooker is determined[2], thus the parabolic solar cooker attains the maximum temperature and maximum cooking power than

the other type. However, the efficiency of parabolic type is less due to heat loss to the surrounding, on the other hand the box type has maximum efficiency due to that it retains heat inside the box while the other types are open and cause heat losses.

The box-type solar heaters are popular in many countries and slow to heat up however work satisfactorily where there is convection heat loss caused by wind, diffuse radiation, low ambient temperature and intermittent cloud cover. The concentration ratios and temperature of box type solar heater is low (up to 10) and (up to 100°C), respectively. While for concentrating type solar cookers the concentration ratio and the temperatures are up to 50 and 300°C respectively. Therefore, the parabolic solar heater is suitable for the types of food that require high temperatures or high rates of heating. Concentrating type solar heaters are expected to exhibit high performance because of the large collecting area employed. However, the net amount of heat used is not as much high. This is due to the large amount of heat losses from the bare of heating pot is used [3].

The use of thermal energy storage system has advantage for solar heaters to work in the cloud and during night time. A latent heat energy storage system was designed and fabricated by [4] to warm food when the solar radiation absent. Even if they design and develop solar thermal storage systems, most of these systems are applicable for box type cookers. The power and thermal performance of the parabolic type heater were higher due to a large collecting area, so it can store heat in much more amounts.

Even if design and construction of parabolic solar cooker in the world as well as in Ethiopia is available the efficiency low and it is not functional in night and cloud time because of intermittency. Considering the power and performance of the parabolic type heater it is clear that increase the efficiency or performance of the solar heater with a storage system can solve the limitations.

## **1.1 Problem statement**

In developing countries like Ethiopia, people mainly use firewood in their day to day activities. Moreover, firing wood has a significant effect on health and environmental issues. The smoke of the wood fuel also has impacts on their health like eye disease and respiratory problem. So, the use of firewood for cooking purpose has many problems. In addition to these females take the burden of gathering firewood and carry at their back, this has to much effect on their physical and health. Farmers, while going to a farm, take their lunch and water to work place. However, they have a problem with getting heat sources. This is because they do not have access to electricity. The food they carry needs to be warmed and they need hot water to prepare milk/tea or wash their hand. To solve these problems many scientists, try to design different types of cookers. Even if many solar cookers are designed, they are not efficient and not localized in rural area of Ethiopia. The other most drawback of solar cookers are their intermittency. Heaters energized by renewable energy sources are a good option to solve such problems.

As an option, this research work focuses on experimenting with solar heater to be used easily by locally in rural area specially at off pick time.

## **1.2 Objectives**

### **Main objective**

The main objective of this research work is to develop and test a thermal storage system in a solar parabolic dish concentrator.

### **Specific objectives**

- Design the thermal storage system.
- Develop the model of the thermal storage system using solid work.
- Fabricating the parabolic dish thermal storage system.
- Test the experimental unit.

## **1.3 Delimitation**

- To design and develop an effective parabolic type solar heater with a storage system needs additional materials and parameters like manufacturing of the good storage container, smooth operation of the overall system and automatic tracking system are required, because of this the overall cost of the heater may be increased.
- Another limitation of this paper is difficult to get good phase change material in the local market.

## **1.4 Significance of the research**

In optimum cases, solar heating can significantly reduce the use of wood or biomass and all of the associated negative effects. Since it is mainly women who take the burden in the household. Their time is being saved by using a solar dish heater. The potential of time-saving essentials related with the use of a solar heater is resulting from the reduction in a wood gathering. In addition to this, the economic benefits with time-savings can be important if the time is spent on the income-generating activities. Its contribution to controlling the environment in developing nations is a promotion on equitable access to energy (especially rural areas), improvement of health conditions and poverty mitigation from buying kerosene are the key benefits from this paper.

## CHAPTER TWO

### 2. LITERATURE REVIEW

#### 2.1 Introduction

Solar energy is one of the renewable energy sources from sun light. It also source for most of other renewable energy like wind energy and bioenergy. In this research the solar energy is used as a source of energy or heat to warm food and heat water. The on-grid electrification in Ethiopian is very less compared to the number of populations, because of this, the need of address none electrified places by using off grid electrification. Off grid electrification can be addressed by using most of renewable energies. For lots of people living in rural areas of Ethiopia who lack access to the electric power, off grid electrification is another best choice to electrify. Solar energy represents the best option to access energy ladder. Since 79.5% of Ethiopian people live in rural area almost all of them use kerosene, candle and dry cell battery for lighting purpose and fire wood for cooking food and heating water.

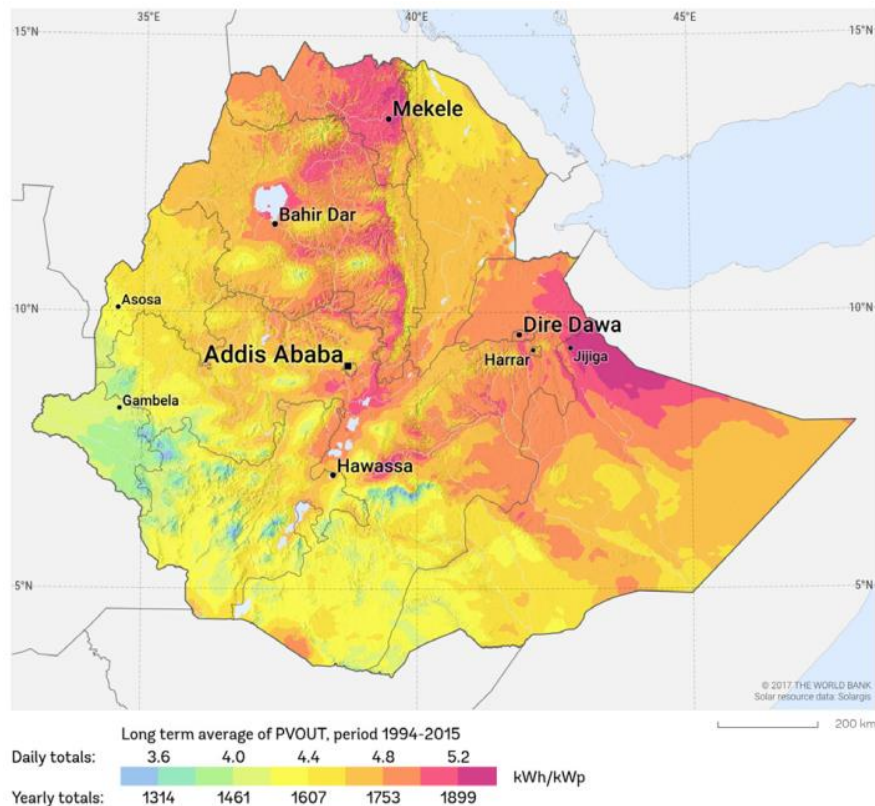


Figure 2-1 Solar energy potential in Ethiopia[5]

Ethiopia has a high solar energy potential to develop PV projects with the average irradiation level of 5.2 kWh/m<sup>2</sup>/day as shown in Figure 2-1. In addition to PV system the solar energy is used as thermal energy storage system due to solar radiation. So, by using solar energy it can electrify these rural peoples, especially for cooking and heating purpose easily. There are many types of solar heater based on shape of collector or concentrators, use of storage material and assembling system (direct or indirect).

## 2.2 Different types of water heating techniques or methods

Start from ancient time different types of heating methods are used by peoples, some of the heating methods are:

**2.2.1 Biogas heating:** Biogas is a gaseous mixture of anaerobic digestion processes using solid waste, organic waste, and other sources of biomass. In developing countries, biogas is an interesting energy option, in particular for those countries that depend on traditional biomass technology for their energy needs. Biogas can be produced on a very simple way for household use, mainly for cooking and water heating purposes. The feedstock is like animal dung or sewage, is mixed with up to 95% of water.



*Figure 2-2 Biogas for cooking and heating [6]*

**2.2.2 Heating by Charcoal:** Charcoal is used as a domestic fuel for cooking and heating in many developing countries. It is the most popular flame fuel throughout the world. It has the advantages of less smoke, has a higher energy content, needs no preparation before actual use, can be easily transported and stored, and reused. The raw material for charcoal production has been mostly fuelwood. In Ethiopia, charcoal is also produced from the traditional earth kiln method, earth mound kiln and earth pit kiln. Most of the people use woody biomass to produce

charcoal. In addition to this biochar is produce from flower waste, 10 kg of biochar is produced from 18 kg of flower waste with the conversion efficiency of 55.5 % [7].

**2.2.3 Ethanol heat stove:** Ethanol can be used for cooking, water heating and heating of buildings. Ethanol is produced by fermentation of sugars from various crops, such as maize, wheat, sorghum, cassava and sugarcane. The advantage of the ethanol heat stove is that it does not have the air pollution problems, provides a higher heat flux with no soot or smoke, cooking and hot water production can take place faster and pollution free. It can be used for different energy applications varying from water heating and cooking up to boiler heating in industries.



*Figure 2-3 Ethanol heat stove [8]*

In addition to these cooking and heating technology most of the developing countries use biomass. The pollution and fuel consumption of biomass cooking is high compared to other types of cooking technology. To minimize these effects biomass micro gasifier was designed by [9] with the thermal efficiency of 36.9 % and fuel consumption of 57 g of fuel per liter of water.

#### **2.2.4 Solar heater**

Solar heaters are used to warm food and to heating water. The solar heater concentrates the incoming solar radiation on the side, top, and bottom of a pot. The solar collectors do need its space, the larger the collector surface, the power to heat is stronger. Solar heating can significantly reduce the use of wood or biomass and all of the associated negative effects. In optimum cases, it has been proposed as a potential solution for the GHG emission reduction.

Box type solar heater is an insulated box container with a multiple or single glass cover. This kind of heater depends on the green-house effect in which the transparent glazing permits the

passage of incoming solar radiation. A double-walled insulated box can also serve to hold the heat inside the cooker. Mirrors may be used to reflect incident solar radiation into the heating chamber. The speed of the heating depends on the design and thermal efficiency of the system. These box type have a very simple to construct and they are made of low-cost materials, which basically consist of a black painted metallic cooking tray with single, double and multiple glazing systems.

Review on design, development and performance of box type solar cookers along with prominence on the need for development of small size for small families has been developed and named as Single-Family Solar Cooker (SFSC). Three new characteristic design parameters: area ratio ( $A_r$ ), size reduction parameter for gross area ( $SRP_1$ ) and size reduction parameter for aperture area ( $SRP_2$ ) have been introduced for quantitative comparison of the performances of different box types. The features of developed Single Family Solar Cooker (SFSC) are: Small size and light weight makes it convenient to handle even by old age or physically weak person. Good thermal and cooking performance due to the use of newer materials for various components and reasonably low cost [10].



*Figure 2-4 Box type solar cooker[9]*

This type of solar heater is very much used in all over the world due to the faster heating ability. In the concentrating solar heaters, the heating pot is placed at the focus of a concentrating mirror. Concentrating type solar heater is working on automatic or manual tracking mechanism in one or two axes with a concentration ratio up to 50 and temperature up to 300°C. All concentrating solar cookers were found to provide adequate temperature needed for heating and cooking. But the common problem of these systems is the need for

frequent tracking, and standing in the sun. Concentrating type of heaters usually employs mirrors to concentrate the total incident solar energy on the absorber surface. So, to achieve high temperature the collector surface is usually very wide. Parabolic dish heater has the highest efficiency in terms of the utilization of the reflector area.

The first performance evaluation of paraboloid concentrator type solar cooker is tested by [11]. The aperture area of the concentrator was  $0.58 \text{ m}^2$  with the pot surface area of  $0.08 \text{ m}^2$  and overall heat loss factor of  $17.2 \text{ W/m}^2 \text{ K}$ . From the solar radiation data for three days ( $635, 465$ , and  $264 \text{ W/m}^2$ ) the overall heat loss factor for these three day was  $0.454$ ,  $0.453$ , and  $0.447$  respectively. Accordingly, they proposed that the effect of wind speed and orientation of the reflector effect on the performance of solar cooker and the heat losses from a paraboloid concentrator type. The heat loss factor and optical efficiency factors are the two terms that evaluated the performance of the paraboloid concentrator type. The optical efficiency factor is depending on the reflectance of the concentrator surface, smoothness of the reflector area, intercept area and absorbance of the outer surface of the heating utensil and positioning of the concentrator. At the end of the experiment it was observed that both the heat loss factors and optical efficiency factors increase with increasing load.

Then after performance evaluation of parabolic type solar cooker is evaluated by [12], based on this evaluation the parameters influencing the thermal performance of parabolic type solar cookers are controlled and uncontrolled parameters. The uncontrolled variables are climatic and geographical parameters (wind speed, solar irradiance, ambient temperature, solar azimuth and altitude angles), whereas controlled variables related to sun tracking, loading, and such type of parameters etc. this paper tests only two performance parameters of the cooker, namely, adjusted cooking power, and overall heat loss coefficient. Instrumentation error analysis of a paraboloid concentrator type solar cooker was identified [13]. Based on the parametric evaluation of [11] tested parameters, the amount of water was not specified to be taken as the load under the testing and graphical methodology of evaluation of the performance parameters cause more uncertainty and the acceptable range of the climatic parameters are not tested here. It also identified the gaps by statistical analysis to determine inconsistencies and analyze it in a rational manner. By using instrumentation fixes the acceptance range of parameters.



*Figure 2-5 Concentrating type solar heater[9]*

Different types of solar cookers and heaters were designed, developed and tested by many scientists. Design and development of small-scale hybrid solar box heater attaching with solar panel to increase the efficiency of the heater (38%) and reduce the heating time due to photovoltaic power from the panel. With the power of 30 W, 0.35 g of water was boiled at 70 min. Advantage and disadvantage of different types of solar heater is identified, based on this the disadvantage of parabolic type solar heater is, it is sensitive to wind [14].

Most of the heaters are stationary and they are used only for residents. Portable solar heater which is important for those move from place to place i.e. for Bedouins, campers and nomads. The mode of operation was in two ways with bare pot and glazing the pot with aluminum, then the glazing pot increases the power triple times than that of bare pot (from 200 W to 600 W). The type of glazing material also determines the power and efficiency of heater and collectors [15].

Polished aluminum reflectors have lower performance than glass reflectors. Booster glass mirror reflectors are preferred to use because of their reflectance. Box type solar heaters have lower performance than reflector heaters. Therefore, reflector heaters with glass mirror reflectors or glazing achieved highest temperatures and accordingly have shortest heating time than the other types [16].

Design and development of performance of inclined single booster mirror with parallelepiped shaped cooking vessel was designed, this parallelepiped shaped cooking vessel is efficient for cooking especially in winter due to its shape which is inclined to the south wall and the

trapezoidal cavity on the cooking vessel transfers greater heat to the cooking material. Compared to horizontally placed cooker the time taken to boil water was 37% less and cooking power was 40% more [17].

Sub Saharan Africans have no access to modern energy. In sub Saharan Africa solar heater is one of the modern energy technologies which solves the problems in energy crises. It can improve the heating technology especially if it is combined with the storage system, back up, or hybrid system at evening and rainy time. Solar energy technologies in terms of solar thermal applications can improve the energy situation at a household and institutional level. Solar thermal applications such as solar water heaters and solar cookers convert the sun rays into heat energy [18].

Multipurpose truncated pyramid non-tracking type solar cooker or hot water system was designed and tested, which has features to achieve higher temperature than solar box cooker, reduced cooking time, and low cost. The maximum collector efficiency was 54% with the heat loss coefficient of  $5.7 \text{ W/}^\circ\text{cm}^2$ . The shape of the cooker is pyramidal which is effective to collect direct radiation, the external part of the cooker is paint black and the internal is aluminum. The truncated pyramid type solar cooker and water heater was designed and fabricated to penetrate the market and diversify the solar products to meet the requirements of poor people [19].

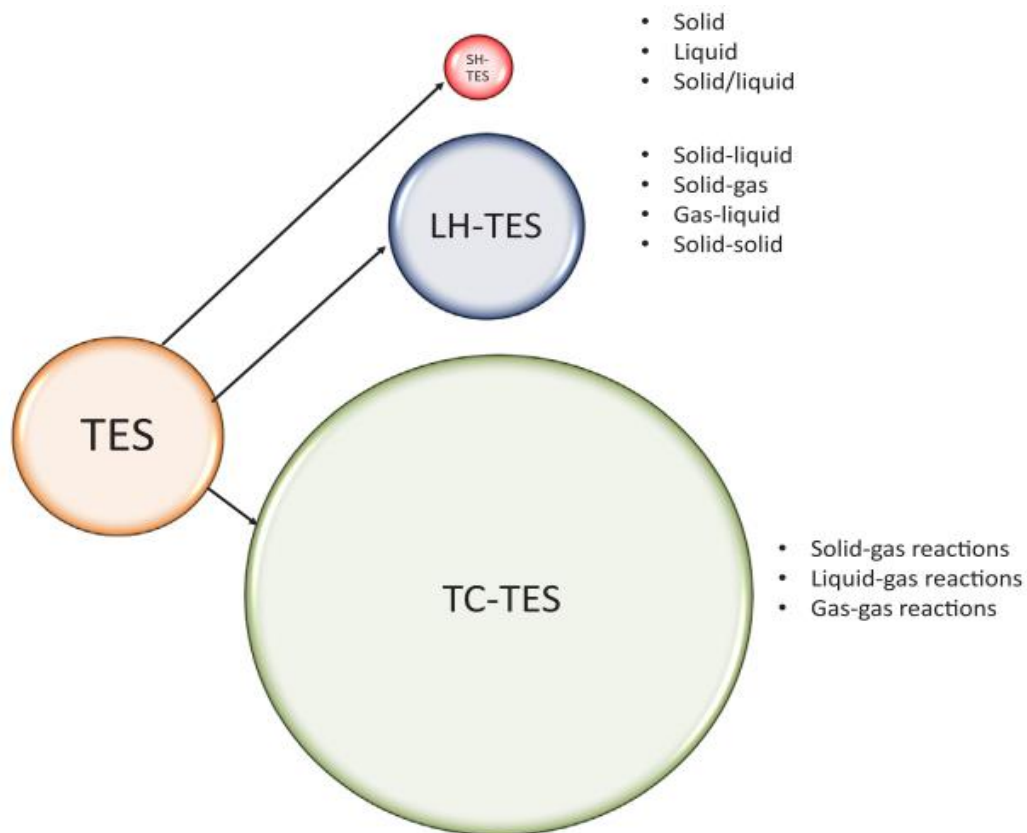
## **2.4 Thermal energy Storage**

A major disadvantage of solar energy is its temporal intermittency. To minimize this problem, the first solution is to use a backup system (energy hybridization) that burns fossil fuel or biomass. The second solution is to use a thermal energy storage (TES) system to store heat during sunshine periods and release it during the periods of no solar irradiation.

Thermal energy storage system for concentrated solar power plant was reviewed. Thus, the use of TES allows heat storage during high solar intensity periods and provides productions during high electricity cost periods. The sensible storage systems are more reliable because of their cost and availability, but latent storage systems have more energy density and cost. Hybridization systems used to be a standard option to increase the dispatchability of solar power plants. However, they usually consume fossil fuels with increasing costs and high  $\text{CO}_2$  emissions. In

the meantime, thermal energy storage systems have no such problems and could become an alternative or even a replacement [20].

Thermal energy storage systems are classified in to three basic groups: sensible heat thermal energy storage, latent heat thermal energy storage and thermochemical heat thermal energy storage. The sensible heat thermal energy storage is used to store energy for low storage medium, whereas latent heat thermal storage is used for low, medium and high energy storage system. The thermochemical heat energy storage is the most one and can store the highest amount of energy than both sensible and latent energy storage but it is costly and not available in the market, it is in the laboratory stage.



*Figure 2-6 TES methods and the scheme of TES heat storage capacity of each one[21]*

Energy storage technology and latent heat storage materials or phase change materials (PCM) were the mostly used storage materials since they have higher heat storage densities compared to sensible ones [21]. In addition to this, they can provide heat at a nearly constant temperature.

Different types of solar cooker with and without thermal storage. As they proposed that the box type solar cooker has low concentration ratio 10 and low temperature 100°C than that of concentrating type solar cookers with the concentration ratio up to 50 and temperature up to 300°C [22]. Among the different types of concentrating type cookers parabolic type is the perfect one and have highest efficiency than the other, have highest temperature and cook with in short period of time. The disadvantage of parabolic type of cooker is that it needs perfect tracking system.

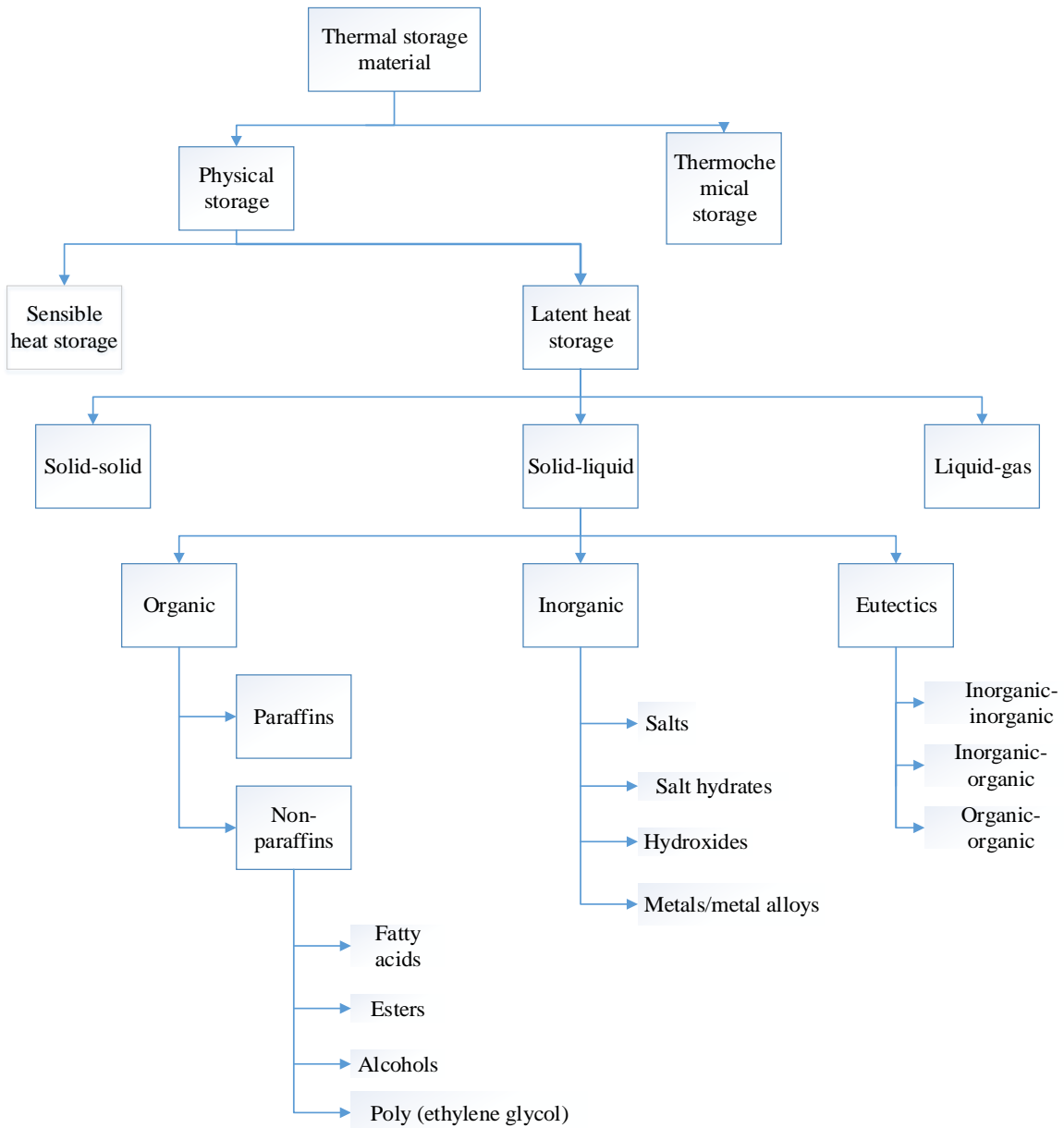


Figure 2-7 Thermal energy storage material

## 2.5 Principles of solar heating system

There are a variety types of solar heaters. The basic principles of all solar heaters are:

**Concentrating sunlight:** Some device mostly a mirror or some type of reflective metal like aluminum, are used to concentrate incoming rays from the sun on collector into a small heating area of absorber.

**Converting light to heat:** Any black on the focus of the collector and certain materials for absorbers, will improve the efficiency of changing light into heat. A black painted absorber will absorb almost all of the sun's light and turn it into heat. Also, the better an absorber conducts heat, the faster the heater will work.

**Trapping heat:** Separating the air inside the heater from the air outside the heater have a significance. Plastic bag or a glass cover allows light to enter, however once the light is absorbed and converted to heat, a plastic bag or glass cover will trap the heat inside the heater. This makes it possible to achieve similar temperatures at the time of cloudy and windy days as on hot days.

## 2.6 Research gap

Most of the articles are done by different parameters (design, development, instrumentation error, efficiency, review) of solar cookers and water heaters. Some are integrated with a thermal storage system for box type. The performance of the parabolic type solar cooker is higher than that of box-type solar heater. This is due to temperature collected by concentrating type is higher (300°C – 400°C) but for box type is around 100°C. The designed parabolic dish solar heaters are large in size and the storage systems are not portable or they are not easily transported from place to place. Integrating the solar heater with a thermal energy storage system will improve the overall performance of heater.

So, this paper focus on the development and experimental testing of thermal storage system for solar parabolic dish concentrator. The losses are minimized by applying the glazing system. A small size portable solar thermal storage system is designed in this paper. This solar heater has two functions at a time i.e., using the heat stored by PCM inside the house and using heat by direct radiation from concentrator outside of the house.

## CHAPTER THREE

### 3. Materials and Methods

#### 3.1 Materials

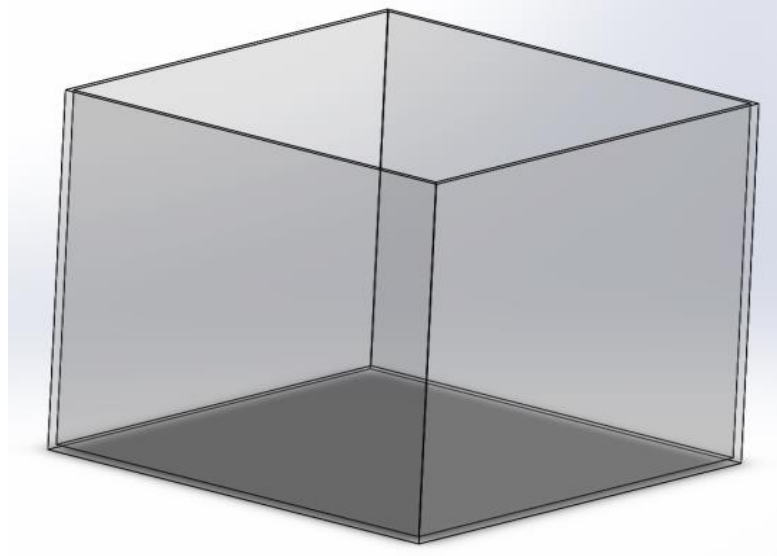
This section contains the materials, methods and preliminary design used to construct the parabolic dish solar heater for each part. The best suitable materials used to construct the heater are selected and designed by studying appropriate properties. The amount of storage material used to heat water at night time is determined. The comparison and the selection of materials are shown and explained in each subsection and the design specification and the data gathered from the metrology are also explained.

##### 3.1.1 Material for the Reflecting Surface

Reflection is the main purpose of the parabolic dish heater which is used to increase the direct or beam incident radiation concentrates by reflecting to achieve high temperature. Aluminum foil sheets to the satellite dish as reflector was used by [2]. But the reflectivity of aluminum sheet is less than that of mirror. A light glass mirror of high external surface quality and good specular reflectance was selected. Glass mirror was selected over polished aluminum surface because its reflectivity is 95% which is better than that of aluminum (85%)[23]. For this case booster mirror is used to get more solar energy, it become less effective when the solar incidence angle increases and more effective when the mirror angle changes according to the position of sun.

##### 3.1.2 Material for Glazing

Glazing's are transparent covers used to prevent heat loss by convection from the collector. The refractive index and density of Polymethyl methacrylate (PMMC) are 1.49 and 2450 kg/m<sup>3</sup> respectively. And polycarbonate (PC) have the refractive index of 1.58 and density of 1177 kg/m<sup>3</sup>, whereas the refractive index of glass is 1.52 with the density of 1172 kg/m<sup>3</sup>. Based on these properties PMMC and PC have favorable properties required for effective solar radiation collection, but for the case of this paper glass was selected because it is available at local market, cheaper and withstands high temperatures.



*Figure 3-1 Glazing*

### **3.1.3 Material for the Vertical Support of the Dish**

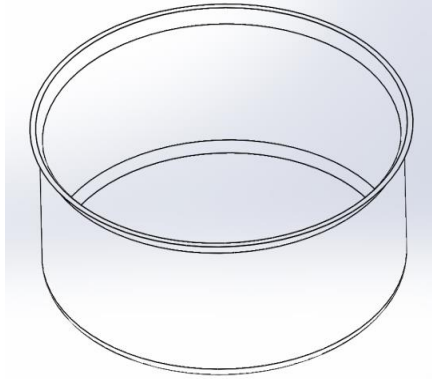
A rectangular, hollow, iron bar was used for the support of the dish. This is due to durability, strength, resistance to deflection, and its ability to withstand transverse and cross-sectional loads of the entire heating portion of the heater.

### **3.1.4 Material for the Body of the Dish**

Steel was selected over aluminum because of its durability, strength and energy effectiveness in use of material. Commercially available satellite dish was adopted to reduce errors in the process of manufacture, its smooth contour shape minimizes the sloping error of the reflective glass material.

### **3.1.5 Material for heating vessels (pot)**

Usually cylindrical shaped heating vessels made of aluminum are used for heating. The outside of vessels is coated black and attached to the center of the storage container to achieve the desired contact between the pot and the absorber plate; in order to increase the rate of heat transfer by conduction between the absorber plate and the heating vessels.



*Figure 3-2 Heating vessel (pot)*

### **3.1.6 Material for heat storage container (Absorber)**

Stainless steel is the best compatible with all phase change materials tested. Mild steel is a fairly good material being corrosion resistant to most PCMs. Copper was compatible with all heat storage materials confirmed, except sodium thiosulphate 5-hydrate.

Aluminum (A199.5) and aluminum alloy AIMg<sub>3</sub> are incompatible with the salt hydrates [24].



*Figure 3-3 Absorber (PCM container)*

From these and other results, it may be concluded that mild steel and stainless steel are essentially compatible with most heat storage materials, whereas aluminum and copper or their alloys are only preferentially compatible. But in this paper galvanized iron sheet was used for thermal storage container because of its availability and simplicity to manufacture.

### **3.1.7 Material for the heat storage container Surface Coating**

Black paint (black car spray) was selected for the heat storage container coating. At normal incident angle it has high absorptivity and has good durability in exposed weather conditions, cost effectiveness, and protection to the absorber material.

### **3.1.8 Material for thermal energy storage**

A major problem of solar energy is its temporal intermittency. To overcome this problem there are two types of solution, the first solution is to use energy hybridization method. A second solution is to use a thermal energy storage (TES) system to store heat during sunshine periods and release it during the periods of weak or no solar irradiation [20].

Solar thermal applications need thermal energy storage systems to solve the problem of the intermittent nature of the irradiance of the sun.

Based on the method used to store the heat thermal energy storage systems (TESS) can be classified as:

1. Sensible heat thermal energy storage (SHTES)
2. Thermochemical thermal energy storage (TCTES) and
3. Latent heat thermal energy storage (LHTES)

**Sensible heat thermal energy storage (SHTES)**- is the simplest method to develop TESS but the amount of heat stored by this method is the lowest, it takes large amount of space due to this it is bulkier. Sensible heat thermal energy storage materials store heat energy in their specific heat capacity ( $C_p$ ) [25].

During the heat energy storing process, there is no phase change happening however the heat stored by materials experience is in temperature raise. Thermal energy is stored or released by raising or decreasing the temperature of a storage material respectively. Therefore, the amount of heat stored depends on the mass of the product, specific heat, and temperature variation of the storage material.

**Thermochemical thermal energy storage (TCTES)**- uses a reversible chemical reaction. The heat energy stored is equal to the reaction enthalpy. During the charging process, a forward endothermic reaction absorbs heat and the absorbed thermal energy is used to

dissociate a chemical reactant into products. During the discharging process reactants undergo backward exothermic reaction producing a product and releasing heat [26].

It has capable to store highest energy but due to some technical barriers this technology is not completely full-implemented in the market. Energy density stored in thermochemical heat storage is higher compare to both sensible and latent heat storage materials [25]. Storage temperature in case of sensible and latent heat storage is at temperature charging process where as in chemical storage it is the ambient temperature. Thus, heat loss and insulation requirement are minima for thermochemical storage.

**Latent heat thermal energy storage (LHTES)** – has a capable to store 3-4 time more energy than sensible heat thermal energy storage [21]. Latent heat thermal storage materials are selected due to their isothermal phase change and their high storage density property.

Latent heat materials work by changing the phase without change of composition. The stored heat by latent heat is with the constant temperature. This constant temperature is the melting temperature. With small space latent heat materials store high amount of energy [20]. The latent heat transfer of a material is expressed by the change in enthalpy ( $\Delta H$ ) between the two different phases

$$\Delta Q = \Delta H \quad (3.1)$$

The thermal energy stored in phase change material can be expressed [25]

$$Q = m\Delta H \quad (3.2)$$

These phase change materials are selected by that the melting point approximately the same as the required applications [27]. Latent heat storage method is one of the best energy storage techniques because of its high energy storage density and its characteristics to store heat at constant temperature called phase transition temperature of PCM [28].

The main drawback of PCMs is their low thermal conductivity usually ( $0.2\text{--}0.8 \text{ W m}^{-1}\text{K}^{-1}$ ) resulting in very slow heat transfer rate. To enhance the thermal conductivity of PCMs fins or extended surfaces, different types of metal alloys and additives like graphite are used. The thermal conductivity of PCM/graphite composites could reach  $5\text{--}10 \text{ W m}^{-1}\text{K}^{-1}$  depending on the amount of graphite added [29][30].

The use of Phase Change Material (PCM) which has its melting point around 100°C to 110°C is recommended for cooking (heating) because boiling takes place in the parabolic solar collector between 95°C to 97°C [31]. The melting temperature of a PCM should be between 105 and 115°C for evening heating [32]. So, based on the above requirement of PCM, the selected heat storage materials for heating purpose are listed in Table 3-1 based on their melting temperature which almost near to boiling temperature and within the range of review temperature.

*Table 3-1 Thermochemical property of selected PCM*

<b>PCM Material</b>	<b>T<sub>m</sub> (°C)</b>	<b>Δh (J/g)</b>	<b>C<sub>ps</sub> (J/gK)</b>	<b>C<sub>pl</sub> (J/gK)</b>	<b>K<sub>s</sub> (W/mK)</b>	<b>K<sub>l</sub> (W/mK)</b>	<b>ρ<sub>s</sub> (g/cm<sup>3</sup>)</b>	<b>ρ<sub>l</sub> (g/cm<sup>3</sup>)</b>
Erythritol	118	315	1.38 (20°C)	2.76 (140°C)	0.733 (20°C)	0.326 (140°C)	1.480 (20°C)	1.300 (140°C)
Xylitol	93	233	1.33	2.36	-	-	1.500	-
<b>MCHH</b>	<b>117</b>	<b>134</b>	<b>2.1</b> (25°C)	<b>2.61</b> (120°C)	<b>0.704</b> (110°C)	<b>0.570</b> (120°C)	<b>1.569</b> (20°C)	<b>1.450</b> (120°C)
Acetanilide	119	222	2	-	0.14	-	1.21	-

Magnesium chloride hexahydrate (MCHH) was selected as heat storage material because of its availability in the local market and melting point which is approximately the same as boiling temperature. The specific heat and thermal conductivity are also good compared to other phase change materials. Erythritol is the best PCM material but not available at local market.

The selected materials for parabolic dish solar water heater are listed in Table 3-2 below.

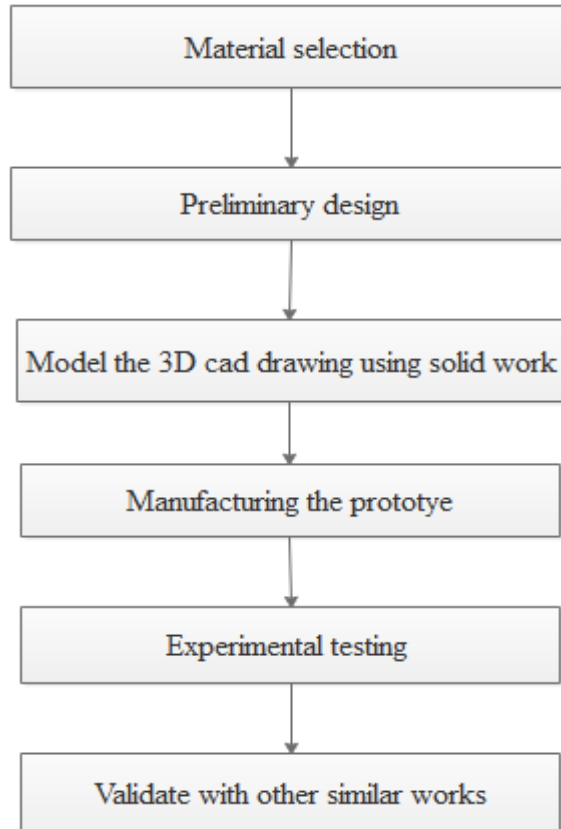
*Table 3-2 List of materials used for experiment*

<b>No</b>	<b>Part name</b>	<b>Material used</b>
1	Absorber	Sheet metal
2	Heating vessel	Aluminum
3	Body of the dish	Steel
4	Reflecting surface	mirror
5	Glazing	Glass
6	Vertical support of the dish	Hollow iron bar
7	Fins	Copper
8	PCM	MCHH
9	coating	Black paint

Sheet metal was used as absorber material in experimental test because it is easily manufactured at local workshop laboratory. But it affects the heat transfer analysis because the conductivity of sheet metal is very small. For the heating vessel aluminum made vessel is used which is available at the local market. satellite dish made of steel is used as collecting surface due to its smooth surface to concentrate at focal point. and at the surface of satellite dish mirror is anodized to reflect the all incident rays to the absorber. To minimize the conventional heat loss glass was glazing system (glass) is used. Coppers are good conductors to transfer heat, to increase heat transfer rate of PCM fins made of copper is used. And the absorptivity of the absorber is increased by black coating.

### 3.2 Methods

This section describes the technique or method used to develop the parabolic dish solar heater by sequential order starts from material selection. The method section used in this paper are as shown in Figure 3-4.



*Figure 3-4 Methodology*

Material selection: -

In this section the materials for construction of prototype are discussed. The materials for absorber, cooking vessel, parabolic dish, glazing, reflecting surface, coating, dish supporters and heat storage materials are selected.

Design parameter of the solar heater: -

In this section some parts of the solar heater are designed and manufactured. The size of absorber, heating vessel, and the size of the heat storage material used to store enough amount

of heat for heating purpose is determined. To design these parameters solar data is gathered from meteorological data.

Model the 3D cad drawing using solid work: -

In this section the designed materials for prototype are drawn by solid work with the 1:1 scale and dimension as shown in Appendix A.

Manufacturing the prototype: -

The materials used for prototype are manufactured in the workshop. Most of the parts are simply selected with the appropriate property and some like absorber are manufactured. Manufacturing process is done by using arc welding and other bending, cutting and machining processes.

Experimental testing: -

The main part of this paper is done or tested by using manufactured prototype and different types of instrument. Temperature of storage material, water, absorber, heating vessel, glazing, ambient temperature and wind speeds are recorded in this part.

### **3.3 Preliminary design**

The concentrator is the component of the collector system which directs solar radiation onto the receiver. Absorber is the part of the collector system where solar rays reflected from the concentrators are focused and absorbed. The elementary purpose of a parabolic dish solar heater is to collect incident solar radiation at the large surface area of collector and reflects it onto a smaller area of the absorber, where the heater or pot containing the food is located.

The total amount of heat absorbed, ( $Q_{Abs}$ ) by the absorber required to heat water and warm food is calculated as: -

$$Q_{abs} = \rho\alpha\tau I_b A_a \quad 3.3$$

The aperture area of the parabolic dish is  $0.216\text{m}^2$  [33]

The 2018 monthly daily analyzed average solar radiation data for Addis Ababa have been collected from National Meteorological Agency are listed below in Table 3-3.

*Table 3-3 Monthly average radiation data analyzed from meteorological data*

<b>Month</b>	<b>Solar radiation for Addis Ababa (W/m<sup>2</sup>)</b>
January	183.86
February	184.37
March	173.92
April	138.06
May	158.89
June	123.11
July	134.32
August	133.08
September	176.61
October	184.63
November	180.25
December	192.28

The values for each month are the average solar radiation incident on a unit aperture area within one day or 24 hours. The minimum amount of radiation has been recorded as 123.1W/m<sup>2</sup> in June 2018. This value is taken for the calculation purpose to get the required amount of heat absorbed.

The useful energy ( $Q_u$ ) of the collector is determined by: -

$$Q_u = Q_{abs} - Q_{loss} \quad 3.4$$

This useful energy equation is used to obtain the required amount of heat for heating and warming activities. The value of this energy can increase by minimizing the loss.

**Heat losses-** Heat within a solar heater is lost in three fundamental ways: Conduction, Radiation, and Convection. The outer surface of the heating vessel is covered with the storage material and this storage material is insulated with the black body because of this, conductive heat loss is almost ignored (approximately zero). So, the total heat lose in parabolic dish solar heater by the absorber or receiver are convective and radiative.

**Heat loss by Convection:** air molecules move in and out of the heater through cracks. Heated air within a solar heater (absorber) escape through the cracks around the different parts of the heater or when opening the cover. Cooler air also enters to the heater from outside. The most

convective heat loss is due to the wind surrounding the absorber, this can be minimized by making coverage system.

The convective losses of the absorber (receiver) is calculated as[34]

$$Q_{conv} = h_c A_r (T_r - T_a) \quad (3.5)$$

**Heat loss by Radiation:** when heaters warm, heat is released in the form of waves to the surrounding. Most of the radiant heat are escaped from the top of warm pots, transparent glazing and bottom trays.

The heat in the absorber is radiated outward due to high temperature, the emissivity of the aluminum is 0.8[35]. Then Stefan Boltzmann equation is used to calculate the radiative heat lose: -

$$Q_{rad} = A_a \varepsilon_{eff} (T_f^4 - T_a^4) \quad (3.6)$$

In addition to these the losses from the system under study (heater) can be studied by taking into consideration of the different faces from which the loss takes place.

1. Side Loss: The losses occurring from the side or cylindrical surface of the heater constitute the side loss. Losses occur from the cylindrical surface due to the temperature difference between the fluid and ambient are in form of convection and radiation.

#### *Convection loss coefficient*

To incorporate the effect of wind in the heat loss calculation by convection, the heat transfer coefficient between the outer surface of heater and ambient is computed using the relation mentioned in [36] for the cylindrical surface:

$$h_{cs} = 5.7 + 3.8V \text{ W/m}^2\text{K} \quad (3.7)$$

The maximum wind speed is measured in March according to national metrological agency data as shown in Table 3-4 below, since this value is taken for calculation of heat loss.

Table 3-4 Analyzed Average wind speed for Addis Ababa

Month	Average of Wind Speed Addis Ababa at 10m (km/h)	Wind Speed at 10m (m/s)	Wind Speed at 1.5m (m/s)
January	3.72	1.03	0.3
February	3.82	1.06	0.3
March	3.95	1.1	0.31
April	3.04	0.84	0.24
May	3.26	0.91	0.26
June	2.34	0.65	0.19
July	2.51	0.7	0.2
August	2.6	0.72	0.21
September	3.25	0.9	0.26
October	3.77	1.05	0.3
November	3.77	1.05	0.3
December	3.68	1.02	0.29
Average	3.31	0.92	0.26

The average wind speed data at 10-meter height are analyzed directly from the daily meteorological data. Hence the experimental test is held at the height of 1.5 meter, the data at 10-meter height are extrapolate to 1.5 meter.

#### *Radiation loss coefficient*

The absorber under study was painted with black material on its surface to enhance its absorptivity.

$$h_{rs} = \varepsilon\sigma \frac{(T_r^4 - T_{sky}^4)}{(T_r - T_{amb})} \quad (3.8)$$

The emissivity of black body was 0.9 and Stefan Boltzmann constant =  $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$

The coefficient of radiative heat loss from absorber wall to ambient depends upon radiation exchange with the sky at sky temperature.

$$T_{sky} = T_{amb} - 6 \quad (3.9)$$

Since the experiment was conducted in the month of October the average ambient temperature is 21.2 °C as shown in Table 3-5 below, then the sky temperature is 15.2°C.

Table 3-5 Analyzed average ambient temperature in Addis Ababa

Month	Average Temp(°C)
January	20.87
February	21.96
March	22.48
April	22.88
May	22.74
June	21.89
July	20.55
August	20.33
September	21.76
October	21.2
November	20.47
December	20.97
Average	21.51

These ambient temperature values are analyzed from daily average data to monthly average data, with the maximum average ambient temperature at April and minimum at August.

Calculating the side overall heat loss coefficient ( $U_s$ )

$$\frac{1}{U_s} = \frac{1}{h_{cs} + h_{rs}} \quad (3.10)$$

$$Q_s = U_s A_s (T_r - T_{amb}) \quad (3.11)$$

$$Q_s = \left[ 5.7 + 3.8V + \frac{\varepsilon \sigma (T_r^4 - T_{sky}^4)}{(T_r - T_{amb})} \right] A_s (T_r - T_{amb})$$

2. Bottom Loss: The bottom surface is considered a flat surface and heat is lost from it due to convection and radiation.

#### *Convection loss coefficient*

To incorporate the effect of wind velocity on convective heat transfer coefficient between the ambient and heater base is being computed using the relation [36].

$$h_{cb} = 2.8 + 3.0V \quad (3.12)$$

*Radiation loss coefficient*

Computing the radiation heat loss coefficient in the same way as calculated for the side loss

$$h_{rb} = \varepsilon\sigma \frac{(T_r^4 - T_{sky}^4)}{(T_r - T_{amb})} \quad (3.13)$$

Since the temperature of the receiver at the bottom is greater assume 110°C.

Computing the bottom overall heat loss coefficient ( $U_b$ )

$$\frac{1}{U_b} = \frac{1}{h_{rb} + h_{cb}} \quad (3.14)$$

$$Q_b = U_b A_b (T_r - T_{amb}) \quad (3.15)$$

$$Q_b = \left[ 2.8 + 3.0V + \frac{\varepsilon\sigma(T_r^4 - T_{sky}^4)}{(T_r - T_{amb})} \right] A_b (T_r - T_{amb})$$

3. Top loss: The top loss constitutes all the losses taking from the lid or the upper surface of the heating pot. It embraces the heat losses from air volume present above the liquid if the pot is not completely filled. Thus, it includes the conduction loss across the lid of the pot.

*Convection loss coefficient*

The convective heat loss coefficient is computed using above relation for a flat surface

$$h_{ct} = 2.8 + 3.0V \quad (3.16)$$

*Radiation loss coefficient*

The radiation loss coefficient is calculated in the same way as for the bottom part of the absorber and is given by

$$h_{rt} = \varepsilon_p\sigma \frac{(T_p^4 - T_{sky}^4)}{(T_p - T_{amb})} \quad (3.17)$$

$\varepsilon$  – Emissivity of the pot  $\cong 0.77$

The overall heat loss coefficient at the top of the heating pot is ( $U_t$ )

$$\frac{1}{U_t} = \frac{1}{h_{rt} + h_{ct}} \quad (3.18)$$

$$Q_t = U_t A_t (T_p - T_{amb}) \quad (3.19)$$

$$Q_t = \left[ 2.8 + 3.0V + \frac{\varepsilon\sigma(T_p^4 - T_{sky}^4)}{(T_p - T_{amb})} \right] A_t (T_p - T_{amb})$$

The total loss by the absorber and the heating pot are: -

$$Q_{loss} = Q_s + Q_b + Q_t$$

The energy collected by the parabolic dish solar collector is also calculated as

$$Q_c = A_a I_b \quad (3.20)$$

The aperture diameter of the parabolic dish is calculated as

$$D_a = \sqrt{\frac{4A_a}{\pi}}$$

The focal point of solar dish concentrator can be determining from the parabolic equation: -

$$4fZ = \frac{x^2 + y^2}{2} \quad (3.21)$$

The value of y and x are the same based on the Figure 3-5, and z is the vertical distance or height of the dish, then the value of focal distance (focal point) from the vertex (0,0) is: -

$$f = \frac{y^2}{4Z}$$

The height of the parabolic dish, h, is defined as the distance from the origin to a line drawn across its aperture. In terms of focal length and aperture diameter, the height of the dish is:[23]

$$h = \frac{D_a^2}{16f} \quad (3.22)$$

Focal point of the dish is found at the top center as shown in Figure 3-5 below, height and aperture diameter of the solar heat are represented by solid work model.

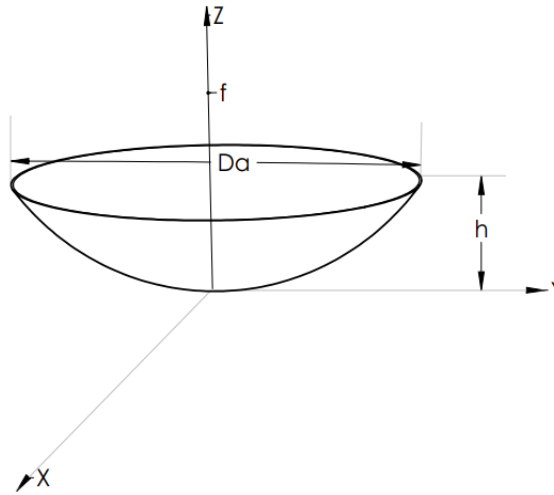


Figure 3-5 Pictorial drawing of parabolic dish

The concentrator collects incident solar (beam and diffused) solar radiation and reflects to the absorber which is found at the focal length.

Concentrators can be defined as in terms of geometric concentration [23][37].

Geometric concentration is the ratio of aperture area to absorber area

$$C_{Rg} = \frac{A_a}{A_{abs}} \quad (3.23)$$

**Optical efficiency ( $\eta_o$ )** - is defined as the ratio of the energy absorbed by the absorber to the energy incident on the concentrator aperture. It depends on solar beam incidence effects, shape of the collector, reflectance of the reflector, tracking type, absorptance of the absorber, transmittance of the glazing material and other factors like shading and dusts.

$$\eta_o = \frac{Q_{abs}}{I_b A_a} \quad (3.24)$$

**Cooking power-** The cooking power of the different solar heaters was calculated using equation given by [2] as follows, since the power is tested in both sensible and latent heat transfer, for water up to starting of boiling point, only sensible heat transfer equation is used Equation (3.25) and after sensible heat latent is followed.

$$Q_p = \dot{m}_f C_{pf} (T_f - T_o) \quad (3.25)$$

**Thermal efficiency ( $\eta_{th}$ )** - is defined as the ratio of the useful energy delivered to the energy incident at the concentrator aperture.

$$\eta_{th} = \frac{\dot{m}_f C_{pf}(T_f - T_o)}{I_b A_a} \quad (3.26)$$

### 3.4. Sizing of PCM material and other parameters

The amount of PCM used is determined by considering energy required to heat the water and warm food.

LHS is worked by the principle of heat storing and releasing under the phase changes from solid to liquid, liquid to gas and vice versa. The storage capacity  $Q_u$ , in J, of the LHS system with a PCM medium [17] is given by

$$Q_u = \int_{T_i}^{T_m} m C_p dT + \Delta m h + \int_{T_m}^{T_f} m C_p dT \quad (3.27)$$

$$Q_u = m [C_{ps}(T_m - T_i) + \Delta h + C_{pl}(T_f - T_m)] \quad (3.28)$$

Phase change materials has three important phases as shown in Figure 3-6. The solid phase, after some heat applied (the combination of solid and liquid) and liquid (after melting point) are the three stages.

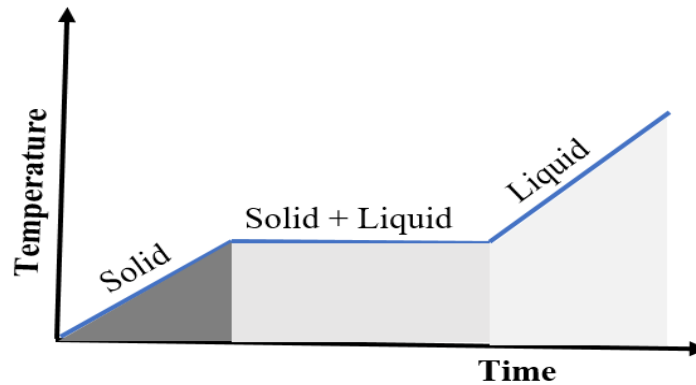


Figure 3-6 Temperature – Time diagram of Phase change material

The heat up to starting of melting point is sensible, most of the heat is stored from starting of melting point to the end of liquid phase (starting of vapor).

The heat is stored by both sensible and latent heat storage. The selected PCM is magnesium chloride hexahydrate because of its melting temperature approximately the same as cooking or boiling temperature and availability in the local market. Initially the heat is added to rise the salt temperature from ambient to 117°C which is melting temperature, then followed by latent heat addition until all solid convert to liquid. Finally, to ensure the phase change is completed that the heat is added sensibly up to the salt temperature reaches greater than 117°C.

Then the amount of PCM is determined as: -

$$m = \frac{Q_u}{c_{ps}(T_m - T_i) + \Delta h + c_{pl}(T_f - T_m)} \quad (3.29)$$

After determining the amount of PCM it can be determined that the volume of PCM in solid and liquid phase. Calculating the volume of MCHH is used to determine the volume of storage container material, based on this the volume of PCM is calculated as: -

$$V_{spcm} = \frac{m_{pcm}}{\rho_{spcm}} \quad (3.30)$$

And the volume of liquid PCM is

$$V_{lpcm} = \frac{m_{pcm}}{\rho_{lpcm}} \quad (3.31)$$

The volume of PCM container and volume of liquid MCHH is must be approximately the same, because the heated liquid PCM must contact with the storage material container to transfer heat to the pot.

So, the volume of cylindrical shape material (PCM container) is calculated as: -

$$V = \pi r^2 h \quad (3.32)$$

The volume of cylinder (absorber) is 3000cm<sup>3</sup> which is the volume of liquid MCHH and consider the height of cylinder is 5cm then the radius of absorber is: -

$$r = \sqrt{\frac{V}{\pi h}}$$

The volume of pot is approximately the same as the volume of water.

$$V_p = V_w \quad (3.33)$$

The radius of heating vessel or pot is approximately less than or equal to the radius of PCM container, then the height of pot is: -

$$h = \frac{V_p}{\pi r^2}$$

### 3.5 Heat transfer analysis

#### 3.5.1 Energy balance for absorber

The basic purpose of a solar heater is to heat things up, warm food, purify water, and sterilize instruments. Sunlight both beam and diffused, enters the solar heater (pot) through the glass or plastic top and concentrator. It turns to heat energy when it is absorbed by the dark painted absorber plate and heating pots. Temperatures sufficient for heating water are easily achieved. The PCM container (absorber) receives heat from the concentrator which focuses a part of the radiations falling on it. This heat is being absorbed by receiver material and then transferred to the working fluid (PCM) and the air volume present in the container. The rest is being lost to the atmosphere in the form of convection and radiation.

Accordingly, heat balance equation for the absorber (PCM container) is [38].

$$Q_{abs} = Q_{pcm} + Q_{loss} + m_R C_R \frac{\partial T_R}{\partial t} \quad (3.34)$$

$$Q_{abs} = \rho \alpha \tau I_b A_c \quad (3.35)$$

The total loss by the absorber or PCM containers are side loss and bottom loss

$$Q_{loss} = Q_s + Q_b \quad (3.36)$$

#### 3.5.2 Energy balance for heating pot

Energy balance of the heating pot is the same as that of PCM except that of changing the phase in the case of PCM.

$$Q_p = Q_f + Q_{loss} + m_p C_p \frac{\partial T_p}{\partial t} \quad (3.37)$$

$$Q_p = UA_p(T_r - T_p) \quad (3.38)$$

The overall heat transfer coefficient is the summation of each heat transfer coefficient with the specific area and resistance of the material. It can be calculated as the sum of heat transfer

coefficient and reciprocal of the sum of a series of thermal resistances (absorber and heating pot).

$$\frac{1}{UA} = \sum \frac{1}{hA} + \sum R \quad (3.39)$$

$R = \frac{x}{KA}$ , this represents heat coefficient by conduction.

The resistance to the flow of heat by the material of wall can be expressed as a "heat transfer coefficient of the material wall". Then the heat transfer coefficient for the material wall can be calculated as if the wall were not curved.

$$h = \frac{k}{x}$$

The heat absorbed by working fluid in side cooking vessel is:

$$Q_f = Q_{fa} + m_f C_f \frac{\partial T_f}{\partial t} \quad (3.40)$$

$$Q_{fa} = h_a A_a (T_f - T_a) \quad (3.41)$$

$$h_a = \frac{NuK}{D} \quad (3.42)$$

Since the flow is laminar with a constant temperature inside the cooking vessel then the Nusselt number is approximately 4.36 [36].

From property of air at 76 kPa atmospheric pressure the thermal conductivity of air at 90°C is 0.02945 W/m.K [39].

The area of section above the fluid inside the pot is the same as that of area of pot containing the fluid.

The total losses by the heating pot are side loss and top loss, this is because at the bottom of the heating pot there is absorber (PCM container). Then the total loss by the pot is

$$Q_{loss} = Q_s + Q_t \quad (3.43)$$

### 3.6 Fins and extended surfaces

To enhance the rate of heat transfer between the PCM and the inner wall of the PCM container (absorber) and bottom of heating pot, fins are welded at the inner wall of the PCM container and extended it to the upper part of the absorber. The usual materials for the fin are steel,

copper, graphite foil or aluminum. Copper was used as a fin material because of its high thermal conductivity as compared to others graphite foil, aluminum and steel. Rod shaped copper fins are welded inside the absorber (storage container), which contact with the lower and upper surface of the absorber to transfer heat from lower part to upper part.

Since the fin is attached to a base surface of absorber, the base temperature  $T_{(0)} = T_b$  and extends into a fluid of temperature  $T_\infty$ . For the uniform cross-sectional fins,  $A_{cf}$  is a constant and  $A_{sf} = Px$ . where  $A_{sf}$  is the surface area measured from the base to  $x$  and  $P$  is the fin perimeter.

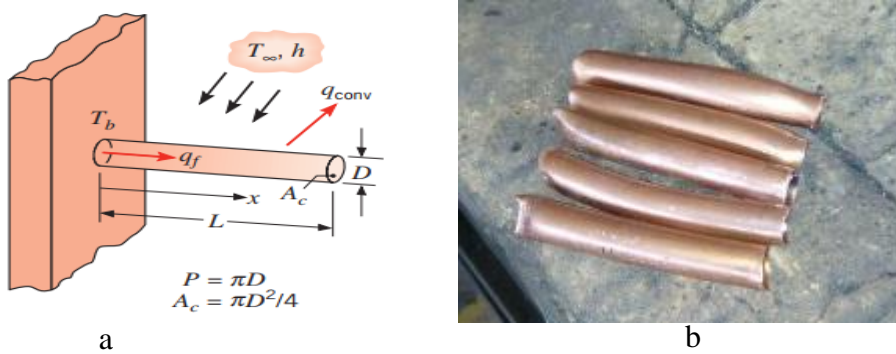


Figure 3-7 a) Straight fins of uniform cross section[39] b) fin used for experimentation

The fin heat transfer rate  $q_f$  is evaluated in two ways at fin base ( $x=0$ ) and with the temperature distribution of length  $x$ .

$$q_f = q_b = -kA_{cf} \frac{dT}{dx} \quad (3.44)$$

And

$$q_f = \sqrt{hPkA_c} \theta_b \frac{\sinh mL + (h/mk) \cosh mL}{\cosh mL + (h/mk) \sinh mL} \quad (3.45)$$

Where  $m = \sqrt{hP/kA_c}$  ( $m^{-1}$ )

$$\theta_b = \theta(0) = T_b - T_\infty \text{ (}^\circ\text{C)}$$

For laminar flow with fully developed hydrodynamic and thermal profiles in tubes, for constant wall temperature and for constant heat flux the Nusselt number is 3.7 and 4.4 respectively. In a solar collector the thermal condition is thoroughly represented by constant

temperature setting[36]. Since the flow is laminar with constant temperature, the Nusselt number is 3.7 then the convective heat transfer coefficient is calculated as

$$h = Nu \frac{k}{D}$$

The perimeter of fin is also calculated as

$$P = 2(\pi D + l) \quad (3.46)$$

$$A_{cf} = \frac{\pi D^2}{4}$$

$$m = \sqrt{hP/kA_c}$$

$$\theta_b = T_b - T_\infty$$

Then the heat transfer rate at the fin is calculated using equation 3.45

The heat transfer rate by only single fin is 13.91W, for five fin the heat transfer rate at the length of 5cm is 69.55W.

Then the temperature at the end length of the fin is calculated by using equation 3.44

$$T_x = \frac{q_f}{-kA_c} + T_b$$

Where  $T_x$  – temperature at the end of fin (at 5cm length)

The 368K of temperature is distributed at the top part of the absorber by using fins. The fin itself represents a conduction resistance to heat transfer from the original surface. Because of this, there is no assurance that the heat transfer rate will be increased through the use of fins. This is checked or evaluated by fin effectiveness.

$$\varepsilon_f = \frac{q_f}{hA_{c,b}\theta_b} \quad (3.47)$$

The value of fin effectiveness should be as large as possible, the use of fins may rarely be justified unless  $\varepsilon_f \geq 2$ . But in this designed fin the effectiveness of fin is 97, so the use of fin is necessary.

### 3.7 Construction technique

The construction of parabolic dish solar heater has been carried out in different steps

- 1) parabolic dish construction
- 2) Tracking mechanism
- 3) Receiver (absorber) construction

#### 3.7.1 Parabolic dish construction

The aperture diameter of 59 cm parabolic dish is constructed at an angle of  $82.95^\circ$  to the south direction. It is supported by the rectangular iron at two side of the dish and small rectangular metal at the bottom of the dish which is joint by the bolt and nut. The reflecting material used for parabolic dish construction was mirror glass of 3 mm thick. This is used to having the good strength and reflectivity. In this design parabolic dish of flat segmented mirrors was divided into rectangular fields, each field containing a number of mirrors. The whole radiated (incident) rays were collected on the surface of the dish, the mirror then reflects the 98% of incident ray to the absorber. The mirror dimensions in the same field were the same and its number was determined according to the circumference of the circular dish.

#### 3.7.2 Tracking mechanism

For maximum energy collection orientation of the concentrator and absorber relative to the direction of propagation of beam radiation is needed. Sun tracking in some degree will be required for focusing systems. When the axis is parallel to earth axis, the rate of rotation is constant, one revolution per day or  $15^\circ/\text{hr}$ .

To indicate the location of the sun in the sky, relative to a point on the ground is described in terms of two angles, the solar altitude  $\alpha_s$  (complement the solar zenith angle,  $\theta_z$ ) and the solar azimuth  $\gamma_s$ .

**Solar altitude ( $\alpha_s$ )** is the angle between the line passing through the point and the sun and the line passing through the point tangent to the earth and passing below the sun.

$$\sin\alpha_s = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \quad (3.48)$$

**Solar azimuth ( $\gamma_s$ )** is the angle between the line under the sun and the local meridian pointing to the equator.

$$\cos \gamma_s = \frac{\sin \alpha_s \sin \varphi - \sin \delta}{\cos \alpha_s \cos \varphi} \quad (3.49)$$

**Latitude ( $\varphi$ )** is a geographic coordinate that specifies the north–south position of a point on the Earth's surface. So, the coordinate of current project site is 9.038°N, 38.763°E.

The manual tracking mechanism was used to track the system. The tracking system is held within 15-minute interval with an altitude and azimuth angle of 89.00° and 82.95°. This manually tracking system was controls the movement of a solar concentrator. So that it was constantly aligned towards the direction of the sun. As the plane of the concentrator was always maintained normal to the sun's rays, maximum power was generated by the concentrator. Tilting the concentrator in single axis were used as manually tracking mechanism.

### 3.7.3 Absorber construction

After construction of parabolic dish with the tracking mechanism absorber construction is followed. Here in this setup there are two types of heating processes. The first one is 16.2 cm diameter with 5 cm height PCM container made of aluminum with black coating placed at the focal length of the concentrator to melt the PCM. After melting the PCM, heating is held inside the home, since the PCM container is portable (it has handling system) as shown Figure 3-8. To get the maximum concentration the absorber must stand at the focal point.



*Figure 3-8 Absorber*

The second one is at the same time when heating is held inside the home with melted PCM another heating process can held outside by using the constructed parabolic dish directly. The heating pot (14.2 cm diameter with 8 cm height) made of aluminum is stand over the

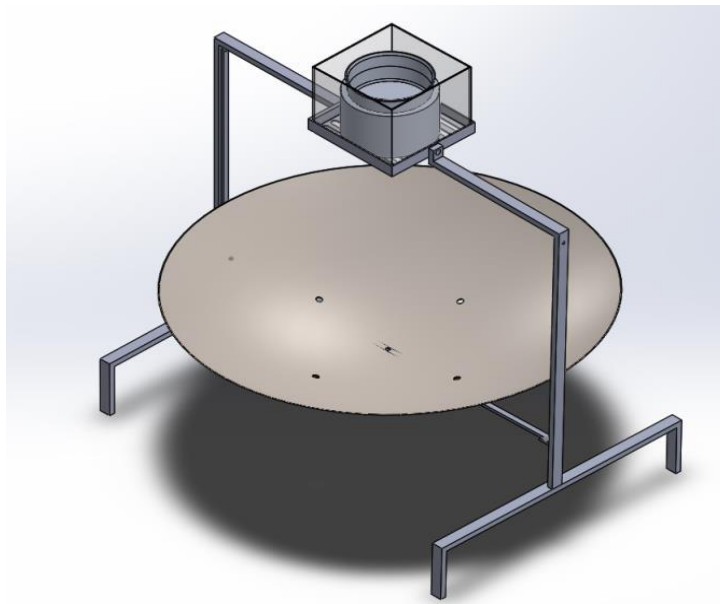
constructed focal length of the concentrator to warm the food or to boil water. Since the wind has an effect on the decreasing temperature of the absorber by means of convectional loss. To minimize this effect on the temperature of the absorber, 16.4 cm length, 16.4 cm width with the height of 15 cm glazing system is used as shown in the Figure 3-10.

The absorber was filled with the phase change material used to store heat by solar radiation. Three and half kilogram of phase change material was used as shown in Figure 3-9 below.



*Figure 3-9 Magnesium chloride hexa-hydrate*

Positioning the PCM at the surrounding of the heating pot increases the rate of heat transfer between the PCM and to the pot, because of this heating can be faster[32].



*Figure 3-10 The overall set up the parabolic dish solar heater*

The overall 3D cad drawing model of parabolic dish solar water heater is as shown in Figure 3-10 above. At the focal length absorber contains PCM is found. Above the absorber heating vessel (pot) and glazing surrounded the absorber and cooking vessel are found.

*Table 3-6 Values of designed parameter*

<b>No</b>	<b>Parameters</b>	<b>Value</b>	<b>Unit</b>
1	Aperture area	0.2160	m <sup>2</sup>
2	Aperture diameter	0.59	m
3	Focal length	0.40	m
4	Absorber energy	1088	kJ
5	Side loss	26.46	W
	Convection loss coefficient	6.87	W/m <sup>2</sup> K
	Radiation loss coefficient	7.8	W/m <sup>2</sup> K
6	Bottom loss	14.17	W
	Conventional loss coefficient	3.73	W/m <sup>2</sup> K
	Radiation loss coefficient	7.43	W/m <sup>2</sup> K
7	Top loss	15.02	W
	Conventional loss coefficient	2.73	W/m <sup>2</sup> K
	Radiation loss coefficient	6.75	W/m <sup>2</sup> K
8	Total loss	55.65	W
9	Minimized loss by glazing	41.48	W
10	Loss by Absorber	40.63	W
11	Loss by Pot	41.48	W
12	Useful energy	937.5	kJ
13	Mass of PCM	3.5	kg
14	Volume of solid PCM	0.002622	m <sup>3</sup>
15	Volume of liquid PCM	0.002853	m <sup>3</sup>
16	Radius of absorber	0.162	m
17	Height of absorber	0.05	m
18	Volume of pot	0.001000	m <sup>3</sup>
19	Height of pot	0.052	m
20	Heat transfer coefficient of PCM	17.71	W/m <sup>2</sup> K
21	Perimeter of fin	0.10628	m
22	Area of fin	0.0000785	m <sup>2</sup>
23	Heat transfer rate by single fin	13.91	W
24	No of fin	5	
25	Temperature of fin at the end of 5 cm length fin	368	K

## CHAPTER FOUR

### 4 Experimental Investigation

The experimental set up consists of parabolic dish collector, absorber (PCM container), aluminum vessel (heating pot), manual tracking mechanism, booster mirror reflecting surface, glass (glazing system), measuring instruments and overall supporting mechanism, Figure 4-4. Mirror anodized parabolic dish collector having aperture area of  $2160\text{cm}^2$  with focal length of 40cm is used as solar collector. The aluminum absorber having outer diameter of 16.2cm with 8cm height and inner diameter of 14.4cm with 5cm height is used as thermal energy storage material container. It contains heated PCM and transfers heat to the food inside heating vessel. The aluminum vessel is main heating vessel in which heating is carried out. This vessel is inserted into the absorber in such a way that it remains continuously in contact with heating fluid. In addition to this, the storage tank is affected by moisture at night and rainy time, this moisture can cause the failure of the absorber and minimize the overall life of the material. So, to minimize this problem the storage tank must be portable by applying handling system. Then at night and rainy time it can entered to the house.

Aluminum vessel has 14.2cm diameter and 8cm height is used. Hence after every 10 or 15 minutes, the position of the collector is adjusted to bring radiation in correct position. The temperature measurement is very important because it is necessary to examine heating condition of various surfaces (sides and bottom), food and heat transfer from PCM for the analysis purpose. For this temperature measurement, K type thermocouples are used. Wind speed also measured by using five in one environmental meter. To the outer surface of the aluminum tank rectangular glass covering (glazing) material is used, this glazing system minimizes the conventional heat loss caused by wind speed.

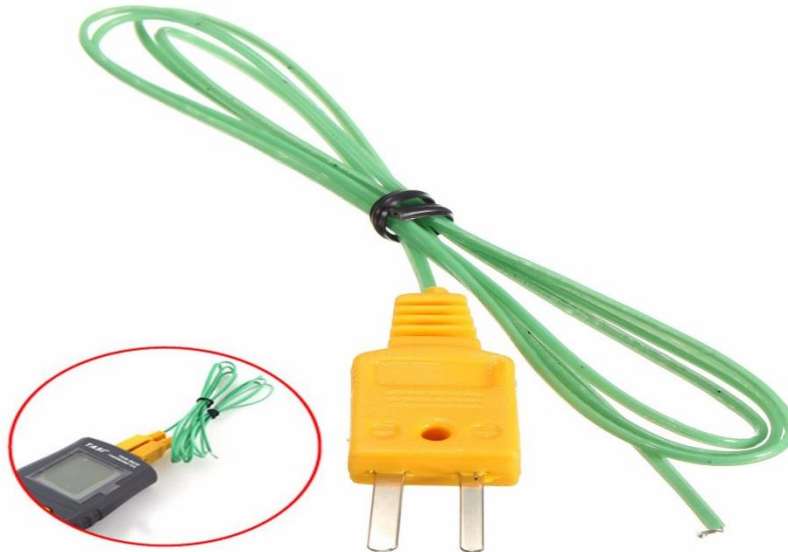
Total of two thermocouples are used in this setup for measuring the variation of temperature across the system. Out of these thermocouples, one thermocouple is mounted at the inner surface of absorber and one is at the inner surface of aluminum vessel (heating pot). Another infrared temperature measurement device is used to measure the outer surfaces. These are used to measure the outer surface of absorber, outer surface of heating pot, glazing material and ambient temperature.

#### 4.1 Instruments used for experimentation test

Performance evaluation of parabolic dish collector requires accurate recording and precise measurement of all parameters related to the system and surroundings. Instruments used are described as below.

##### 4.1.1 Temperature recorder (thermocouple)

The temperatures at different locations were measured by means of K- type thermocouple. These thermocouples are used to record the temperature at the inner side of the absorber and cooking vessel.



*Figure 4-1 K- type thermocouple*

##### 4.1.2 Digital infrared thermometer

The digital infrared thermometer was used to measure the temperatures of concentrator and outer surface of the receiver, outer surface of absorber, glazing and ambient temperature. The range of instrument is from -20 to + 500°C.



*Figure 4-2 Digital infrared thermometer*

#### **4.1.3 Environmental meter**

The wind speed, which has a major effect on the performance of a solar heater was measured using environmental meter. The environmental meter was used to measure many parameters like air velocity, light intensity, ambient temperature, and sound intensity. The instrument measured air velocity from 0.1 to 40 m/s.



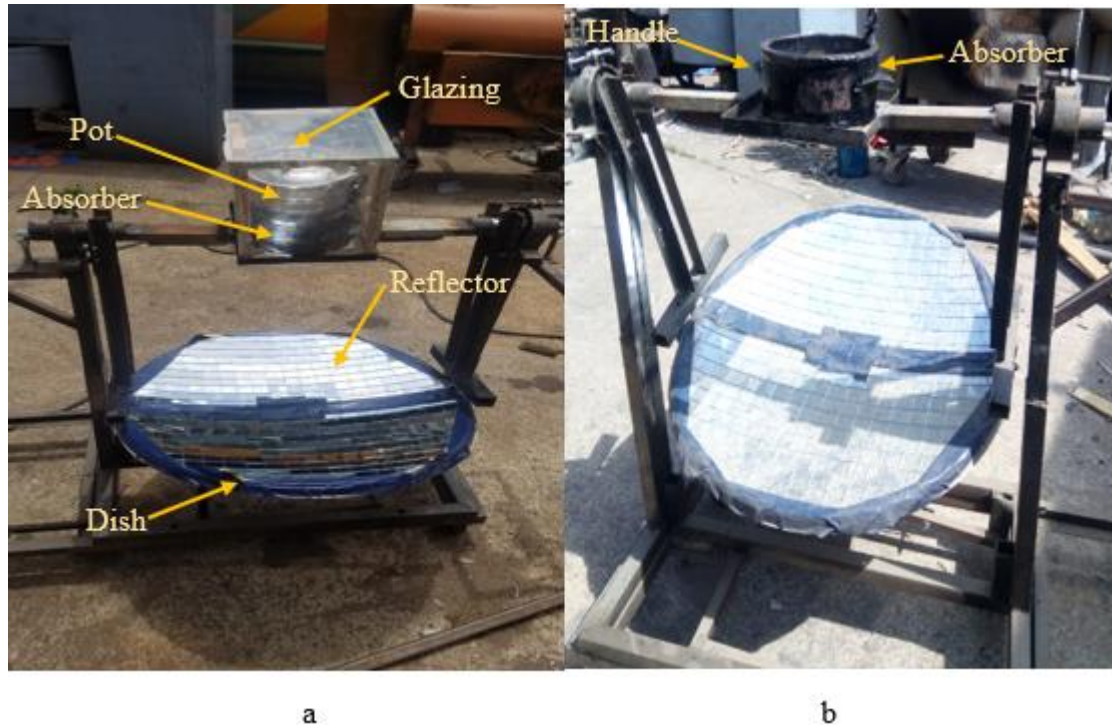
*Figure 4-3 Five-in-one Environmental meter*

## **4.2 Outdoor Experimental Set-up of Parabolic Dish Solar Heater**

This experimental work mainly studies the solar transformation energy into thermal energy by using a solar parabolic dish concentrator with a manual tracking mechanism. In order to investigate the parabolic dish solar concentrator performance, an experimental unit

has been designed, built and tested in experimental held station. This station is located at Addis Ababa University where, Longitude of 38.7 ° E and Latitude of 9.04 ° N.

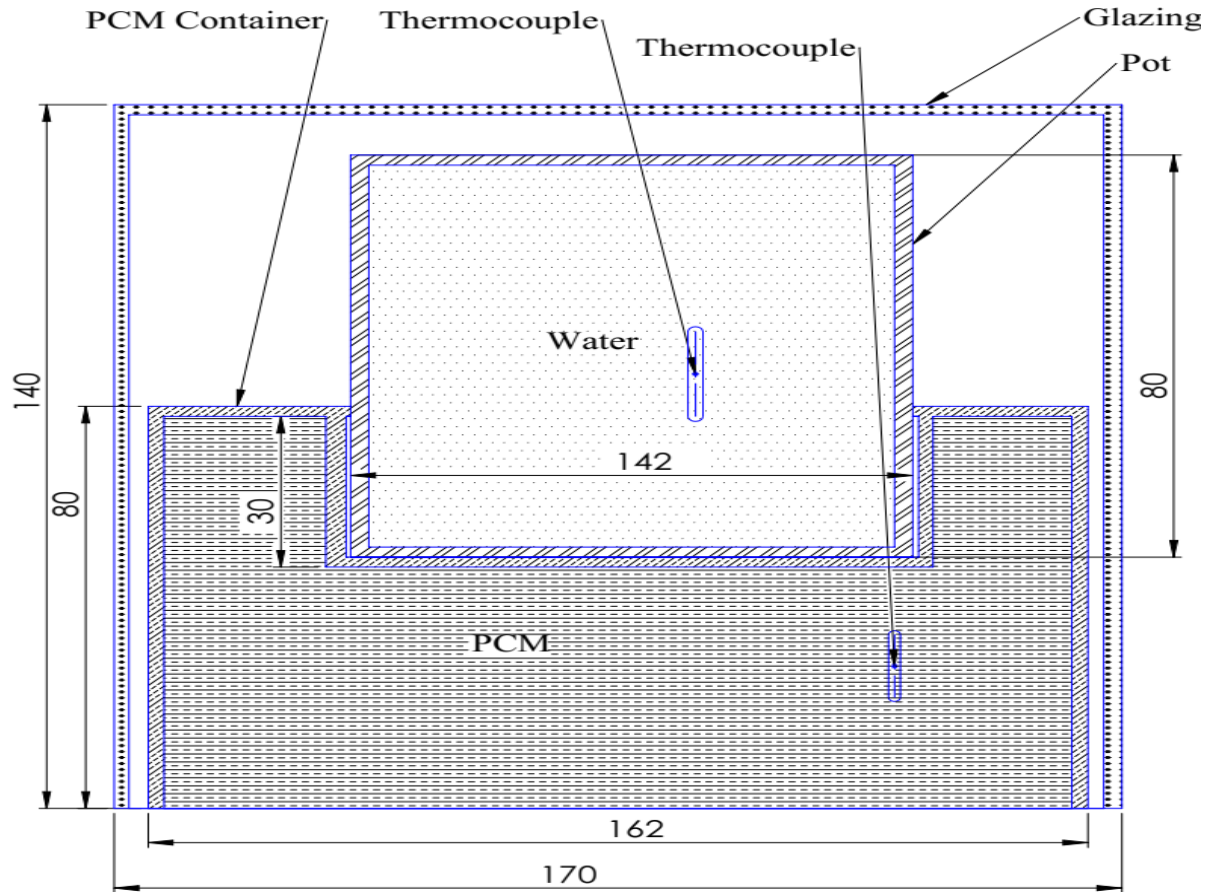
The experimental tests on the parabolic dish solar heaters were carried out during the duration starting from October 09/2019 to October 17/2019 between 09:00 am to 4:00 pm.



*Figure 4-4 Experimental set up of absorber (a) with the load and glazing (b) without load and glazing*

### **4.3 Experimentation test setup**

To determine the time required to heat water, different experiments were conducted for nine consecutive days. The ambient temperature, the temperature of the PCM, the water, the absorber (PCM container), the pot as well as the glazing were recorded in 15-minute intervals. In addition, the speed of wind was recorded to calculate the conventional heat loss by absorber and heating pot. Solar radiation was taken from meteoblue site for the experiment conducted date and site[40]. Compared to the local meteorological data value the meteoblue site have 0.04% variation, this is almost the same. The experimental setup of the absorber, cooking vessel and glazing is shown in Figure 4-5.



*Figure 4-5 Setup of the measurement devices with parts to be measured*

One liter of water was used as the experimental test. To reduce heating time of the water half part of the heating pot was inserted into the absorber filled by 3.5 kg of PCM as shown in Figure 4-5. The absorber and the heating pot were covered by the transparent glass cover. The temperature of the water inside the heating pot and the PCM inside absorber were measured by using K-type thermocouple. The temperature of outer part of the absorber, the heating pot and glazing were measured by infrared thermometer. Wind speed was measured by using five in one environmental meter.

## **CHAPTER FIVE**

### **5. Result and discussion**

#### **5.1 Melting the storage material with the load and glazing**

The melting temperature of storage material was 117°C. To achieve this melting temperature, it needs heat energy at high temperature. Experimental test, to melt (heat) of the PCM were held for six different days. The first three days were with load (water) as shown in Figure 4-4 a, and the next three days were without load as shown in Figure 4-4 b. For the first three days (with load), the first and second days test were conducted with the glazing whereas the third day test was without glazing. In these first three days, the melting temperature of the storage material was not reached. The main reason was the type of the absorber material. Since the manufacturing of aluminum was not available locally, sheet metal was used to manufacture the absorber (storage container).

The second reason was the weather condition of the testing time and location. Since the average wind speed in Addis Ababa in October was higher than the other months. The last reason was to melt the PCM by applying load directly outdoor as shown in Figure 4-4a. The heat stored by the PCM directly transferred to the load and couldn't store the required amount of heat. But for the next days (day 4 and day 5) the PCM was melt in each day. From nine consecutive day tests, different types of tests were conducted.

The three types of test conducted were: -

##### **5.1.1 Test the solar heater with storage material, glazing, and load**

In the first three days test, measurements were recorded to evaluate the performance of the storage material (PCM) with load and glazing (cover). Ambient temperature, temperatures of the PCM, the water, the absorber (storage container), the pot, the glazing (cover) as well as the wind speeds were recorded. Here, the wind speed was recorded to know the amount of conventional heat losses. The results are recorded in Table 5-1, 5-2 and 5-3.

Table 5-1 First two day recorded data with load, storage material and glazing

## Day 1

Time	$I_s$ (W/m <sup>2</sup> )	$T_{amb}$ (°C)	$T_{pcm}$ (°C)	$T_w$ (°C)	$T_R$ (°C)	$T_P$ (°C)	$T_{gl}$ (°C)	V (m/s)
9:00 AM	408.5	22.9	33.3	25.9	54.0	28.1	27.7	0.7
10:00 AM	350.6	23.8	62.2	44.3	113.1	38.8	33.2	0.3
11:00 AM	375.5	23.8	82.4	60.1	129.2	48.8	36.3	1.2
12:00 PM	475.2	23.8	93.8	70.0	139.8	64.1	37.9	1.0
1:00 PM	397.8	23.6	98.4	77.4	143.6	84.5	38.3	0.4
2:00 PM	390.7	23.5	103.0	85.5	139.0	88.0	37.8	0.5
3:00 PM	532.2	22.5	106.5	91.0	132.5	91.1	37.3	0.8
4:00 PM	374.6	22.0	103.7	91.0	125.3	88.6	35.1	0.9
Average	413.1	23.4	83.3	65.5	121.7	63.9	35.5	0.7
Max.	532.2	23.8	106.5	91.0	143.6	91.1	38.3	1.2
Min.	350.6	22.0	33.3	25.9	54.0	28.1	27.7	0.3

## Day 2,

Time	$I_s$ (W/m <sup>2</sup> )	$T_{amb}$ (°C)	$T_{pcm}$ (°C)	$T_w$ (°C)	$T_R$ (°C)	$T_P$ (°C)	$T_{gl}$ (°C)	V (m/s)
9:00 AM	206.4	22.9	32.6	25.7	48.8	28.0	27.3	1.2
10:00 AM	277.6	23.6	62.9	41.2	93.0	38.8	32.9	1.4
11:00 AM	385.3	23.9	81.4	57.7	120.2	46.7	37.7	0.9
12:00 PM	411.1	23.8	91.8	68.9	139.1	54.0	38.5	0.9
1:00 PM	427.2	23.8	98.9	77.5	143.0	68.4	38.3	0.6
2:00 PM	396.0	23.2	106.5	87.9	137.9	89.5	37.8	0.8
3:00 PM	477.0	22.5	107.8	90.7	135.3	94.5	37.3	1.1
Average	368.71	23.5	80.5	61.4	114.8	56.4	35.5	1.0
Max.	477.0	23.9	107.8	90.7	143.0	94.5	38.5	1.4
Min.	206.4	22.5	32.6	25.7	48.8	28.0	27.3	0.6

The maximum temperature achieved by the storage material (PCM) on day 1 and day 2 were 106.5 °C and 107.8°C respectively. This stored heat can be used to heat water indoor or outdoor during cloudy time. In day 2, discharging the stored heat (PCM) was conducted inside the house by heating one liter of water. During discharging, test the resulting temperatures of the PCM, the water, the absorber and the pot were recorded, as shown in Table 5-2. The absorber was kept in at insulated vessel to prevent heat loss.

*Table 5-2 Day 2, Discharging of PCM and heating of water inside home*

<b>Time</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>
3:00 PM	107.0	23.2	130.8	27.6
4:00 PM	104.6	40.1	120.8	42.3
5:00 PM	94.4	75.9	96.3	76.6
6:00 PM	83.2	82.1	81.4	81.1

The water temperature reached 82.1°C at 6:00 PM and could not go beyond that while the PCM temperature reduced from 107.0 °C to 83.2°C.

In day three, a test was conducted on the solar heater with the load, the PCM and without a cover plate (glazing). The Absorber was loaded with one liter of water. Starting from 9:00 AM to 4:00 PM, the results are recorded, Table 5-3.

*Table 5-3 Day 3, Measured data with load, storage material and without glazing*

<b>Time</b>	<b>I<sub>s</sub> (W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	236.7	22.5	26.0	23.1	30.7	25.8	0.7
10:00 AM	328.4	23.0	39.0	33.2	55.8	33.6	0.7
11:00 AM	728.9	23.7	50.5	46.0	90.0	45.0	1.0
12:00 PM	641.6	23.8	60.7	56.1	109.4	59.0	0.5
1:00 PM	559.8	23.7	70.7	62.2	115.4	66.5	0.8
2:00 PM	351.5	22.9	80.4	67.9	118.2	71.8	0.6
3:00 PM	389.8	22.5	89.0	70.9	108.3	74.2	0.9
4:00 PM	283.9	22.2	89.5	70.0	101.8	71.5	0.8
Average	440.1	23.1	60.2	51.8	90.0	54.1	0.7
Max.	728.9	23.8	89.5	70.9	118.2	74.2	1.0
Min.	236.7	22.2	26.0	23.1	30.7	25.8	0.5

Starting from 9:00 AM to 4:00 PM the water temperature increased from 23.1°C to 70.9°C, with the maximum temperature of PCM 89.5°C.

### 5.1.2 Test the solar heater with storage material, glazing and without load

In days four and five, tests were conducted on the unloaded solar heater with PCM and glazing. The temperature of the PCM, the receiver, the glazing, ambient temperature, and wind speeds were measured, Table 5-4, to determine the performance of the unloaded receiver.

*Table 5-4 Two days measured data with storage material, glazing and without load*

Day 4,

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>gl</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	97.0	22.7	53.2	58.0	26.9	0.6
10:00 AM	156.6	23.7	85.2	102.6	28.5	0.6
11:00 AM	198.5	24.2	98.4	128.9	33.2	0.8
12:00 PM	254.5	24.2	106.9	146.2	38.1	1.0
1:00 PM	362.2	23.5	115.9	154.3	38.3	0.8
2:00 PM	277.7	22.6	118.3	143.1	34.0	0.6
3:00 PM	406.7	22.7	118.0	138.8	31.9	0.9
Average	250.5	23.5	101.5	121.6	33.1	0.7
Max.	406.7	24.2	118.3	154.3	38.3	1.0
Min.	97.0	22.6	53.2	58.0	26.9	0.6

Day 5,

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>gl</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	110.3	22.6	54.2	57.2	27.2	1.4
10:00 AM	210.9	23.3	97.8	101.1	30.7	1.0
11:00 AM	545.5	24.0	111.0	121.6	37.7	1.1
12:00 PM	728.0	23.9	116.9	132.8	38.7	1.1
1:00 PM	485.0	23.7	117.8	115.0	35.3	0.5
2:00 PM	399.6	23.5	118.7	100.8	30.0	0.3
Average	413.2	23.5	102.7	104.1	33.3	0.9
Max.	728.0	24.0	118.7	132.8	38.7	1.4
Min.	110.3	22.2	54.2	57.2	27.2	0.3

In day four and day five, the maximum temperatures of PCM were 118.3°C and 118.7°C respectively. These temperatures are greater than the melting temperature of the PCM, 117°C.

After storing heat energy, the solar heater was loaded with one liter of water and discharging its heat by heating the water. The temperatures of the PCM, water, absorber and glass cover were recorded as seen in Table 5-5.

*Table 5-5 Discharging of the PCM and heating of water inside home for day 4 and 5.*

Day 4,

<b>Time</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>
3:10 PM	118.1	38.8	121.9	39.7
4:00 PM	116.8	70.8	118.7	71.0
5:00 PM	105.5	87.5	106.2	80.4
6:00 PM	94.1	91.8	97.3	88.9
Average	112.1	68.6	114.7	65.3
Max.	117.7	91.8	121.9	88.9
Min.	94.1	38.8	97.3	88.9

Day 5,

<b>Time</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>
2:10 PM	118.6	39.9	135.6	41.2
3:00 PM	116.9	74.5	123.4	79.6
4:00 PM	107.4	89.2	107.9	90.8
5:00 PM	96.1	92.6	99.3	92.2
Average	112.8	71.4	115.0	74.1
Max.	117.8	92.6	135.6	92.2
Min.	96.1	39.9	99.3	41.2

In day four and day five the temperature of the PCM was discharged from 118.1°C to 94.1°C and 118.6°C to 96.1°C respectively. The water temperature also rises from 38.8°C to 91.8°C and 39.9°C to 92.6°C at day four and five respectively. In both days the water was boiled at 6:00 PM (91.8°C) and at 5:00 PM (92.6°C). In this result it can be concluded that the melting of PCM without the load is preferable than melting with the load. After melting the PCM, it could be boiled the water outside directly from the PSC or indoor from the melted PCM.

In day six, the solar heater with PCM was tested without applying load and glass cover. In this day the melting temperature of PCM (117°C) was not achieved due to conventional loss by wind. The results are recorded in Table 5-6.

*Table 5-6 day 6, Recorded data for storage material without load and without glazing*

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	517.0	20.8	43.5	43.1	0.7
10:00 AM	667.	22.1	64.7	74.9	1.0
11:00 AM	412.9	23.4	77.0	105.5	1.0
12:00 PM	455.6	23.7	88.7	119.2	0.6
1:00 PM	481.4	22.7	90.7	114.6	0.8
2:00 PM	445.0	22.1	86.8	99.2	0.7
3:00 PM	590.0	21.9	80.1	92.9	0.8
4:00 PM	469.9	21.6	76.4	87.0	0.8
Average	504.9	22.3	75.9	92.6	0.8
Max.	667.5	23.7	90.7	119.2	1.0
Min.	412.9	20.8	43.5	43.1	0.6

The maximum temperature achieved by the PCM was 90.7°C with the average solar insolation of 504.9W/m<sup>2</sup>.

### 5.1.3 Test of the solar heater with load, glazing and without storage material

In day seven and eight the solar heater with load and glazing was tested. Here, the temperature of the water, pot, glazing, ambient temperature, wind speed and solar radiations are recorded, Table 5-7.

*Table 5-7 Two days recorded data with load and glazing*

Day 7,

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>	<b>T<sub>gl</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	365.7	23.1	32.4	32.4	24.9	0.4
10:00 AM	421.8	23.6	53.3	55.1	33.0	0.4
11:00 AM	439.6	23.9	66.9	83.6	37.6	0.7
12:00 PM	452.1	23.4	88.9	100.6	37.7	0.9
Average	419.8	23.5	57.8	64.9	32.9	0.5
Max.	452.1	23.9	88.9	100.6	37.7	0.9
Min.	365.7	23.1	32.4	32.4	24.9	0.4

Day 8,

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>w</sub>(°C)</b>	<b>T<sub>p</sub> (°C)</b>	<b>T<sub>gl</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	525.99	22.6	34.0	34.9	28.3	0.5
10:00 AM	723.57	23.4	66.7	62.4	35.9	0.5
11:00 AM	863.3	23.8	85.7	89.2	37.5	0.6
12:00 PM	919.37	23.7	96.1	96.7	36.4	0.5
Average	758.058	23.3	63.9	64.0	34.1	0.5
Max.	919.37	23.8	96.1	96.7	37.5	0.6
Min.	525.99	22.6	34.0	34.9	28.3	0.5

The water temperature was rises from 32.4°C to 88.9°C and from 34.0°C to 96.1°C at day seven and eight respectively. In day eight the water was boiled before 12:00 PM.

In day nine, the load (water) was tested without storage and without glazing. The test result is shown in Table 5-8.

*Table 5-8 Day 9, last day measured data of load (water) without PCM and glazing*

<b>Time</b>	<b>I<sub>s</sub>(W/m<sup>2</sup>)</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>w</sub>(°C)</b>	<b>T<sub>p</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	516.2	23.0	37.5	29.7	1.2
10:00 AM	614.1	23.1	52.2	36.8	1.2
11:00 AM	610.5	23.6	55.4	43.0	0.9
12:00 PM	894.4	23.7	57.9	47.3	0.9
1:00 PM	801.0	23.5	59.6	52.3	1.0
2:00 PM	507.3	23.0	60.5	52.6	0.6
Average	657.2	23.3	53.4	43.1	1.0
Max.	894.4	23.7	60.5	52.6	1.2
Min.	507.3	23.0	37.5	29.7	0.6

From the above three tables, it can be concluded that the effect of wind was high on the heating of the water, the maximum temperature of water with glazing (day 7 and 8) was 88.9°C and 96.1 °C respectively. While the maximum temperature of water without glazing (day 9) was 60.58 °C, this shows that the conventional heat loss minimizes the temperature of the load. The wind speed increases the loss as a result it will decrease the temperature of water.

The performance different types of the experimental testing of solar heater and thermal storage system are discussed as shown in the following portions. Most of the results are expressed using temperature and time graph in order to indicate the performance.

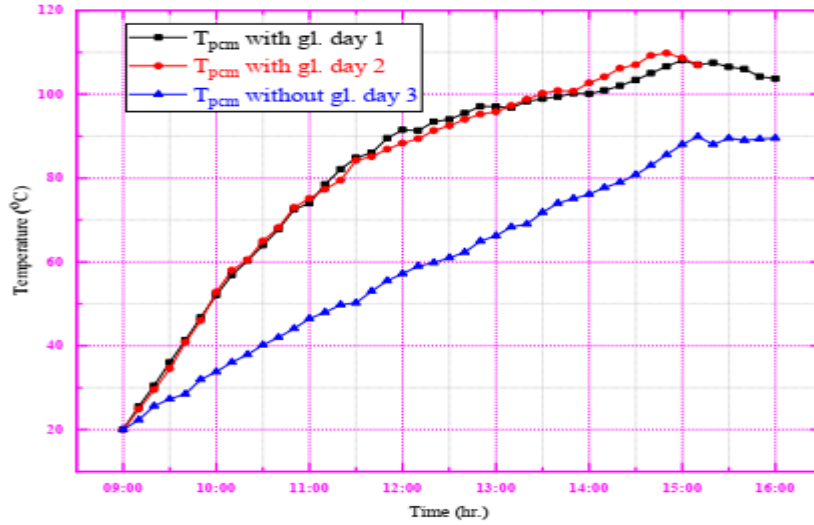


Figure 5-1 Temperature vs time graph of PCM with load and glazing

The maximum temperatures of the phase change material for the first three days test were 106.6°C, 107.8°C and 89.5°C respectively. The maximum solar radiation for these three days tests were 532.2W/m<sup>2</sup>, 772W/m<sup>2</sup> and 728.912W/m<sup>2</sup> and their wind speed were 1.25m/s, 1.4m/s and 1m/s respectively. Even if, the solar radiation value for day three was high, the conventional loss minimizes the heat of the water.

For these first three days, the load (water) temperature varies based on the temperature of the storage material as shown figure 5-2 below.

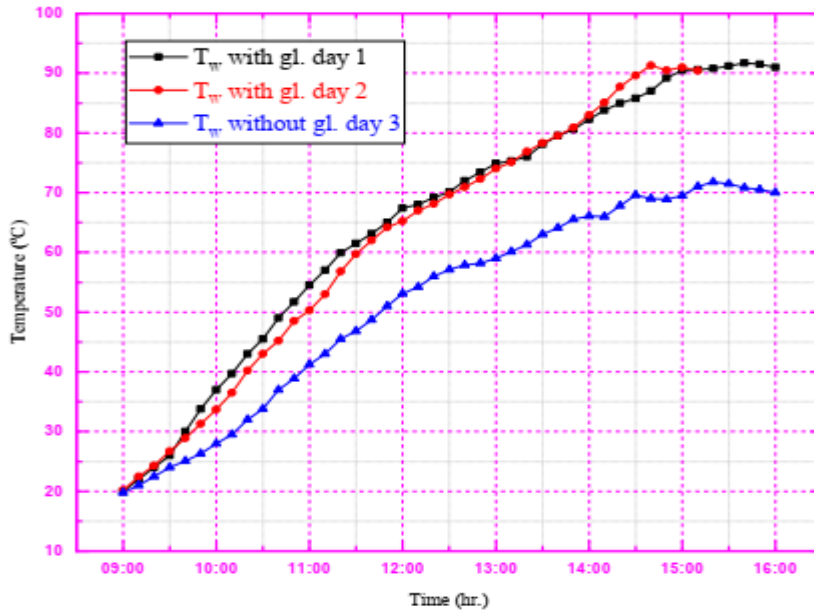


Figure 5-2 Temperature vs time graph of water with and without glazing

The first three days test results are plotted in Figure 5-2. In the first and second days, experimentations of the solar heater were conducted using glass cover. In these two days, the water was boiled and reached up to 91.2°C and 91.3°C at 3:30 PM and at 2:40 PM respectively. In the third day the glazing was removed and tested. However, the water couldn't be boiled and its temperature could not go beyond 71.8°C.

The temperature of water at the second day was achieved early at 2:40 PM and greater (91.3°C) as compared to the other two days (91.2°C and 71.8°C).

### 5.2 Melting of the PCM without load

Starting from the 4<sup>th</sup> day up to the 6<sup>th</sup> day, experimental tests were conducted without load. After melting the storage material, it is brought to a house to heat water or warm food. The 4<sup>th</sup> and 5<sup>th</sup> day were tested using cover (glazing) to minimize the conventional heat loss and the 6<sup>th</sup> day was tested without glazing system. Depending on the weather condition, the storage material was melted at different time. Figure 5-3 shows the 4<sup>th</sup> day average ambient temperature, the temperature of the PCM, the absorber, the glazing as well as wind speed during experimentations. The storage material reaches its melting temperature (117°C) at 1:10 PM. Then started to store latent heat up to 3:00 PM.

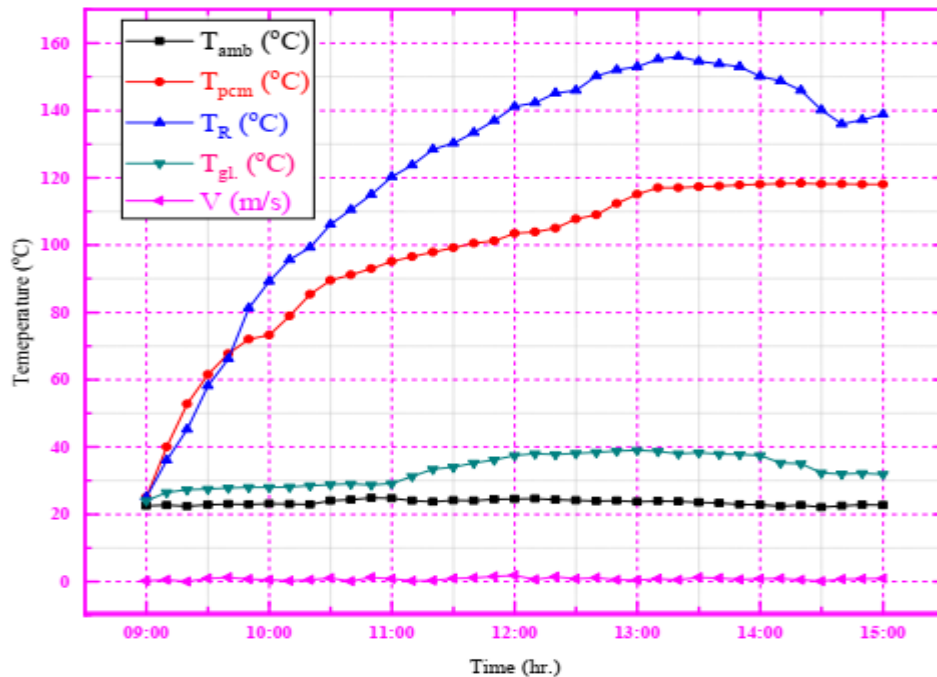


Figure 5-3 Temperature vs time graph for 4<sup>th</sup> day tested data

Melting temperature of PCM without using glazing was not achieved up to 4:00 PM. In the fourth and fifth day, when it was tested with glazing, the PCM was melted around 1:10 PM and 12:20 PM respectively, as shown in Figure 5-4. However, without glazing the maximum temperature of PCM was 92.5°C achieved at 12:50 PM, after that the temperature was reduced due to increase wind speed.

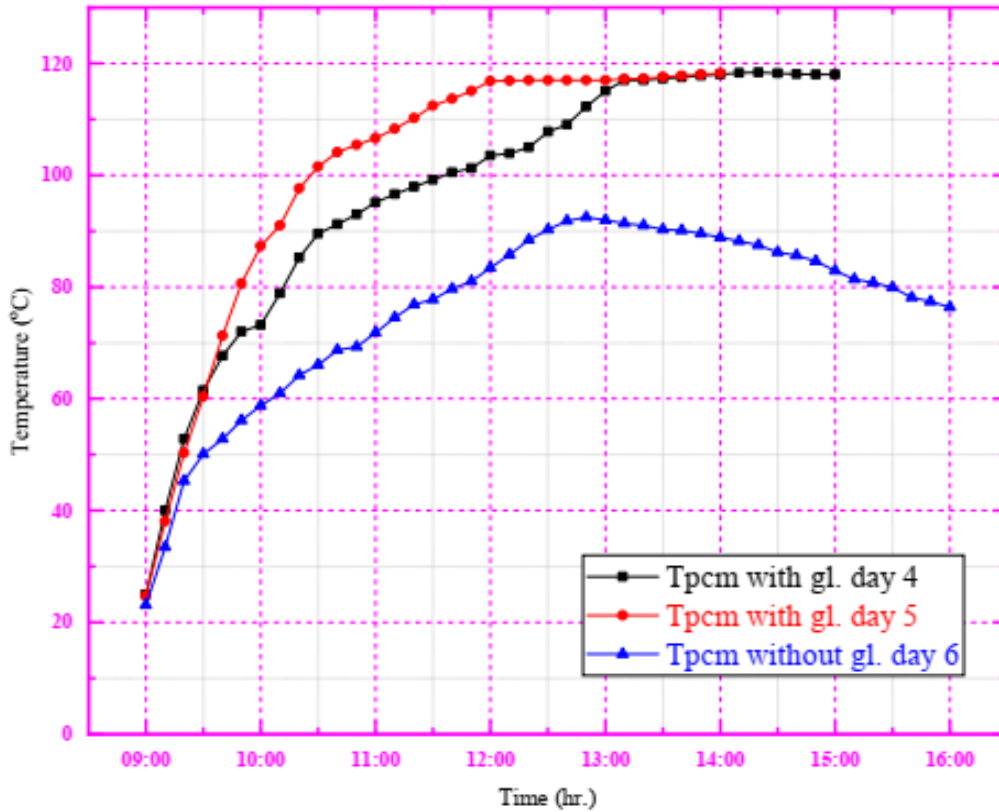


Figure 5-4 Melting of PCM with and without glazing

Since, in day four and five the maximum temperature of the PCM (118.3°C and 118.7°C) were greater than melting temperature (117°C). In these days the PCM was totally melted as shown in red and blue line, Figure 5-4. The green line shows the temperature of the PCM with out glazing material.

### 5.3 Discharging of the PCM

A discharging test was conducted for three days. The temperatures of PCM were 107°C, 118.1°C, and 118.6°C for day two, four and five experiments, respectively. These stored heat by PCM was used to heat water. When PCM was discharged, the water temperature increased.

The water temperature raised starting from 21°C, 20.5°C and 20°C for day two, four and five respectively. The temperature of water was increased up to 75.3°C, 91.8°C and 92.6°C at 6:00 AM, 6:00 AM and 5:00 PM, respectively as shown in figure 5-5 below.

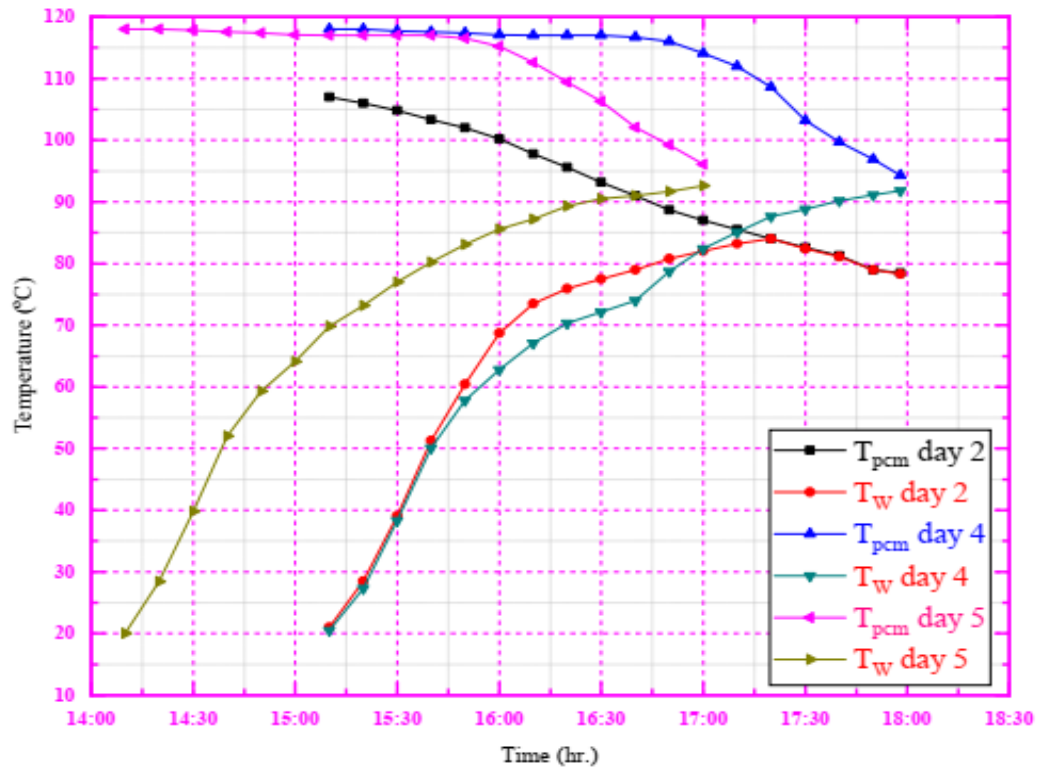


Figure 5-5 Discharging temperature of PCM and heating of water

In day four and day five test, the temperature of decreases constantly for one hour, then the storage material started to solidify. In these two days, the stored energy was used to heat one liter of water. The water was boiled after 2.67 hours. These the time is long compared to three stone firing, but minimizes the other effects like environmental and health and labor impacts.

#### 5.4 Heating of the water with and without glazing using solar heater

This experiment was conducted from 15<sup>th</sup> of October to 17<sup>th</sup> of -October between 9:00 AM to 2:30 PM. The first two days were tested for water temperature using glazing and the third day without glazing. According to the meteorological data the average solar radiation for these three days were 758.06W/m<sup>2</sup>, 419.86W/m<sup>2</sup>, 657.26W/m<sup>2</sup>. The ambient air temperature and the wind speed were 23.5°C, 23.3°C, 23.39°C and 0.5m/s, 0.5m/s, 1.03m/s respectively. As it is depicted in Figure 5-6, the time required to boil water with glazing was 2.67 hour and 3

hours. The maximum water temperature was 96.1°C and 95.8°C at day seven and day eight respectively. This variation in time was due to difference in weather condition. Since, the boiling of water in Addis Ababa is approximately 91 °C to 93°C.

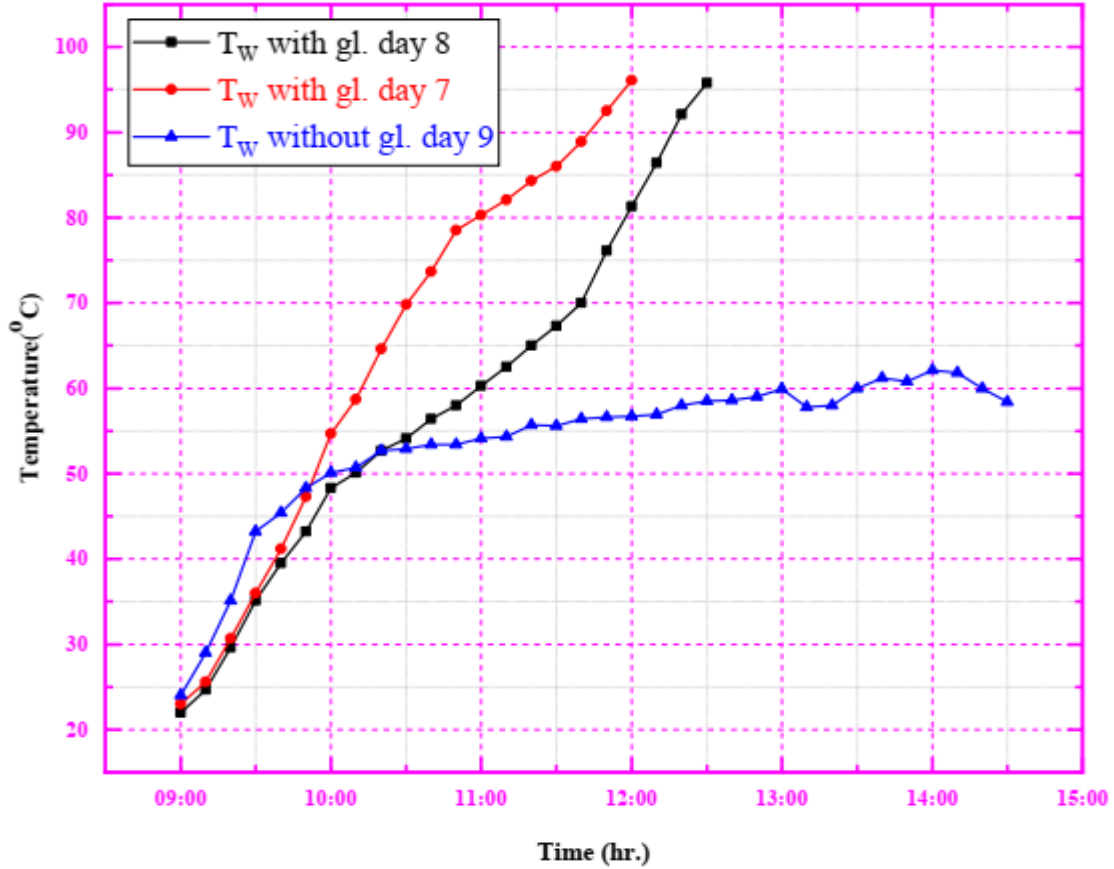


Figure 5-6 Water temperature vs time with and without glazing

In day 9, the maximum temperature of water was 62.1°C up to 2:20 PM. This is due to the conventional heat loss. While using glazing in day 7, though the solar insolation was better than day 8, the water was heated early. From this it can be concluded that performance of the heater with the glazing was much higher. The overall efficiency of the solar heater with the glazing was 75.8%, while without glazing was 65.9%.

## 5.5 Heating power

As literatures say, standard heating power of the parabolic dish solar heater is much higher as compared to the heating power of box type heater. As the temperature difference between water and ambient temperature increases, the heating power of paraboloid heater also increases.

The heating power of the solar heater was evaluated by heating water during nine sunny days from October 09/2019- October 17/2019. The experiments started at 9 AM in the morning and temperature rises (water in the pot and PCM in the absorber) were recorded to determine the time required to boil water and melt storage material. It was observed that the time required to boil water directly from the collector and from stored heat by storage material was approximately the same. About 2.67 hours were needed to boil the water.

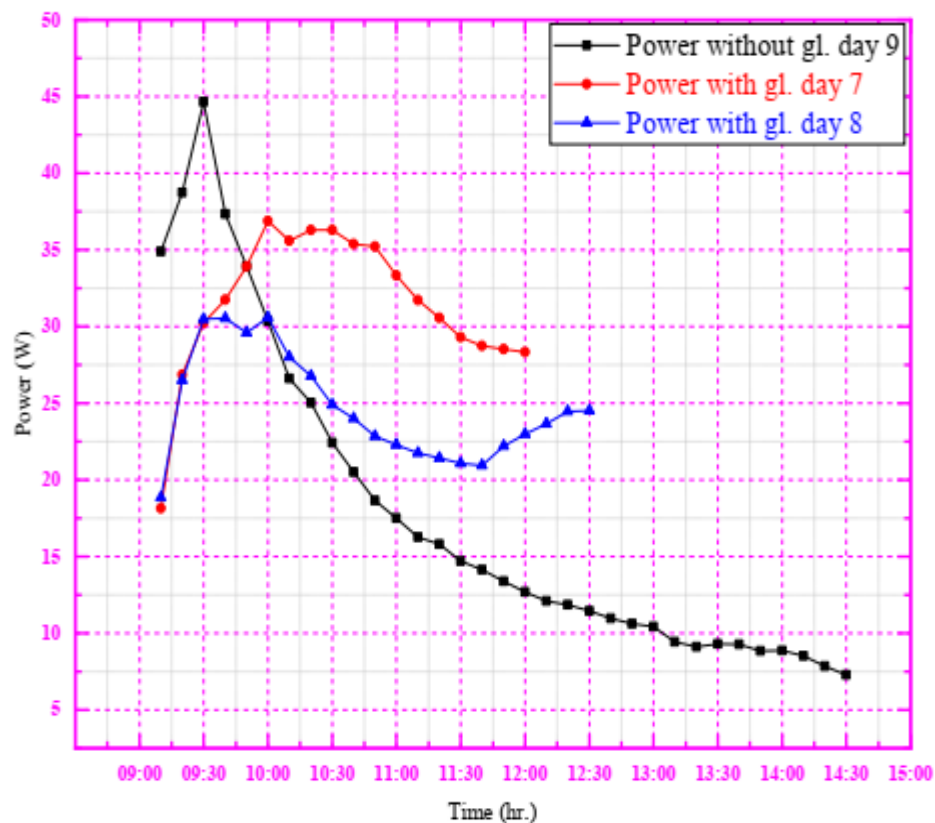


Figure 5-7 Heating power vs time graph

Heating power increases at high rate for the first 40 minutes then decreases slowly, Figure 5-7. This is due to the time and temperature increment are not proportional. As the time increase

at faster rate the temperature of the water increases slowly. The maximum heating power was 37W with glazing and 45W without glazing. The power without glazing was decreased immediately due to loss. However, with glazing decreased slowly up to 29W. the power for the first 40 minutes without glazing was higher than with glazing, this due to that the load receives the temperature in all direction (at bottom, side and top) of the pot. While using glazing some amount of temperatures ray was reflected (bounded) by the glazing.

## 5.6 Heating efficiency

Figure 5-8 describes the overall efficiency of the solar heater with glazing and without glazing. The first two days (day 7 and day 8), tests were made with glazing. The third day (day9), was tested without glazing which resulted in minimum efficiency.

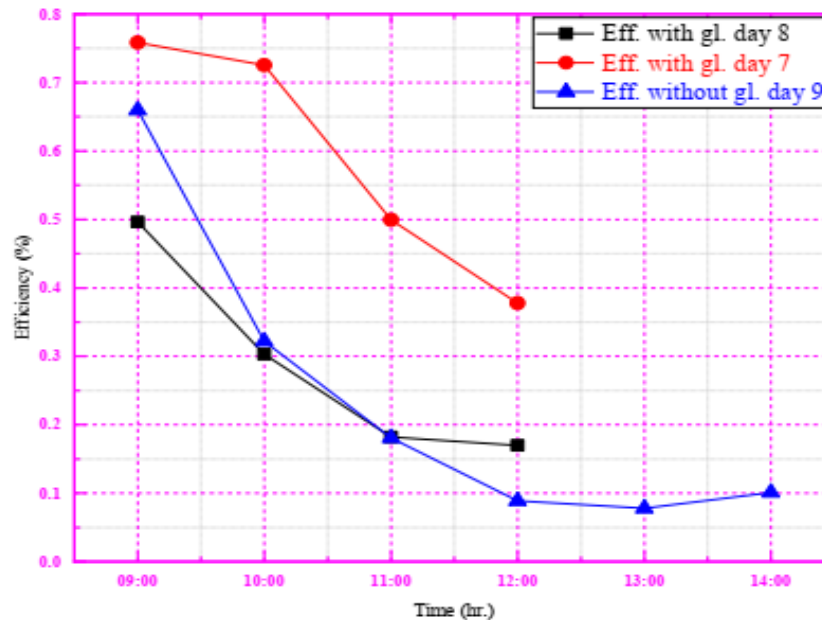


Figure 5-8 Graph of efficiency vs time

The maximum and minimum efficiency with glazing for day 7 was 75.8% and 37.8%, for day 8 was 49.6% and 16.9%, while in absence of glazing was 65.9% and 7.8% respectively.

The corresponding solar radiation data for these three days were as shown in Figure 5-9 below. The value of radiation for day 7 was higher than the other two since the efficiency was higher for this day. Maximum solar radiation data for these three days were 919W/m<sup>2</sup>, 452W/m<sup>2</sup> and 894W/m<sup>2</sup> respectively.

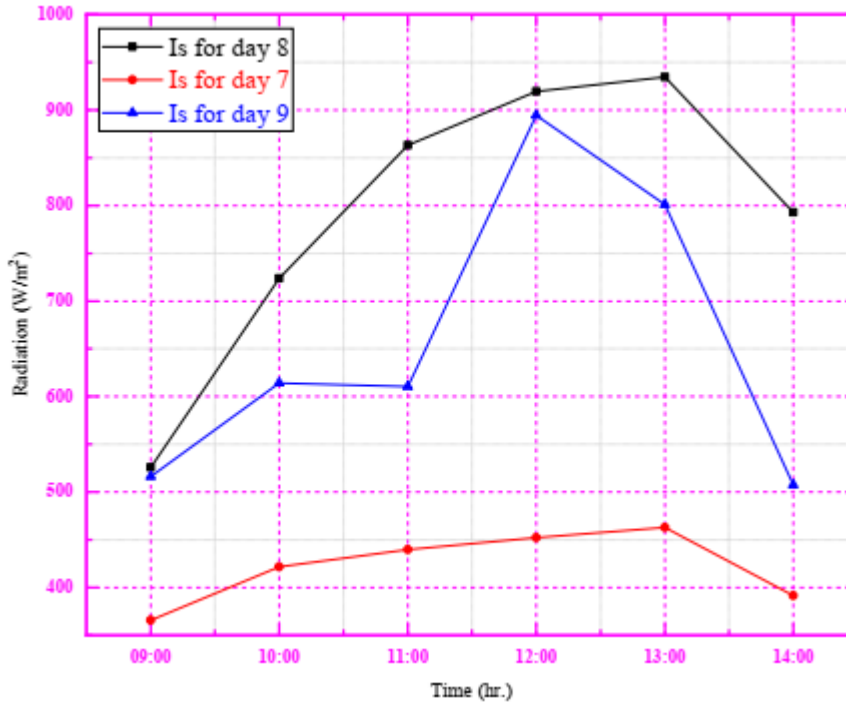


Figure 5-9 Radiation vs time graph for last three days

From the experimentation, it can be justified that direct boiling the water without using glass cover was not possible. The heat stored by the PCM within 5 hours was 1155 kJ using glass cover. The energy required to heat one liter of water is about 393kJ. This stored heat by PCM was used for different purposes such as heating water, warming food or pasteurizing milk.

## 5.7 Validation

The boiling point of water varies with atmospheric pressure. With the lower atmospheric pressure, higher ambient temperature and higher solar insolation, the boiling time of water becomes small. Material selection and material size have great effect on the result of the experimental work. To increase the amount of heat, the size of dish (collector) must be larger. However, the larger the size of the collector, makes it difficult to move from place to place. The basic drawback of heating by solar energy was intermittency. The maximum working hours of most solar heater was approximately six hour per day.

According to Al-Soud et al [41], the time required to heat one liter of water using parabolic dish solar heater was 5 hours with the maximum water temperature of 90°C as indicated by

red line in Figure 5-10. The maximum solar radiation and maximum ambient temperature of the researcher were  $5\text{kWh/m}^2$  and  $36^\circ\text{C}$  respectively.

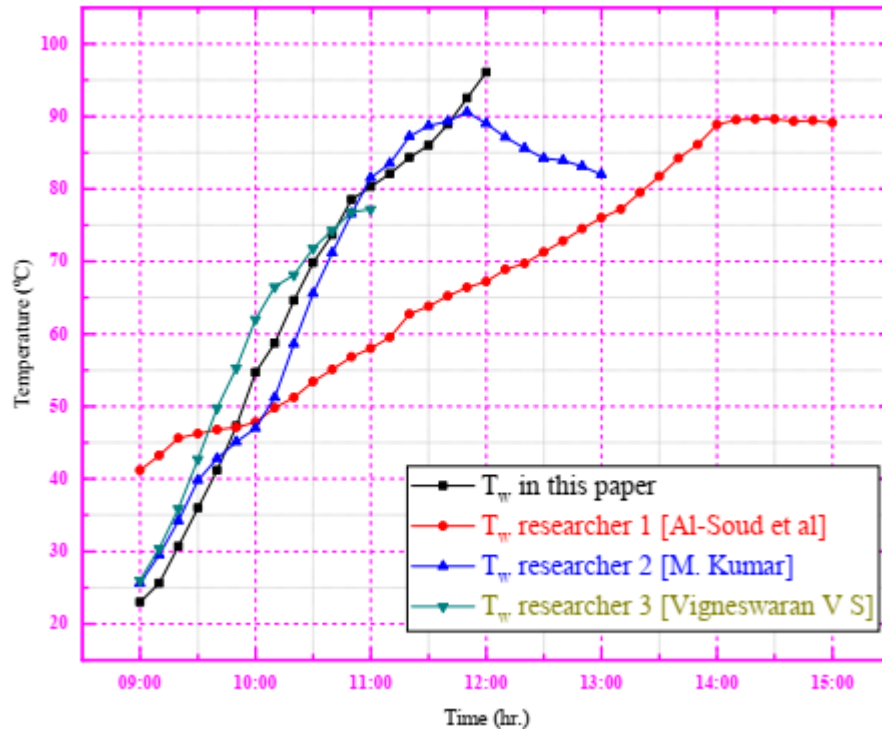


Figure 5-10 Validation of water temperature with another similar work

However, in this work the time required to heat water was 2.67 hours with the water temperature  $91.8^\circ\text{C}$ , which is the boiling temperature of water in Addis Ababa. The maximum solar radiation and maximum ambient temperature was  $3.6\text{kWh/m}^2$  and  $23.8^\circ\text{C}$  respectively in this experimental study. In Figure 5-10, the black line is for this paper work (with glazing).

Another validation held by comparing the collector area with the water temperature and time required to heat water. One liter of water was heated, with the collector area of  $2.04\text{m}^2$  in 2.5 hours M. Kumar [42]. However, in this paper the same amount of water was heated with the collector area of  $0.216\text{m}^2$  in 2.67 hours Figure 5-10 blue line.

Compared to the box type solar cooker, with the aperture area of  $0.2401\text{m}^2$  400 kg of water was heated from  $25^\circ\text{C}$  to  $78^\circ\text{C}$  with in the time of 2 hours Vigneswaran V.S. [43]. Figure 5-10 dark yellow line. This aperture area is almost the same as area of parabolic dish collector in this paper but the variation by heating time is large. and also, the amount of load (water) is almost double in this paper (1 liter).

## CHAPTER SIX

### 6. Conclusion and Recommendation

#### 6.1 Conclusion

In this work, a parabolic dish solar heater with a storage system and single axes (east to west) manually tracking system was designed, constructed and tested experimentally. The experimental results showed that the low efficiency of the parabolic solar heater is recognized as the conventional losses from the reflector and the absorber or pot. The use of a glazing system minimizes the loss by 10.1%. Cylindrical shaped heating vessels made of aluminum and cylindrical storage tanker made of sheet metal with black painted was used. Storage tank made from aluminum has better thermal performance. However, due to its simplicity to manufacture sheet metal was used. This reduces the heat transfer rate of the heating vessel.

In experimental testing within 5 hours around 1155kJ of heat was stored by storage material without load. This stored heat was used to heat one liter of water indoor. The parabolic heater with glazing and storage systems presents encouraging results as compared to other types of solar heater those without glazing and storage system. As a conclusion of this paper, the following main points can be considered.

1. Integrating a thermal energy storage system in solar heater increased the overall performance of the heater.
2. Storage system minimized the time required to heat water approximately by 50%, i.e. after the storage material stores enough amount of heat, then the stored heat was taken indoor to heat water or warm food. At the same time another water was heat outside directly from the collector. So, it saves time and energy.
3. About 75.9% and 65.9% maximum efficiency of the collector with the glazing and without glazing achieved in the experiment with a minimum efficiency of 37.8% and 7.8% respectively. This maximum efficiency 75.9% is good achievement.
4. The same type of study was held by other researcher, heating one liter of water with aperture area ( $2.04\text{m}^2$ ) at 2.5 hours. However, in this study with the smaller aperture area ( $0.216\text{m}^2$ ), heat the same amount of water at 2.67 hours.

## **6.2 Recommendation**

Ethiopia has so many resources regarding with renewable and sustainable energy such as solar, biomass, wind and so on. But as the availability of the resources the rural community problems related to electricity are not solved. The following points are recommended for the future work on this area.

- I. To get perfect sun direction, design two axis automatic tracking mechanism is best compared to manual tracking mechanism.
- II. To increase the enhancement of heat stored by the storage material high conductivity material like aluminum or copper storage tank should be used.

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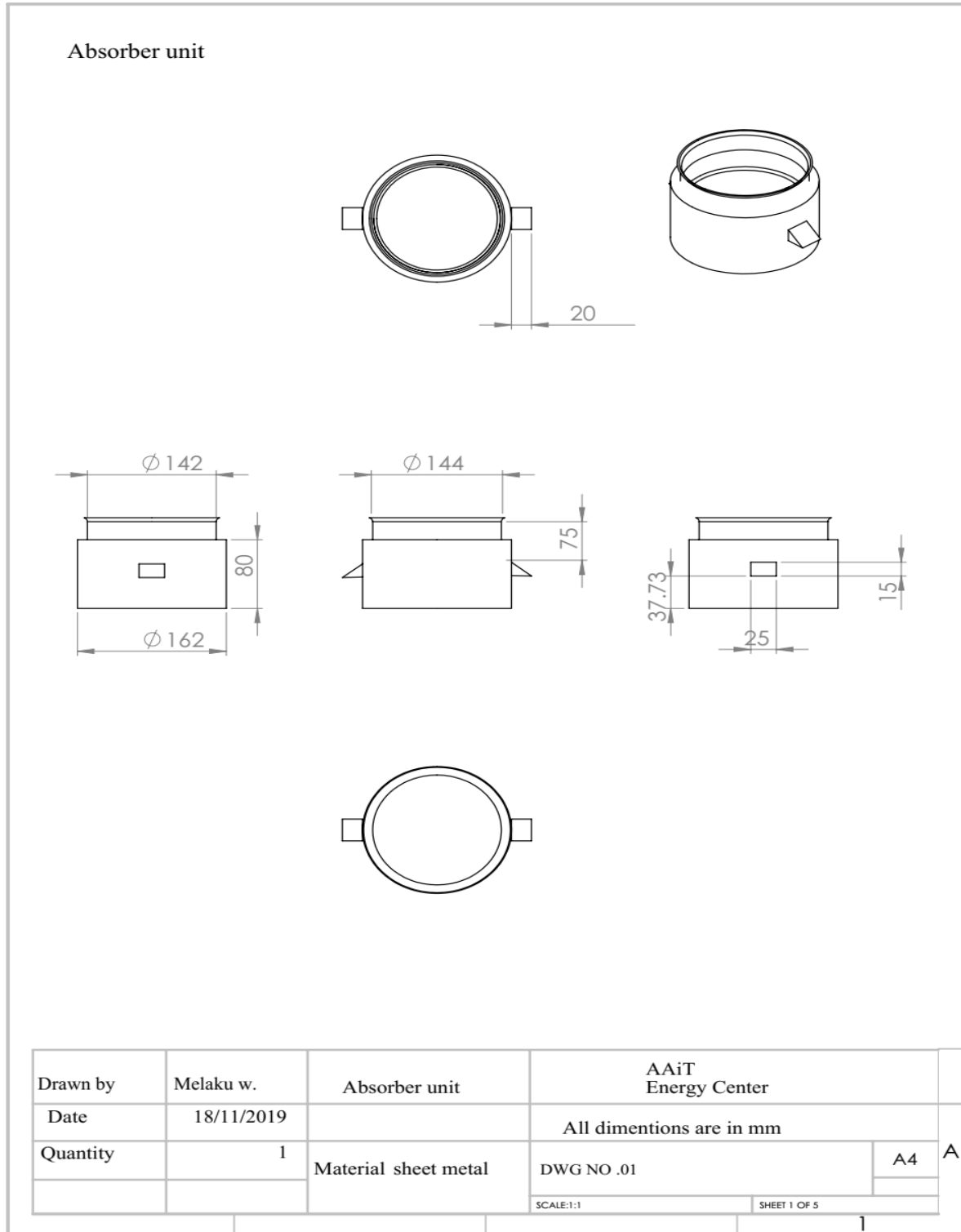
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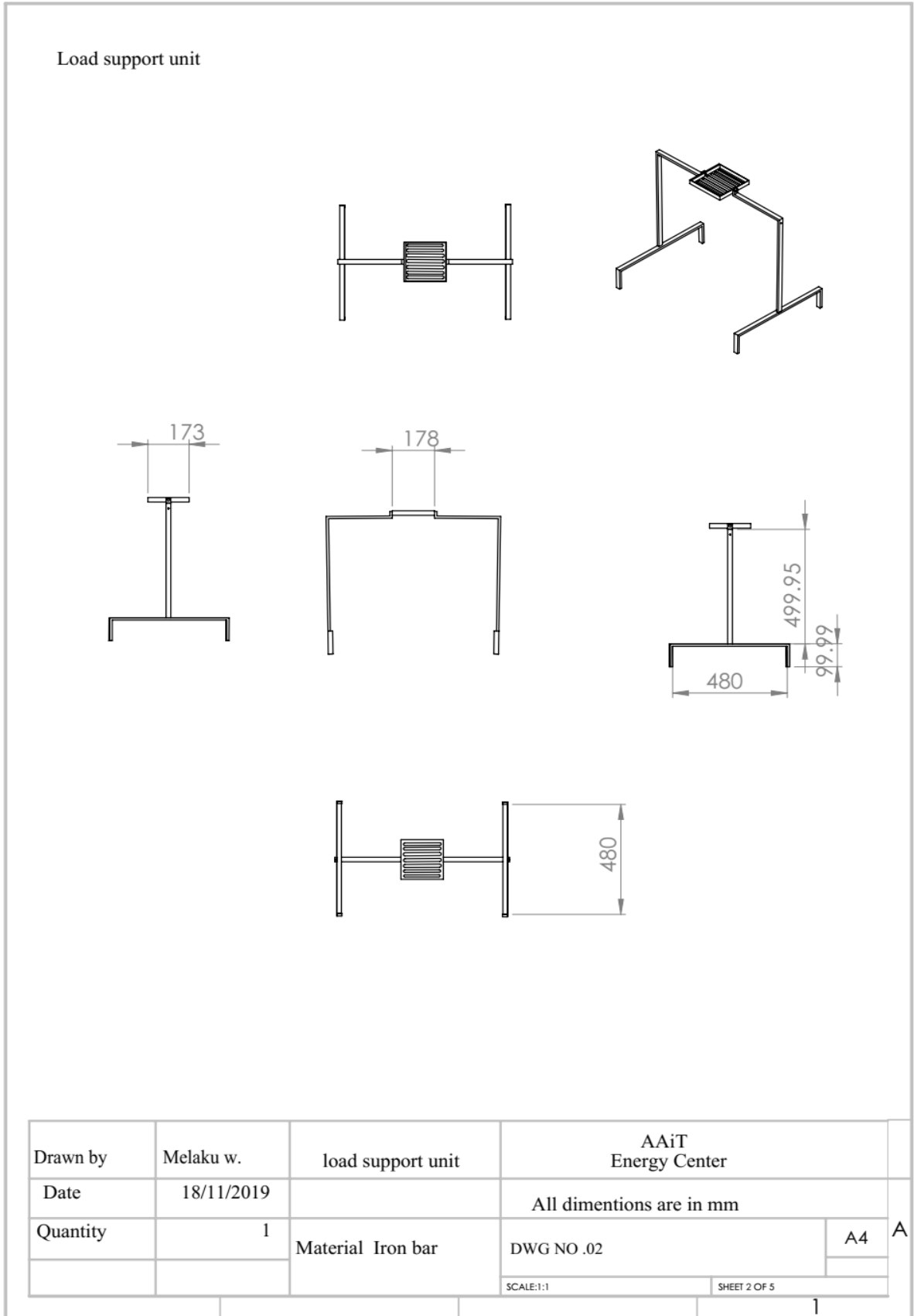
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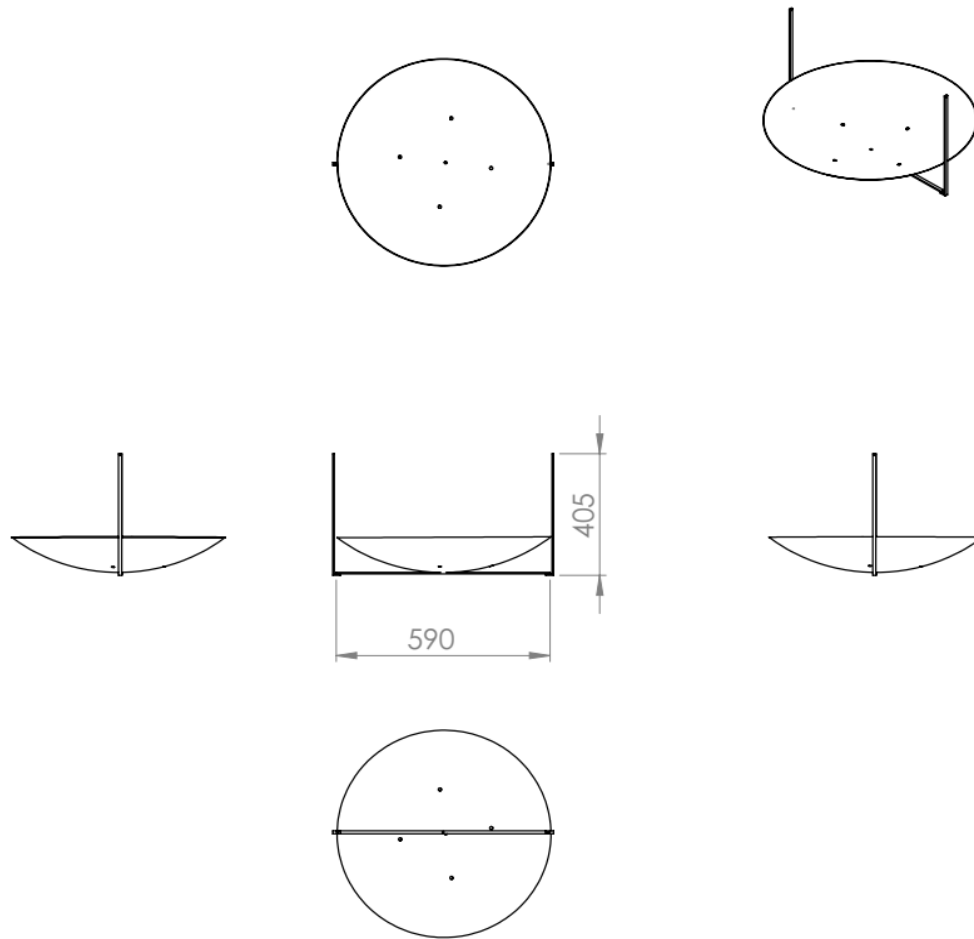
# APPENDIX

## Appendix A: part drawing



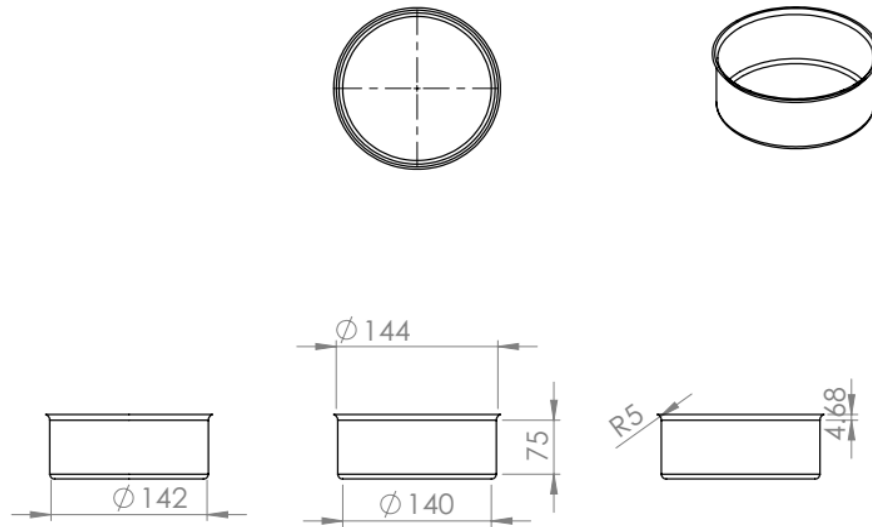


Dish and dish support unit



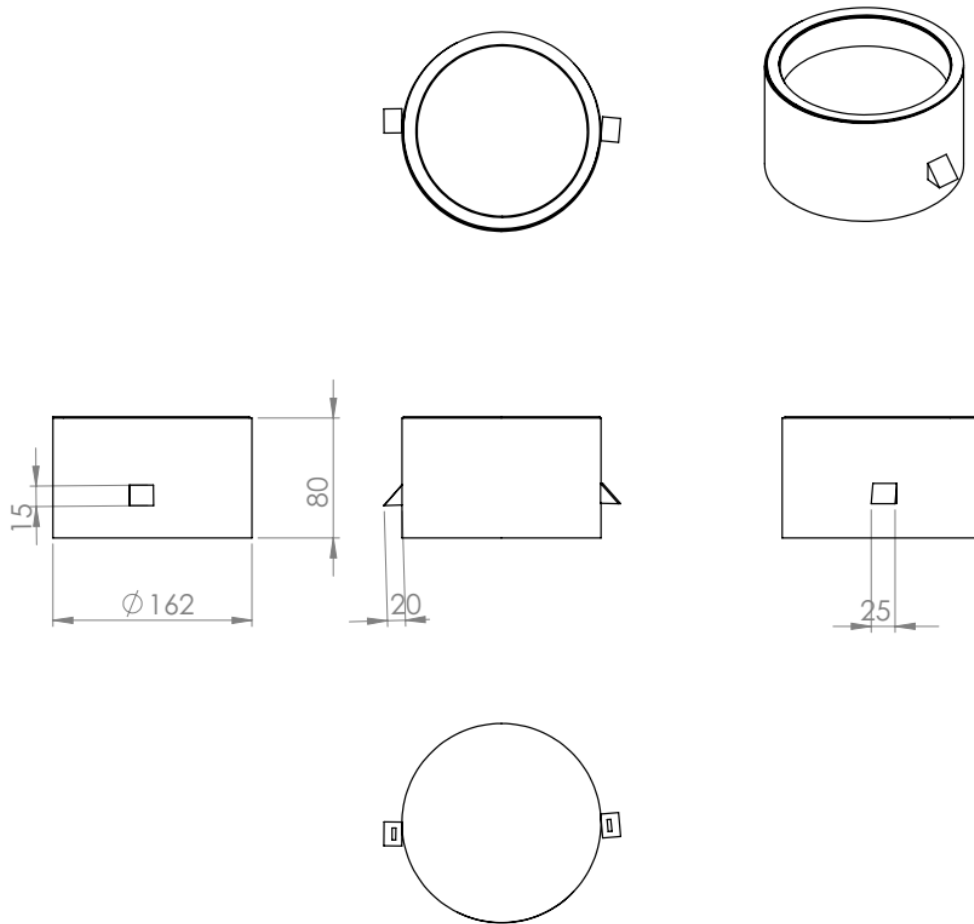
Drawn by	Melaku w.	dish support unit	AAiT Energy Center	
Date	18/11/2019		All dimentionations are in mm	
Quantity	1	Material- iron bar and steel	DWG NO .03	A4
			SCALE:1:1	SHEET 3 OF 5
				1

Pot (cooking vessel)



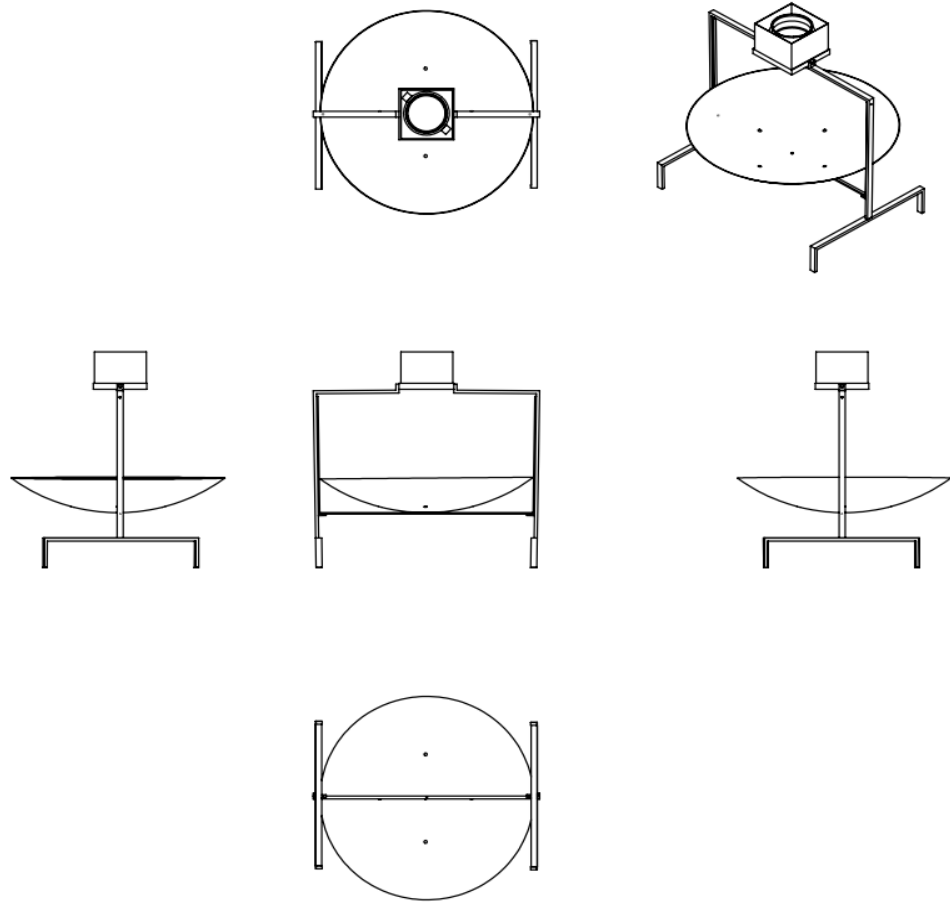
Drawn by	Melaku w.	Pot (cooking vessel)	AAiT Energy Center	
Date	18/11/2019		All dimintions are in mm	
Quantity	1	Material Aluminum	DWG NO .04	A4
			SCALE:1:1	SHEET 4 OF 5
				1

PCM container with handle



Drawn by	Melaku w.	PCM container	AAiT Energy Center	
Date	18/11/2019		All dimintions are in mm	
Quantity	1	Material sheet metal	DWG NO .05	A4
			SCALE:1:1	SHEET 5 OF 5
				1

Assemble



Drawn by	Melaku w.	Assemble	AAiT Energy Center	
Date	18/11/2019		All dimintions are in mm	
Quantity	1	Material- sheet metal, Aluminum, iron bar, glass, steel.	DWG NO .06	A4
			SCALE:1:1	SHEET 6 OF 5
				1

## Appendix B

### Direct experimental test measured data

#### 1. Temperature of PCM with load

##### Day 1: with glazing

Time	T <sub>amb</sub> (°C)	T <sub>pcm</sub> (°C)	T <sub>w</sub> (°C)	T <sub>R</sub> (°C)	T <sub>P</sub> (°C)	T <sub>gl</sub> (°C)	V (m/s)
9:00 AM	22.5	20	20	24	24.5	25	0.5
9:10 AM	22.8	25.5	22	27.6	26	26.5	0.2
9:20 AM	22.7	30.5	24	50.1	27.8	27	1.5
9:30 AM	22.9	36	26	62.3	28.5	28.4	0.5
9:40 AM	23	41.3	30	70	30	27.7	0.8
9:50 AM	23.3	46.7	33.8	90.5	32.3	31.8	0.7
10:00 AM	23.6	52.1	37	99.8	35.4	29.7	0.5
10:10 AM	23.5	56.9	39.7	108	37.3	31.7	0.2
10:20 AM	23.7	60.3	43	115.3	38.5	34.5	0.1
10:30 AM	23.8	64	45.5	117	39.4	33	0.2
10:40 AM	24.1	67.8	49	118.5	40	35.6	0.1
10:50 AM	24	72.5	51.7	120	42.5	35	0.8
11:00 AM	23.8	74	54.5	123.4	45.3	36.1	0.7
11:10 AM	23.9	78.5	57	125	46.7	35.8	1.9
11:20 AM	23.6	82.1	59.9	126.1	48.5	35.1	1.5
11:30 AM	23.7	84.8	61.5	132	49.9	36	0.8
11:40 AM	23.9	86	63.1	133.4	50.8	37.6	1.1
11:50 AM	23.8	89.5	65	135.8	52	37.5	1.5
12:00 PM	23.5	91.5	67.4	138	53.1	37.1	0.9
12:10 PM	23.4	91.3	68	137.8	56.7	38.6	0.8
12:20 PM	23.8	93.4	69.2	139.5	59	38.9	1.6
12:30 PM	24.3	94	70.1	139	65	38	1.2
12:40 PM	24.1	95.5	72	141.4	73	37.3	1
12:50 PM	23.9	97.1	73.4	143.5	77.9	37.5	0.5
1:00 PM	23.9	97	74.9	144	84	39.1	0.2
1:10 PM	23.5	96.8	75.3	146	85.7	38	0.5
1:20 PM	23.3	98.3	76	145.6	84	37.1	0.8
1:30 PM	23.4	98.9	78.1	143	85.7	38.6	0.7
1:40 PM	23.7	99.4	79.5	140.5	84	38.5	0.2
1:50 PM	24	100.2	80.6	142.7	83.7	39	0.4
2:00 PM	24.1	100.1	82.3	138	85.3	39.5	0.7
2:10 PM	23.8	100.9	83.8	141.3	86	37.7	0.2
2:20 PM	23.7	102	85	142.5	87.3	36	0.4
2:30 PM	23.5	103.4	85.8	139	88	37.2	0.8
2:40 PM	23	105	87	138.5	89.8	38	0.5
2:50 PM	23.1	106.6	89.2	135.2	92.1	38.5	0.4

3:00 PM	22.8	108.1	90.5	136	92.8	38.2	0.8
3:10 PM	22.5	107	90.6	134	91.5	38	1
3:20 PM	22.4	107.5	90.8	133.6	91.2	37.5	0.8
3:30 PM	22.6	106.5	91.2	132.8	91.4	37.6	0.9
3:40 PM	22.3	106	91.7	130.2	90.5	36.5	0.7
3:50 PM	22.1	104.2	91.5	128.4	89.4	36	1
4:00 PM	22	103.7	91	125.3	88.6	35.1	0.9

**Day 2: with glazing**

Time	T <sub>amb</sub> (°C)	T <sub>pcm</sub> (°C)	T <sub>w</sub> (°C)	T <sub>R</sub> (°C)	T <sub>P</sub> (°C)	T <sub>gl</sub> (°C)	V (m/s)
9:00 AM	22.8	20	20.2	24	24	24.3	0.9
9:10 AM	22.7	24.9	22.5	27.6	25.5	25.9	1.1
9:20 AM	22.9	29.5	24.3	46	27.2	27	1.3
9:30 AM	23	34.5	26.7	58	27.9	28.8	2
9:40 AM	22.8	40.8	28.9	65	31	28.7	0.5
9:50 AM	23.1	46	31.3	72	32.3	29	1.5
10:00 AM	23.5	52.8	33.7	80.5	34.9	29.5	0.2
10:10 AM	23.8	58	36.5	85.3	36.8	31	1
10:20 AM	23.7	60.5	40.2	90.8	38.5	32.3	2.1
10:30 AM	23.4	65	43	96.7	39	34	2.1
10:40 AM	23.5	68.2	45.2	99.5	40.8	34.5	1.8
10:50 AM	23.8	73	48.5	105	43	36.1	1.2
11:00 AM	23.9	75.1	50.3	109.7	44.8	35.3	0.9
11:10 AM	24	77.3	53	113.1	46	37.1	0.8
11:20 AM	23.8	79.5	56.8	118	48.1	38	0.4
11:30 AM	24.1	84.2	59.7	123.1	45	38.8	0.9
11:40 AM	23.8	85.1	62	127.4	47.2	39	1
11:50 AM	23.9	86.9	64.2	129.8	49	37.7	1.2
12:00 PM	23.7	88.3	65.2	133.5	49.9	38.7	0.5
12:10 PM	23.4	89.4	67	140	52.1	39	0.4
12:20 PM	23.8	91.3	68.1	138.1	53.3	37.5	0.6
12:30 PM	23.9	92.5	69.7	139.9	55.1	38.3	0.8
12:40 PM	24	94	70.9	141	56	39.4	1.3
12:50 PM	24.2	95.2	72.3	142	57.8	38	1.5
1:00 PM	23.7	95.8	74	143.8	59.9	37.8	0.9
1:10 PM	23.8	97.3	75.1	142.9	62	37.7	0.7
1:20 PM	23.5	98.8	76.9	140.8	65.8	38.1	0.5
1:30 PM	23.9	100.2	78.3	142.1	69.5	38.5	0.2
1:40 PM	24	100.8	79.5	145	74.2	39.1	0.5
1:50 PM	23.8	100.7	80.9	143.1	79.1	38.8	0.6
2:00 PM	24.1	102.7	83	138	82.3	38.3	0.8
2:10 PM	23.5	104.1	85.1	139	85.6	37.5	1.1

2:20 PM	23.2	106.2	87.7	137.8	88.9	37.8	0.8
2:30 PM	23.3	107	89.6	139.1	91.3	37.5	0.9
2:40 PM	22.8	109.2	91.3	138	93.5	38	0.5
2:50 PM	22.5	109.8	90.5	135.2	95.1	37.6	0.8
3:00 PM	22.6	108.6	91	136	94.9	37.5	1.2
3:10 PM	22.4	107	90.4	134.6	94	37	0.9

**Day 3: without glazing**

<b>Time</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	21.3	20	19.8	23.5	23.8	0.2
9:10 AM	22.5	22.3	21	24	24	0.4
9:20 AM	22.8	25.6	22.5	28	25.1	0.8
9:30 AM	22.9	27.3	24	33.2	25.8	1.3
9:40 AM	22.8	28.5	25.1	36	27.2	0.8
9:50 AM	22.5	32	26.3	39.5	29.1	0.5
10:00 AM	22.8	33.8	28	43	31.5	1.1
10:10 AM	23	36.1	29.5	48.3	32	0.9
10:20 AM	22.9	37.9	32	52.1	33.1	0.2
10:30 AM	23.1	40.2	33.8	57.5	34.1	0.3
10:40 AM	23.2	42	37	63.6	34.9	0.7
10:50 AM	23	44.1	38.9	70	36	0.8
11:00 AM	23.5	46.5	41.2	75.6	37.6	0.7
11:10 AM	23.8	48	43	79.7	39.1	0.9
11:20 AM	23.7	49.8	45.5	86.2	44.3	1.2
11:30 AM	23.7	50.2	46.8	95	47.1	1.5
11:40 AM	23.5	53	48.7	99.8	49.3	1.1
11:50 AM	23.8	55.5	51	103.4	52.5	0.7
12:00 PM	24	57.2	53.1	105.2	54	0.4
12:10 PM	24.1	59	54.2	107	57.1	0.5
12:20 PM	23.9	59.8	56	109.1	58.3	0.8
12:30 PM	23.8	61	57.1	111	59.9	0.2
12:40 PM	23.7	62.3	57.9	112.3	61.1	0.5
12:50 PM	23.2	65	58.2	111.8	63.7	0.6
1:00 PM	23.8	66.2	59	110.8	64.2	1
1:10 PM	23	68.3	60.1	115.2	65	1.2
1:20 PM	23.7	69	61.3	117	65.8	0.9
1:30 PM	23.7	71.8	63	118.7	67.1	0.2
1:40 PM	23.9	74	64.1	118	67.9	0.8
1:50 PM	23.8	75.1	65.5	112.7	68.8	0.7
2:00 PM	23.1	76.1	66.1	116	69.8	0.3
2:10 PM	22.8	77.7	66	120	70.1	0.4
2:20 PM	22.9	79	67.8	118.2	72	0.9
2:30 PM	23	80.8	69.6	117.1	73.3	0.8

2:40 PM	22.5	83	69	117.8	72.8	0.7
2:50 PM	22.8	85.6	68.9	120	72.5	0.6
3:00 PM	22.9	88	69.5	116.7	73	0.2
3:10 PM	22.6	89.9	71	113.2	74.2	0.8
3:20 PM	22.5	88	71.8	110.7	75.1	0.6
3:30 PM	22.3	89.5	71.5	105	76	1.2
3:40 PM	22.8	89	70.8	102.3	74.8	1.5
3:50 PM	22	89.3	70.5	102	72.1	1.1
4:00 PM	22.2	89.5	70	101.8	71.5	0.8

## 2. Temperature of PCM without load

### Day 4: with glazing

Time	T <sub>amb</sub> (°C)	T <sub>pcm</sub> (°C)	T <sub>R</sub> (°C)	T <sub>gl</sub> (°C)	V (m/s)
9:00 AM	22.5	25	25	24	0.2
9:10 AM	22.7	40	36	26.5	0.5
9:20 AM	22.4	52.8	45.2	27.3	0
9:30 AM	22.8	61.5	58.1	27.5	0.9
9:40 AM	23	67.7	66.2	27.8	1.2
9:50 AM	22.9	72	81.3	28	0.7
10:00 AM	23.1	73.2	89.2	28	0.5
10:10 AM	23	78.9	95.6	28.1	0.2
10:20 AM	22.9	85.3	99.3	28.5	0.5
10:30 AM	24	89.5	106.1	28.8	1
10:40 AM	24.3	91.2	110.5	29	0.1
10:50 AM	24.8	93	115	28.7	1.2
11:00 AM	24.7	95.1	120.3	29.1	0.8
11:10 AM	24	96.6	123.8	31.3	0.2
11:20 AM	23.7	97.9	128.4	33.4	0.3
11:30 AM	24.1	99.2	130.3	34	0.9
11:40 AM	24	100.5	133.4	35.2	1.1
11:50 AM	24.4	101.2	137	36.1	1.5
12:00 PM	24.5	103.5	141.2	37.5	1.8
12:10 PM	24.6	103.9	142.3	38	0.6
12:20 PM	24.3	105	145.1	37.8	1.4
12:30 PM	24.1	107.8	146	38.1	0.8
12:40 PM	23.9	109	150.2	38.4	1.1
12:50 PM	24	112.3	152.1	38.8	0.5
1:00 PM	23.7	115.1	153	39	0.4
1:10 PM	23.9	117	155.2	38.7	0.8
1:20 PM	23.8	117	156	38	0.5
1:30 PM	23.5	117	154.6	38.3	1.2
1:40 PM	23.3	117	153.8	37.9	1
1:50 PM	22.9	117.3	153	37.8	0.6
2:00 PM	22.8	118.1	150.1	37.5	0.8

2:10 PM	22.4	118.5	148.8	35.2	0.9
2:20 PM	22.7	118.4	146	35	0.5
2:30 PM	22.1	118.3	140.2	32.3	0.1
2:40 PM	22.5	118.4	139.5	32	0.7
2:50 PM	22.8	118.2	139	32.2	0.8
3:00 PM	22.7	118	140.2	31.9	0.9

**Day 5: with glazing**

<b>Time</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>gl</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	22.8	24.8	24.5	25	2
9:10 AM	22.5	38.1	40	27.1	1.5
9:20 AM	22.1	50.3	52.3	27.8	1.2
9:30 AM	22.8	60.4	66.7	27.7	1.2
9:40 AM	22.9	71.3	77.3	28	1.6
9:50 AM	22.7	80.6	82.5	28.1	0.9
10:00 AM	22.9	87.3	85.6	28.6	0.8
10:10 AM	23	91	91.2	28.9	1.1
10:20 AM	23.1	97.6	95.4	29.5	1.5
10:30 AM	23	101.5	97.3	31	1
10:40 AM	23.3	104.1	100.5	32.3	0.9
10:50 AM	24.8	105.4	113	34.1	0.8
11:00 AM	24	106.6	116	37.3	0.8
11:10 AM	24.1	108.3	118.2	38	1
11:20 AM	24.3	110.2	120.2	37.7	1.1
11:30 AM	24	112.4	122	38.1	1.2
11:40 AM	23.8	113.7	125.4	38	1.4
11:50 AM	23.9	115.1	128.3	38.5	1.3
12:00 PM	24.1	116.8	130.8	39	1.7
12:10 PM	23.7	116.9	134.5	38.1	0.6
12:20 PM	23.8	117	138	38.5	1.7
12:30 PM	24	117	140.2	39.1	1.5
12:40 PM	24.1	117	142.3	39	0.9
12:50 PM	23.8	117	145.1	38.6	0.5
1:00 PM	24	117	143.6	37.9	0.3
1:10 PM	23.9	117.5	144.7	37	0.6
1:20 PM	23.8	117.8	143.6	37.2	1
1:30 PM	23.5	118.3	142.1	36	0.9
1:40 PM	23.5	119	141.7	33.4	0.5
1:50 PM	23.7	118.8	140.2	30.3	0.2
2:00 PM	23.5	118.7	140.6	30	0.3

**Day 6: without glazing**

<b>Time</b>	<b>T<sub>amb</sub> (°C)</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>V (m/s)</b>
9:00 AM	22.7	23.1	24	0.9
9:10 AM	20.1	33.5	35	1.1
9:20 AM	19.7	45.3	40.1	0.8
9:30 AM	19.5	50.1	48.1	0.7
9:40 AM	22.2	52.8	53.6	0.2
9:50 AM	20.3	56.1	57.9	0.4
10:00 AM	20.7	58.8	60.1	0.8
10:10 AM	22.1	61	65.2	1.3
10:20 AM	21	64.2	71.4	1.1
10:30 AM	22.9	66.1	78.3	0.9
10:40 AM	22.8	68.7	84.6	0.6
10:50 AM	23	69.3	89.7	1.2
11:00 AM	22.8	71.8	95.2	1.5
11:10 AM	23.1	74.5	98.7	1.3
11:20 AM	23.4	76.9	104	0.9
11:30 AM	23.3	77.8	108.1	1
11:40 AM	23.8	79.7	111.2	0.7
11:50 AM	23.7	81	115.7	0.8
12:00 PM	23.9	83.4	119.2	0.9
12:10 PM	24	85.8	118	0.1
12:20 PM	23.8	88.4	120.3	0.5
12:30 PM	23.4	90.3	119.7	0.7
12:40 PM	23.5	91.8	118.9	0.6
12:50 PM	23.3	92.5	119	0.8
1:00 PM	23.1	92	118	1.1
1:10 PM	22.9	91.4	118.1	1.2
1:20 PM	23	91	117.7	0.4
1:30 PM	22.7	90.3	116	0.6
1:40 PM	22.3	90.1	111.7	0.9
1:50 PM	22.1	89.5	105.9	0.7
2:00 PM	22	88.9	101.3	1
2:10 PM	22.1	88.2	100.8	0.9
2:20 PM	22.2	87.5	100.1	0.5
2:30 PM	22.1	86.2	98.8	0.7
2:40 PM	22	85.6	97.6	0.3
2:50 PM	22.3	84.6	96.8	0.9
3:00 PM	22.1	82.9	95.7	0.7
3:10 PM	22	81.4	94.6	0.5
3:20 PM	21.8	80.8	93.8	0.7
3:30 PM	21.9	79.9	92.5	0.9
3:40 PM	22	78.1	91	0.8
3:50 PM	21.7	77.4	89.6	1
4:00 PM	21.6	76.4	87	0.8

### 3. Direct heating of water without PCM

#### Day 7: with glazing

Time	T <sub>amb</sub> (°C)	T <sub>w</sub> (°C)	T <sub>p</sub> (°C)	T <sub>gl</sub> (°C)	V (m/s)
9:00 AM	22.7	22	24.8	24	0.5
9:10 AM	23	24.7	28.5	24.2	0.3
9:20 AM	23.3	29.6	30.3	24.3	0.9
9:30 AM	22.9	35.1	33.7	25	0.8
9:40 AM	23.1	39.5	37	26.3	0.1
9:50 AM	23.4	43.2	39.8	25.7	0.3
10:00 AM	23.8	48.3	44.6	27	0.2
10:10 AM	23.5	50.1	48.7	29.4	0.4
10:20 AM	23.1	52.7	52.3	31.3	0.8
10:30 AM	23.6	54.1	56.7	35.1	0.7
10:40 AM	23.7	56.4	61.7	37.2	0.1
10:50 AM	24	58	66.5	37.7	0.6
11:00 AM	23.7	60.3	72.3	38	0.9
11:10 AM	23.8	62.5	77.5	38.2	0.5
11:20 AM	23.9	65	81.5	38.1	0.4
11:30 AM	24.1	67.3	85.9	37.5	0.9
11:40 AM	23.8	70	89.8	35.8	0.7
11:50 AM	23.9	76.1	94.3	38	0.3
12:00 PM	23.7	81.3	98	38.1	0.2
12:10 PM	23.1	86.4	99.1	37.5	0.5
12:20 PM	23.4	92.1	102.1	37.4	0.4
12:30 PM	23.5	95.8	103	37.6	0.8

#### Day 8: with glazing

Time	T <sub>amb</sub> (°C)	T <sub>w</sub> (°C)	T <sub>p</sub> (°C)	T <sub>gl</sub> (°C)	V (m/s)
9:00 AM	22.7	23	25	25	0.2
9:10 AM	22.6	25.6	28.7	25.8	0.5
9:20 AM	22.5	30.7	33.6	27	0.1
9:30 AM	22.7	36	37.4	29.1	0.3
9:40 AM	22.3	41.2	40.3	30.3	0.4
9:50 AM	22.9	47.3	44.5	32.8	0.6
10:00 AM	22.8	54.7	49.8	33.9	0.7
10:10 AM	23.1	58.7	55	34.5	0.8
10:20 AM	23	64.6	59.7	36	0.2
10:30 AM	23.5	69.8	64.7	36.9	0.1
10:40 AM	23.8	73.7	70.3	37.2	0.3
10:50 AM	23.9	78.5	74.6	37	0.4
11:00 AM	24	80.3	78.7	37.5	0.8

11:10 AM	23.9	82.1	89.9	38	0.1
11:20 AM	23.6	84.3	90	38.1	0.9
11:30 AM	24	86	90.3	37.9	0.5
11:40 AM	23.9	88.9	91.8	37	1
11:50 AM	23.6	92.5	94.3	36.6	0.8
12:00 PM	23.7	96.1	96.7	36.4	0.9

**Day 9: without glazing**

Time	T <sub>amb</sub> (°C)	T <sub>w</sub> (°C)	T <sub>p</sub> (°C)	V (m/s)
9:00 AM	22.9	24	24.8	1.4
9:10 AM	23.5	29	27.5	2
9:20 AM	23.6	35.1	29.9	0.5
9:30 AM	23	43.2	32.1	1.5
9:40 AM	22.5	45.4	31	0.9
9:50 AM	22.8	48.3	33	1
10:00 AM	23	50.1	34	2.1
10:10 AM	23.2	50.7	35.1	1.8
10:20 AM	23.1	52.7	36	1.2
10:30 AM	23.3	52.9	37.7	0.9
10:40 AM	23	53.4	38	0.7
10:50 AM	23.4	53.4	40	0.8
11:00 AM	23.6	54.1	42.8	0.6
11:10 AM	23.8	54.3	43	0.7
11:20 AM	23.7	55.7	43.9	1.2
11:30 AM	23.4	55.6	42	1.1
11:40 AM	23.5	56.4	41.5	0.9
11:50 AM	23.7	56.6	45.2	1.3
12:00 PM	23.7	56.7	45.6	1.5
12:10 PM	23.6	56.9	46.2	1
12:20 PM	23.6	58	46.3	0.8
12:30 PM	23.9	58.5	46.6	0.9
12:40 PM	24	58.6	49.3	0.6
12:50 PM	23.6	59	50	0.8
1:00 PM	23.7	59.9	50.8	1.1
1:10 PM	23.9	57.8	52	1.3
1:20 PM	23.7	58	51.7	0.9
1:30 PM	23.5	60	53	0.7
1:40 PM	23.4	61.2	52.8	0.9
1:50 PM	23.3	60.8	54	1.2
2:00 PM	23.3	62.1	53.8	0.8
2:10 PM	23.1	61.8	54.2	0.5
2:20 PM	23	60	52	0.9
2:30 PM	22.8	58.4	50.6	0.5

**Discharging of PCM and heating of water day 4:**

<b>Time</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>
3:10 PM	118	20.5	138	23.8
3:20 PM	117.6	27.3	135.6	29.9
3:30 PM	117.1	38.3	132.3	33.5
3:40 PM	117	50.1	128.6	52
3:50 PM	117	57.8	125.4	59.1
4:00 PM	115.2	62.8	122	63.2
4:10 PM	111.5	67.1	118.4	67
4:20 PM	105.2	70.3	114.7	71.2
4:30 PM	102.2	72.1	110.2	73.1
4:40 PM	99.1	74	106	75.2
4:50 PM	97.2	78.7	101.8	79
5:00 PM	95.4	82.4	96.6	83.2
5:10 PM	92.3	83.4	92	84.5
5:20 PM	88.9	84.5	87.3	85.1
5:30 PM	87.1	85.3	84.1	85.7
5:40 PM	85	85	83.5	85.2
5:50 PM	83.2	84.2	81.1	83.1
6:00 PM	82.6	82.1	79.8	81.6

**Discharging of PCM and heating of water day 5**

<b>Time</b>	<b>T<sub>pcm</sub> (°C)</b>	<b>T<sub>w</sub> (°C)</b>	<b>T<sub>R</sub> (°C)</b>	<b>T<sub>P</sub> (°C)</b>
2:10 PM	118.5	20	140	23
2:20 PM	118.3	28.4	138	30.4
2:30 PM	118	39.8	136.3	35.3
2:40 PM	117.5	52	133.8	55.1
2:50 PM	117	59.3	130.1	62.4
3:00 PM	116.1	64.1	126.5	69.1
3:10 PM	113.6	69.8	122.7	75.6
3:20 PM	111.5	73.2	118	80.4
3:30 PM	110	77	114.6	83.4
3:40 PM	108.2	80.2	110.2	84.5
3:50 PM	105.9	83.1	106.6	85.1
4:00 PM	104	85.6	104.3	86.7
4:10 PM	102.4	87.2	102.1	88.2
4:20 PM	100.2	89.3	99.3	90
4:30 PM	97.4	91.5	97	90.5
4:40 PM	94.3	92.6	93.8	88.9
4:50 PM	91.2	91.7	91	88.6
5:00 PM	90.4	90	89.3	88