

**PERFORMANCE INVESTIGATION OF IMPROVED BOX
TYPE SOLAR COOKER WITH THERMAL ENERGY
STORAGE**

M.Sc. THESIS

BY

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A Thesis Submitted to Thermal and Aerospace Engineering Program, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, in Partial Fulfillment of the Requirements for the Award of the **Master of Science Degree in Thermal Engineering**.

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July, 2019

DECLARATION

I hereby declare that this M.Sc. thesis entitled “*PERFORMANCE INVESTIGATION OF IMPROVED BOX TYPE SOLAR COOKER WITH THERMAL ENERGY STORAGE*” in partial fulfillment of the requirements for the award of the degree of Master of Science in thermal engineering is an authentic record of my own work under the supervision of Dr. Addisu Bekele, Assistant Professor of Thermal Engineering, Adama Science and Technology University.

The matter embedded in this Thesis has not been presented for the award of a degree or any other award in any other university. All relevant resource of information used in this paper has been properly acknowledged in the text and listed in the reference part.

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Date

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This has been submitted for examination with my approval.

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Date

APPROVAL OF BOARD OF EXAMINERS

We, undersigned, members of the board of examiners of the final open defense by Ephrem Milikias Meja have read and evaluated his thesis entitled “*Performance Investigation of Improved Box Type Solar Cooker With Thermal Energy Storage*” and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements of the degree of masters of Science in Thermal Engineering.

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External Examiner	Signature	Date

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ABSTRACT

Using solar energy for cooking is a quick acting solution to overcome the energy scarcity and an effective mitigation way for concerning global climate change, deforestation, and economic problems of the world's poorest people, especially in the solar remote areas. Thus a wide solar remote area, Daassanech woreda, is selected for study which is located in SNNPR of Ethiopia, about 780 km far from Addis Ababa, near to the boarder of both Kenya and Sudan. In daassanech, all domestic energy need have been achieving by biomass only, due to this health, Environment and other social related problems had followed. The main aim of this study is to design, develop and experimentally test the performance of improved solar cooker with thermal energy storage under Daassanech weather condition. Then, the thermal performance of improved solar cooker is compared with conventional box type solar cooker. The weather data was collected from National Meteorological Agency (NMA) of Ethiopia of Jinka station and from four different websites. An average solar radiation is calculated as maximum in February ($6.563 \text{ KW/m}^2/\text{day}$) and minimum in July Month ($5.578 \text{ KW/m}^2/\text{day}$) and Annual Average daily solar radiation is $6.134 \text{ KW/m}^2/\text{day}$. Based on minimum solar intensity, two solar cooking systems are designed and fabricated for experimental testing with solar intercept area of 0.25 m^2 . Then temperature distributions are analyzed in both analytically and experimentally. Experimental study was carried out in 9th to 15th June, 2019 by using two different methods, stagnation testing and load testing. Then performance has explained in both BSI and ASAE standards. As BSI standard the improved cooker is included in grade 'A' due to first figure of merits (F1) is greater than 0.12. Based on ASAE standard results, improved solar cooker without TES has obtained higher power than others; due to this it is able to cook food faster than others. During cooking tests improved solar cooker was able to attain above 100°C temperature of water in morning (8:20 – 10:20) with low solar intensity. The black stone with its better specific heat capacity and relatively high conductivity is chosen as a better storage material. The payback period of improved solar cooker when compared with firewood and charcoal as alternative energy source is 2.5 years. This study can continue further with different storage materials, additional system modifications and with different locally available insulations in various weather conditions.

Keywords: Solar Energy, Box Solar Cooker, Figures of Merits, Improved Solar Cooker

NOMENCLATURES

CBSC	Conventional Box Type Solar Cooker
IBSC	Improved Box Type Solar Cooker
C_{pw}	Specific heat capacity of water (J/kgk)
F1	First Figure of Merit
F2	Second Figure of Merit
BIS	Bureau of Indian Standard
ASAE	American Society of Agricultural Engineers standards
NMA	National Meteorology Agency
KW/m ² /day	Kilo Watts per meter squared per hour
I_a	Average global solar insolation (W/m ²)
I_r	Reflected radiation (W/m ²)
I_b	Beam radiation on tilted surface (W/m ²)
I_d	Diffuse radiation on tilted surface (W/m ²)
Kw	Thermal conductivity of water (W/m ⁰ C)
Mw	Mass of water (kg)
U_b	Bottom loss coefficient, (W/m ² K).
U_L	Overall loss coefficient, (W/m ² K).
U_s	Side loss coefficient, (W/m ² K).
U_t	Top loss coefficient, (W/m ² K).
LCC	Life Cycle Costing
LCS	Life Cycle Saving
T_{p1}	Absorber plate Temperature of CBSC
T_{p2}	Absorber Plate Temperature of IBSC
T_{w1}	Water Temperature of CBSC
T_{w2}	Water Temperature of IBSC

Greek Symbols

θ	Angle of incidence of beam radiation
θ_z	Zenith angle of the sun
β	Angle of absorber inclination
β_c	Tilt angle of Cover
γ_z	Azimuth angle
γ_s	Surface azimuth angle
δ	Angle of declination of the sun
ϕ	Angle of latitude
ω	Hour angle
σ	Reflectivity
ε_g	Emmittance of glass cover
τ	Transmissivity of glass cover
τ_d	Transmittance of glazing for diffuse radiation
α	Absorptance for diffuse radiation
$(\tau\alpha)_b$	Transmittance – absorptance product of beam radiation
$(\tau\alpha)_d$	Transmittance – absorptance product of diffuse radiation
θ_r	Refracted angle
σ	Stephen Boltzmann constant
η	Thermal efficiency
Ψ	Exergy efficiency

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CHAPTER ONE

INTRODUCTION

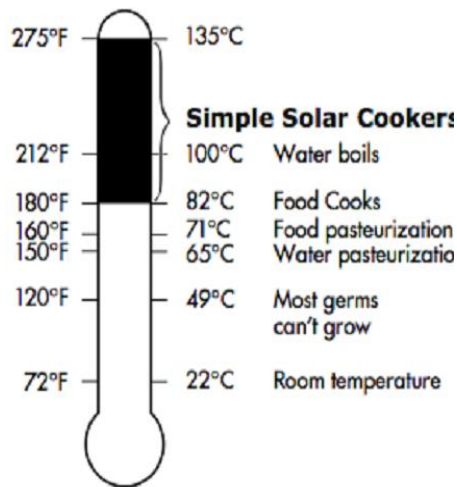
Now a day's several researches have been conducting in energy affairs and it have been became very hot issue in the world. This is because the conventional energy sources have become in short supply to meet primary energy source demand; even though it is simple to get some conventional energy sources, they follow further problems. Conventional energy sources are decreasing from generation to generation but can never increase; this shows us it is limited in amount. Therefore world is now diverting towards renewable energy sources. The Sun is responsible for all renewable energy sources on Earth such as solar energy, wind energy, tidal and etc., which can meet the energy needs of human being. As we know whether developed or developing, urban or rural, where ever in the world one of the common daily energy-consuming jobs of human being is cooking. The difference is the energy that is using for cooking. In the developing countries like Ethiopia, cooking is mostly by using biomass, few urban residents may use electricity and fossil fuel. Therefore, to overcome this energy scarcity in developing country, especially in the solar remote rural areas using solar energy is quick acting solution.

1.1. Solar cooker and its classifications

Worldwide energy demand becomes highly increasing sector. This energy demand is expected to rise by approximately 1.5 –3 times by 2050 because of increasing energy demand in various regions of the world ^[1]. Developing countries will share more of this increasing energy demand. Even now in developing countries, energy demand is sharply increasing due to rapid population growth, increasing of immigration from rural to urban and high holy curiosity to industry development. Energy demand is growing with 3 per cent annually in developing countries in opposite 0.9 per cent in already industrialized countries [Paul W.G. Warnars, 2012]. Nevertheless, because of poor energy infrastructure, especially in most parts of Africa energy facility is characterized by a high dependence on traditional biomass. As Nandwani (1996) explained, large amount of energy generated from different sources is used to domestic activities out of which cooking consume larger percentage.

Cooking is process of preparing food for human consumption by using transfer of energy from heat source to food. It is common daily job for all human beings. In this paper it is focused by the source of thermal energy to get it from free sun light. Energy source can be

traditionally obtained from biomass or in modern form thermal energy can obtain from fossil fuel, electricity or from other renewable energy including sunlight.



- 45-50 °C Most germs cannot grow (For drying products)
- keeping the food warm,
- 65-70 °C Water pasteurization,
- 70-75 °C Food pasteurization,
- 80-85 °C Food cooks,
- 100 °C Water boils ,

FIGURE 1-1: Temperature required for different processes [24]

Pasteurization is invented by the French scientist; Louis Pasteur in 1862, pasteurization is a process of treating foods or liquids like water or milk with heat to kill 100% of pathogens in a few minutes. Therefore solar cooker can entrap sensible heat with at least 49°C temperature which is enough to keep food.

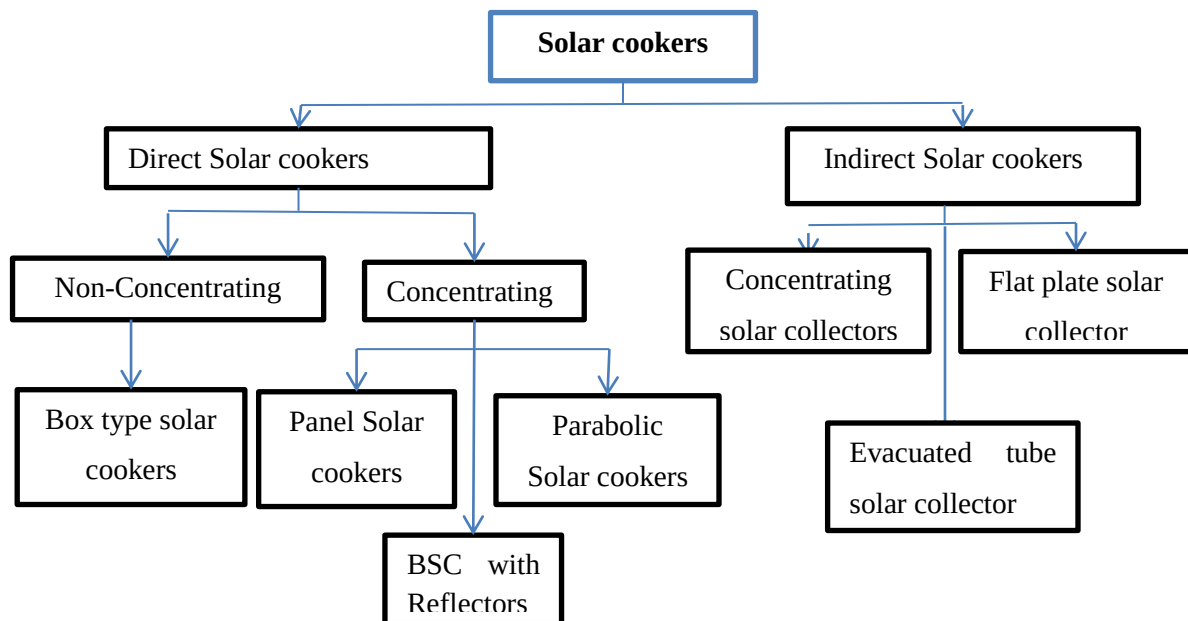


FIGURE 1-2: General classifications of solar cookers

1.2. Draw backs of using biomass as energy source

Many researchers have described about 2.5 billion people in developing countries rely on biomass energy source, such as fuel wood, charcoal, agricultural waste and animal dung, to meet their domestic energy needs including cooking. [1,2,3,4]. As Peace Corps Bolivia (2008) estimation, more than 2.7 billion people will still depend on biomass to meet their domestic energy needs by 2030. Currently majority of those people who are biomass dependent are live in the tropics, mainly in rural areas. As WEO description, household energy use in developing countries is about 10% of world primary energy demand. Household use of biomass in developing countries alone accounts for almost 7% of world primary energy demand [2]. According to Iwu (1998), biomass accounts for over 50% of the overall household energy consumption in developing countries. About 80% of this is consumed as firewood, mainly in the rural household.

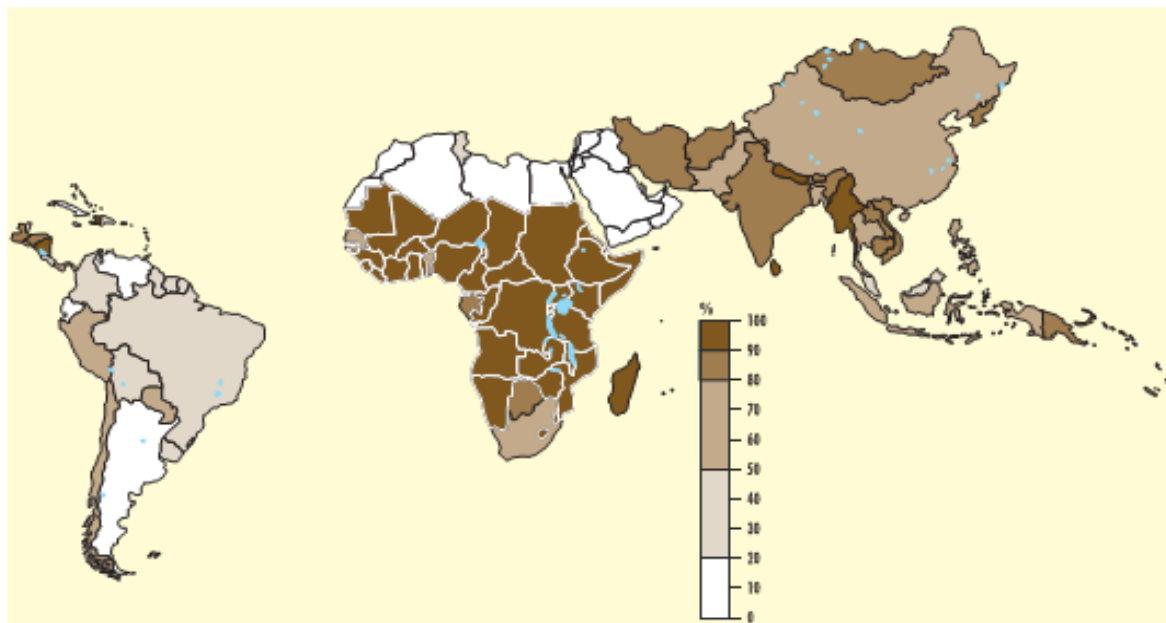


FIGURE 1-3: Share of traditional biomass in residential consumption by country

(Source: IEA databases)

This figure can show us firewood is still the primary energy source in much of the developing world since it is the cheapest way to obtain the energy required to meet increasing energy demand. However, these situations in the developing countries have brought many concerns such as poverty, air pollution, health and environmental problems. Deforestation, forest degradation and associated problems that follow desertification in many developing countries are a result of unsustainable use of firewood. The lives of millions affecting by desertification

in Sub-Saharan Africa can be mention as the noticeable consequence of deforestation. Solomon described in GIZ ECO workshop that in Ethiopia 2 billion m³ top soil is lost annually due to erosion (of which 10% is lost irrecoverably) and approximately 200,000 ha forest cover is lost annually (from 40% of the land area at the turn of the century to less than 2.7% now)^[4].

Fuel wood, agricultural residues and animal dung all produce high emissions of carbon monoxide, hydrocarbons and particulate matter. The low temperature, low oxygen conditions found in cooking fires result in the formation of carbon monoxide, methane, nitrogen dioxide and other gases which are from 5 to 280 times more reactive than carbon dioxide (P.A.Funk, 1996). GIZ reported in their energy related workshop, it was titled “Bringing Gender to Life”, indoor pollution concentrations from a typical wood-fired cook stove (FIGURE 1-4).

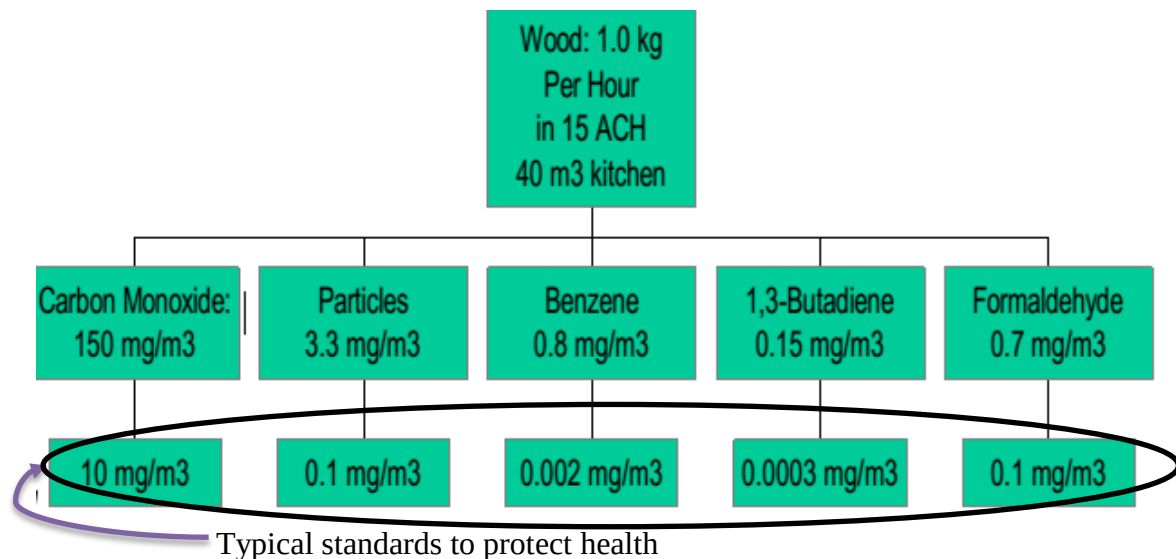


FIGURE 1-4: Typical indoor pollution concentrations of a typical wood-fired oven

(Sources: - GIZ ECO workshop 2011)

According to WHO indoor air pollution from inefficient traditional wood-fired cook stove is leading to serious health damage such as respiratory diseases including pneumonia, tuberculosis and chronic pulmonary disease, obstetrical problems, low birth weight, blindness and heart diseases. The World Health Organization (WHO) estimates that 1.5 million premature deaths per year are directly attributable to indoor air pollution from the use of solid fuels. More than 85% of these deaths (about 1.3 million people) are due to biomass use, the rest due to coal. This number of deaths is more than deaths due to malaria, almost as many as tuberculosis and almost half as many as HIV/AIDS [2].

The most victimizing by indoor air pollution are women and children because they are traditionally responsible for cooking and other household chores.

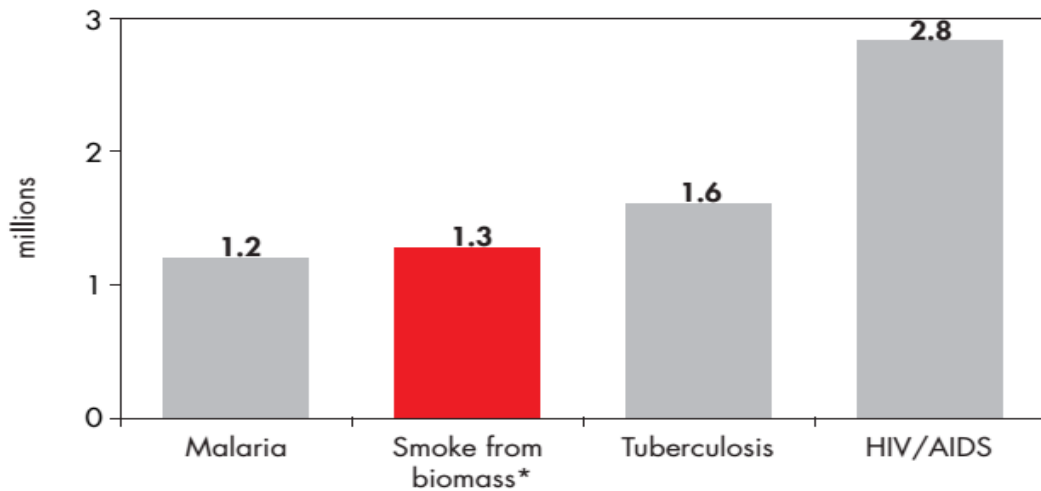


FIGURE 1-5: Annual Deaths Worldwide by Cause

(Source: WHO Statistical Information System, available at www.who.int/whosis.)

Another problem of open door biomass-fired cook stove is high fuel consumption; the reason are not much heat is generated per unit of fuel, only a small amount of the heat is directed to the pot and only a small fraction of the heat that is directed to the pot is actually transferred into the food.



FIGURE 1-6: Traditional biomass Cook stove and fire wood collection

Fortunately, most developing countries are geographically located for optimal absorption of the sun's rays or are most solar remote locations, so they are harsh to live and have very difficult weather condition to human and even for most of animals. In oppositely this high potential solar intensity can serve to meet their almost all domestic energy needs. Using solar energy for cooking and heating can be an effective mitigation way for concerning global climate change, deforestation, and economic debasement of the world's poorest people.

As we can see in the FIGURE 1-3 above, Ethiopia is also one of highly biomass consuming countries and fortunately included in solar remote location. Ethiopia is located in the tropics and thus highly gifted with a wealth of solar energy. Awash T. (2014) described biomass, including wood, dung and crop residues, is the source for above 92.4% of Ethiopia's total energy use, primarily in the household. According to the World Bank collection of development indicators in 2016, about 80.1% of Ethiopian total population are living in rural areas and only 3.51 % of total people have access to clean fuels and technologies for cooking, most of them are live in urban area. Even if '13 months of sunshine' was the motto of Federal Democratic Republic of Ethiopian (FDRE) Ministry of Culture and Tourism, energy sector of Ethiopia is the least developed in the world and highly dependent on traditional sources of energy such as wood, crop residuals and animal waste (Fikremariam, 2014). In daassanech 4 up to 10 kg fire-wood used for open fire daily and women and children spend 2 up to 4 hours to collect this energy source. Using biomass by itself may not be a great problem; the main problem is inefficient use of it and being dependent on these energy sources.

Millions of people living in remote rural areas of Ethiopia have not connected to the electric power grid and even they have no access to get imported fossil fuel oil. Health centers even in these areas have also no better access to get thermal energy for water heating purpose. The purposes of hot water in Health centers are to sterilization and to balance the body temperature of newborn children with under 2.5 kg. High temperature water heating can be achieved by boiling water at high pressure by using a household pressure cooker or Autoclaves in urban area. As explained on Tuttnauer Co. Ltd. Autoclaves with many features to maximize safety, size and automation have cost anywhere from \$3,000 to \$100,000+ USD. Less expensive autoclave designs popular in developing world markets lack progress monitoring features, focus more on robustness, and cost anywhere from \$250 to \$5,000 USD depending on size. So distributing it to all clinics is difficult in developing countries. In order to that the only chance to meet both clinical and domestic primary energy need was biomass especially in the selected site of this research, daassanech district.

This research will focus to utilize some few possible portions from the huge amount of sun energy to cooking and heating purpose by using improved inexpensive solar cooker. Additionally to using captured energy for food preparation purpose, it can solve some socio-economic and ecological problems. The improved solar cooker is structurally inverted pyramid shape inclined wall with inner reflector and flexible outer reflector connected and it has cheap sensible heat storage. Its materials selection is by considering its weight and its cost with relatively low cost.

1.3. Statement of the Problem

Daassanech is one of Ethiopian district administrations that named after inhabitant ethnic groups, traditionally they are Nomadic pastoralists. It is a wide remote area located in south nation's nationalities and people of Ethiopia region, about 780 km far from Addis Ababa, at the boarder of Kenya in the south and south Sudan in the southwest of the Ethiopia.

In daassanech all domestic energy need is achieve by biomass only. This follows so many problems such as related with health, Environment and other social problems.

- Health problems due to indoor air pollution
- Deforestation due to inefficient use of energy from biomass fuels,
- Environmental impacts such as flooding, erosion
- Various social problems
- Delivering firewood, lumberjacking is duty of children and females, so they spend more time to it.

However the area is a remote location, the available solar potential is not utilized because of none of solar technologies have reached to that area; due to lack of transportation and no any solar thermal technologies have been designed by considering daassanech culture.

Even health centers could not be out of these problems in those Ethiopian rural areas. Almost all clinics are using biomass to boil water for sterilization. Actually, in selected site about two health centers have flat plate solar heater but they are even not functional.

The available solar cookers may not solve these problems because most of them are expensive due to importing and it is not easily portable to move from place to place. The daassanech people are not stable in one area, so all their property must be lightweight and portable to move; they cannot buy the existing modern solar cookers due to its high cost. Another problem is as a trend they prepare their food most of a time at afternoon (4pm – 7pm) while there is no enough solar energy to cooking and heating.

In every solar system, the system efficiency is highly dependent on the amount of collected solar energy relative to collector area. The existing solar cooker absorbs relatively low solar energy from wide area, due to its poor concentrating capacity.

Therefore, this research will deliver an improved portable solar box cooker integrated with sensible thermal energy storage with a low cost for both cooking and water heating purposes; as a part of remedy to those mentioned problems and to reduce women's and children's firewood collection task.

1.4. Purpose of the study

The main purpose of this research is providing high performance inexpensive portable box type solar cooker to substitute biomass traditional oven in remote rural area especially for Daassanech conditions. This can solve almost all problems that are mentioned in the problem statements above. If free solar energy achieves energy need for food preparation, purifying water, sterilizing clinical instruments and water heating instead of biomass, so many problems such as social, environmental and health related problems can be solved.

This study included also study about solar potential of the selected place and the traditional energy source and also provided newly designed box type solar cooker technology, these things shall play great role to overcome ecological and socio-economic problems. Women and children can be free and they can use their precious time that spending for firewood collecting, to education and other activities. Solar cooker use a clean and affordable energy, they cannot worry about energy cost its free energy.

1.5. The objectives of the study

1.5.1. General objective

The main objectives of this research work is to design, develop and test the performance of improved box type solar cooker with thermal energy storage to substitute biomass oven in household and health centers under Daassanech weather condition.

1.5.2. Specific objectives

Specific objectives were:-

- To assess the solar potential of Daassanech
- To study thermal energy storage materials and select locally available material to use as sensible thermal energy storage
- To design improved solar box cooker with sensible heat storage.

- Developing two different prototypes (Conventional and improved box type solar cooker with reflectors and integrated with thermal storage)
- To test and compare thermal performance of different types of box solar cookers with each other and with traditional typical firewood stoves,
- Assessment of social and economic benefits of solar cooker in the selected sites and assist carpenters to produce it locally.

1.6. Scope and limitation of the study

An improved box type solar cooker, that is partially focusing and possible for cooking in evening due to storage material, will provide and assess in terms of its performance, cost and benefits, in contrast with the existing cooker for heating water and cooking in developing regions. Experimental testing will conduct at the selected sites.

The limitations on this study are variation of the very hot weather condition is challenging for the researcher, unavailability of transportation from place to place, cost, time and material availability.

1.7. Organization of the thesis

This thesis is organized in to five chapters. The first chapter presents the introduction of the study including the drawback of using biomass as energy source, statement of the problem, purpose of the study, the general and specific objectives, significance, scope and limitation of the study. The second chapter presents detail literature reviews including one paragraph of conclusion for the reviews. Chapter three discusses the methodology for the thesis work that including methods of data collection and its analysis, solar potential estimation, study of thermal energy storage and details about proposed system designs. The fourth chapter is about the results and discussion of the results. The last chapter, chapter five, is finalizing the thesis by conclusion based on the results and recommendations for the future work.

CHAPTER TWO

LITERATURE REVIEW

A solar cooker is a cooking device that makes utilize of only sunlight as an energy supply to cook food, heat up water, purify water and sterilize health instruments. By using solar cooker time, cost and effort that spend to collect firewood to traditional biomass oven can save. Disease causing indoor air pollution, forest deforestation and other related problems can be reduced.

The history of solar cookers started early from 18th century. Some of those documented histories, A German Physicist, named Tschirnhausen (1651–1708), carried out experiments on solar cookers (Soni, 2014). By the year 1767, Swiss scientist Nicholas de Saussure (1740-1799) built a black insulated solar cooker by using greenhouse effect of glass boxes placed inside one another then blackened surface in it (O. Craig(2015), Otte (2013)). In 1876, Mouchot designed solar cookers and W. Adams developed an octagonal oven equipped with eight mirrors after one year. He also wrote the first book on solar energy and its industrial applications (Soni, 2014). As P.Konttinen (1995) explained, the first solar cooker user in Africa was an Englishman, John Fredrick Herchel, in 1837 in Cape of Good Hope (South Africa). He used a black box made of hardwood with a double glass window (without reflectors). He buried the box in sand for insulation and reached a temperature of 116°C. Now days there are countless modification and so many styles of solar cookers. Many researchers have taken theoretical and experimental performance investigations for the different solar cookers for possible uses, such modifications focused on sun tracking system [21], outer-inner reflectors , different insulating materials, a modified absorber plate [11, 13, 15, 16], a modified utensil, and a storage system [19, 28, 29, 30, 31, 37]. Generally solar cookers are classified as Direct and Indirect type solar cookers.

2.1. Direct solar cookers

The classifications of direct solar cookers are three, such as Box type, panel and parabolic type solar cookers.

2.2.1. Box type Solar Cookers

Box Solar Cooker is the most common solar cooker which has a very simple construction and it may use low cost materials to construct [11], which essentially consists an insulated box, covered with a transparent glass glazing or plastic cover and a reflector or reflectors that help to direct sunrays to heat the box and blanked pot. There are different modifications in this category of cooker. These cookers with the possible modification can typically reach temperatures of 300° F (150° C) which is enough temperature to cook any food.

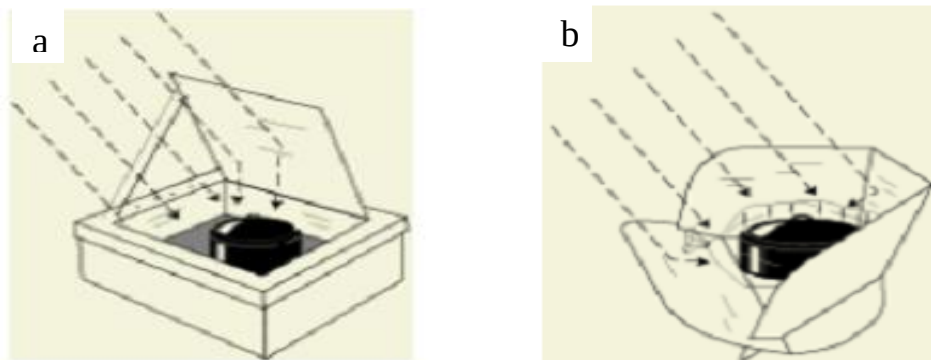


FIGURE 2-1: (a) Box type solar cooker and (b) Panel type solar cooker [24]

2.2.1.1. Conventional Box type cooker

This type of solar cooker has been made from different materials with different absorber modifications and with different insulators.

The components of a conventional solar cooker are can be as follows:

1. Glazing (Glass lid); to create greenhouse effect in the box space, to prevent heat loss that escape by radiation and convection from the absorber. It allow solar light with small wavelength enter to cooker and block long wavelength heat radiation from absorber plate.
2. Dark absorber plate and cooking pots: used to absorb and turn both direct and reflected sun light to heat energy.
3. Outer box of wood with insulation: to prevent heat loss,
4. A booster mirror: to direct sun rays to the absorber from outside of the aperture area.

Most of the time conventional type solar cooker is made of wood and hard card board.

Uhuegbu et al. (2010) in Nigeria designed and constructed successfully a wooden solar box cooker with cheap and locally available materials. The highest temperature gotten both on the

ground floor and at the top of the roof was 72°C both on the days with air temperature of 38°C and 35°C respectively. [6]

Often Conventional solar cookers are designing or fabricating for warming or heating purpose. Among those solar cookers Nandwani's (2014) cooker is one that promoted as Solar Food Warmers for schools in Costa Rica.

2.2.1.2. Modified Box type solar cooker

Box type solar cookers have been modified in different ways in the different country. Shringi et al. (2016) studied optimization of thermal performance of solar radiation for optimum geometrical shape of a box type solar cooker. The study was involved fabrication of different geometries for on field evaluation in region. The three geometrical shapes have been fabricate i.e. square, rectangle and trapezoidal with same aperture area of 40 cm. Then, the average figures of merit for the boxes have been found to be as: Trapezoidal $F_1=0.11$, $F_2 = 0.46$; Square $F_1=0.11$, $F_2 = 0.46$; Rectangular $F_1= 0.11$, $F_2 = 0.45$, respectively. Finally, the results showed that trapezoidal shape is better than other geometrical shapes made. [9]

Mohammed et al. (2013) developed and tested the performance of a truncated pyramid solar thermal cooker in Nigeria. During testing, the highest plate stagnation temperature achieved, under no-load condition and reflector covered with black cloth, was 145°C . In full-load condition the temperature of 5.2 kg of water inside the cooker rose from 60°C to 90°C in 72 minutes. The First Figure of Merit was calculated to be 0.120 and the Second Figure of Merit was found to be 0.410, thus meeting the standard prescribed by the BIS for box-type solar cookers. The 2kg rice was well cooked in 2 hours 45 minutes.

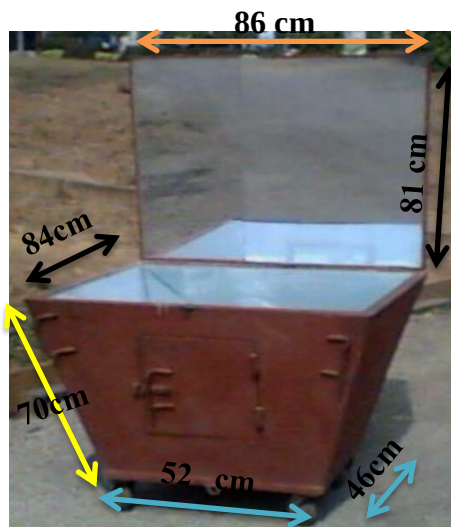


FIGURE 2-2: Photograph of the TPSTC

Awash (2014) designed, prototyped and experimentally evaluated performance of low-cost inverted Pyramid shaped box type solar cooker in Hawassa University, Ethiopia. He used a

black sheet metal as an absorber, newspaper as an insulator and aluminum foil for reflection in the inner part of the cooker. The cooker was manually oriented according to hour angle at an interval of 5⁰(or 20 minute) in order to collect a maximum of solar radiation. Testing has been taken standard of Thermal Test Procedures for Box-Type Solar Cookers, by Mullick et al (1987). This standard, presented in a more technical framework than ASAE-S580, provides two figures of merit, calculated so as to be as independent of environmental conditions (such as wind speed, insolation, etc.) as possible. The pyra-box solar cooker was found to provide adequate temperatures needed for cooking different kinds of foods and reaches a maximum temperature of 104.8 °C for the fluid of oil. He got the average energy efficiency of CSC and pyra-box cooker was about 15.4 % and 26.5 % respectively.

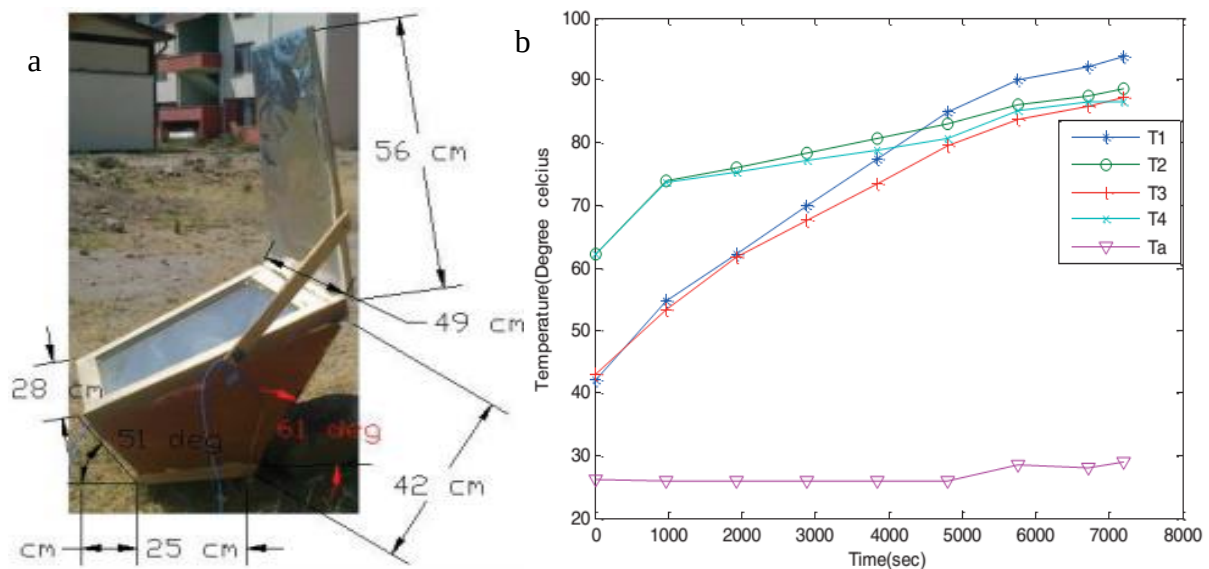


FIGURE 2-3: a) Prototyping dimension b) Experimental water heating test [12]

But the main drawback of this solar cooker is the need for frequent tracking, because according to Jaramillo (2007) explanation, moving whole the system with the sun angle while cooking is one of the main difficulties for social acceptance.

Kumar (2008) designed and fabricated truncated geometry box type solar cooker to eradicate completely the need for tracking the sun during cooking and to achieve high temperatures by concentrating solar energy. He tested to find optimum experimental correlation between the values of angles θ and α and their impact on shape and size of bottom absorbing plate size.

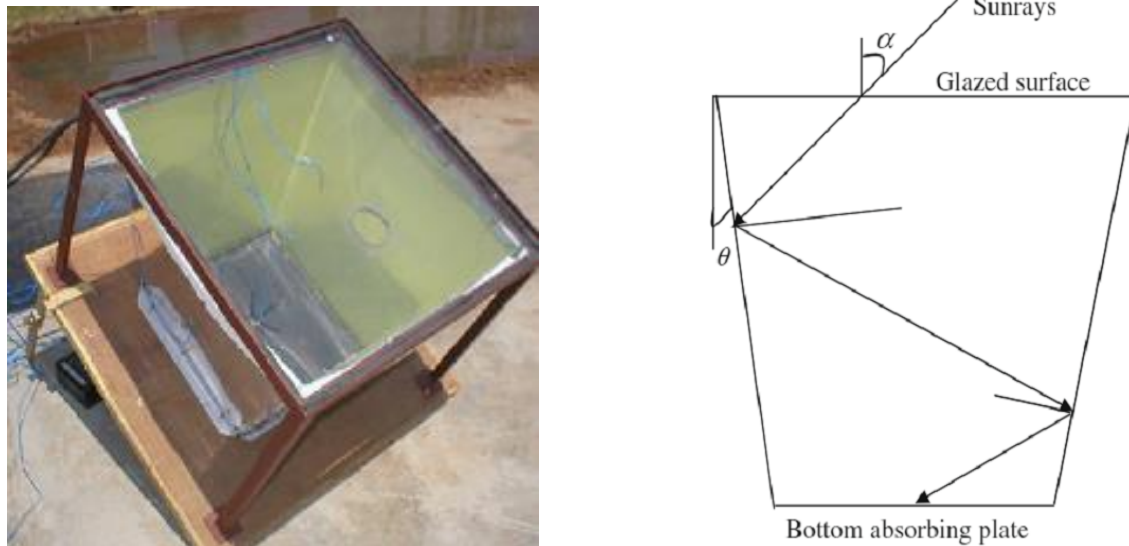


FIGURE 2-4: Inclined and Schematic diagram of truncated pyramid cooker

To receive maximum insolation, despite seasonal variations in the position of the sun, the value of α can be changed by an appropriate tilt to the base of the device. The fabricated solar cooking cum water heater model was with 50 cm x 50 cm glazing surface as Indian standard SBCs and 32.6 cm x 32.6 cm absorbing plate which is made of aluminum black painted sheet metal. Its depth (distance from glazing to absorber) was 49.2 cm.

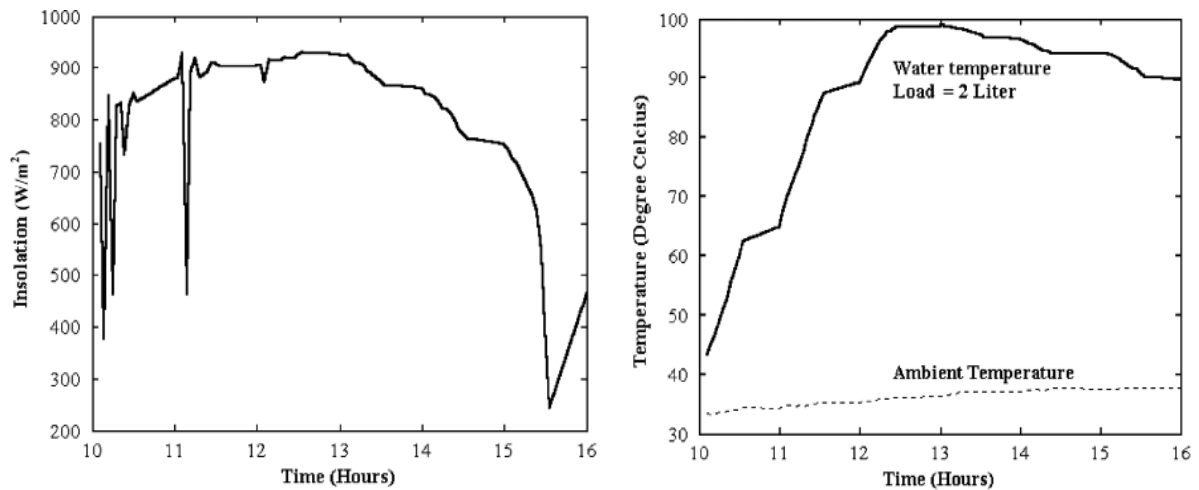


FIGURE 2-5: Variation Insolation and Temperature with Time

Cooking tests were carried out as per requirements of the BIS standard. The result obtained from experiments and calculations are the highest plate stagnation temperature approached 140°C under no-load conditions, the water temperature inside the cooker reached 98.6°C under full-load tests and calculated figures of merit values (F1 and F2) were 0.117 and 0.467, respectively.

Mahavar et al. (2013) fabricated a Solar Rice Cooker (SRC) based on a theoretical model, and testing has been implemented on different days under various climate conditions. The value of the available solar power fluctuates from 82 to 120 W, and its average value is about 107.8 W for the duration of 10:00 to 15:00 solar time. The rice-cooking time for the first and second meal is found to be 2 h and 2 h 20 min respectively. The fabricated Solar Rice Cooker was found to be able to cook 0.4 kg rice twice during the solar hours on a clear day. The Schematic diagram of the SRC is shown in Figure 2-8 below.

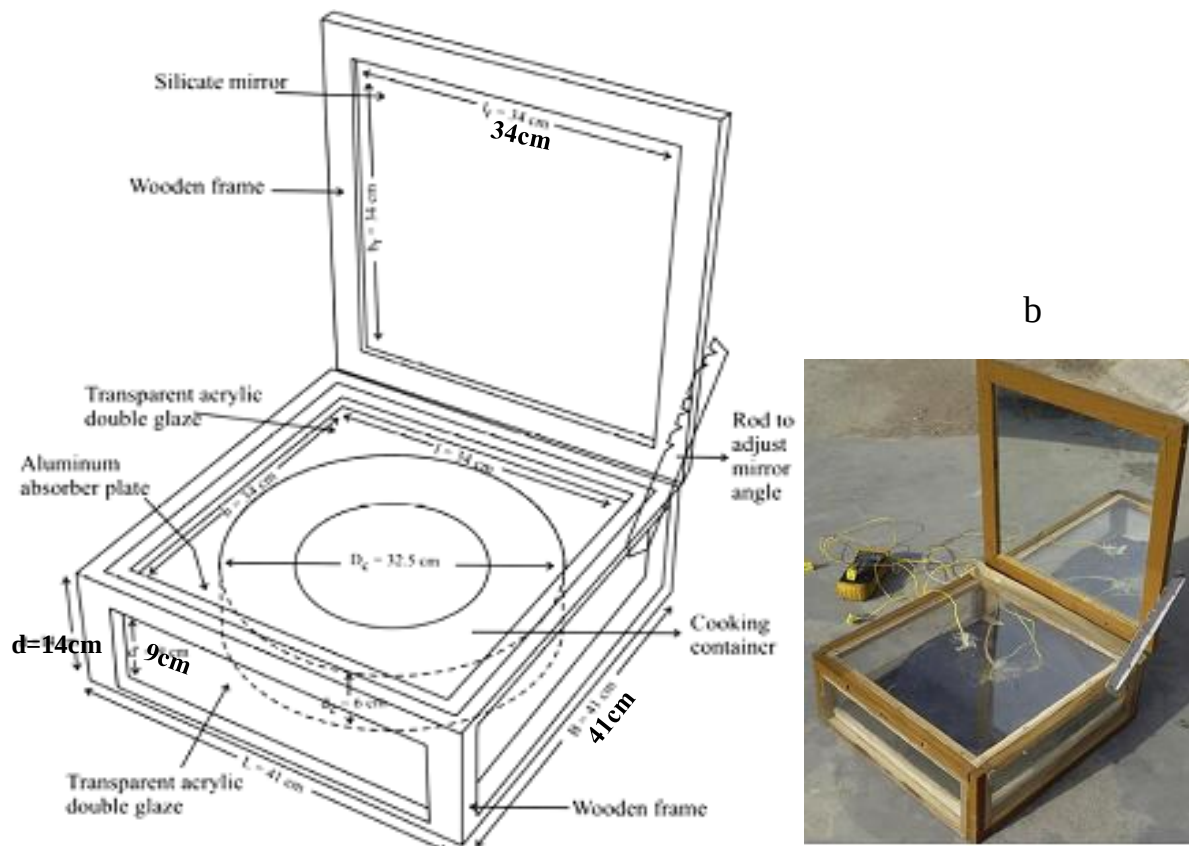


FIGURE 2-6: Solar rice cooker, (a) schematic diagram, (b) experimental arrangement

Several modifications have been taken with reflectors. Some of those modifications are by increasing number of reflectors and using inner walls as reflectors.

Ekechukwu et al. (2003) in their paper presented the design philosophy, construction and measured performances of a plane-reflector augmented box-type solar-energy cooker. Some of features introduced in this paper to enhance the overall performance of the design over the traditional solar-energy box cooker include, a steam-relief line and a specular plane mirror reflector, which increases the magnitude of solar radiation incident on the cooker surface.

They concluded that the solar cooker performance could be improved greatly with the plane reflector in place.

Tariku et al. (2017) designed and tested two major solar cookers, aluminum plated and black coated boxes. Theoretical and practical comparison was conducted to choose which cooker was the best in efficiency with the same working environment. Results from the testing showed that the temperature of the water reached maximum of 46.2°C and 58.3°C for black coated and aluminum laminated solar box cookers, respectively. The experiment results are given by the maximum thermal performance at the aluminum laminated coated box. [15]. So using inner reflector by this principle is more important than painting inner wall with black color.

Dutta (2018) designed and fabricated a highly efficient inclined box solar cooker and described details constructional feature of the cooker in his paper investigation. The cooker, presently fabricated can able to cook 2 Kg rice or equivalent food item at a time within two hours cooking is possible in between 9am to 3 pm afternoon. Improved performance over a conventional box type solar cooker is the main feature of this cooker. But it can't be socially acceptable due to its inclined absorber which is not safe to put pan.



FIGURE 2-7: Temperature rise on Dec 24 around noon. [8].

El-Sebaif et al. (1996) presented a transient mathematical model for a box-type solar cooker with a one-step outer reflector hinged at the top of the box cooker. [10]. Again in 1997 he analyzed numerically a box-type solar cooker with outer-inner reflectors. It is based on analytical solution of the energy-balance equations for different elements of the cooker. He investigated cooker performance by computer simulation in terms of the cooker efficiency as well as characteristic and specific boiling times. At the optimum tilt angle of the outer

reflector (60°), 50 and 35% decrease the specific and characteristic boiling times respectively, compared to the case without the outer reflector. The overall utilization efficiency of the cooker obtained was 31%^[11].

2.2.2. Panel type solar cooker

Panel solar cooker is concentrating type solar cooker which usually consists of a darkened or painted with black color cooking pot or pan, an oven cooking bag or transparent glass bowl along with a reflective panel. These panels can be made from aluminum foil over corrugated cardboard, or from tin or sheet metal panels polished to a high sheen and also with mirrors.

Nakajo et al. (2014) conducted one-year survey under the support of Japanese ODA to investigate the possibility of their newly developed durable and powerful panel type solar cooker being used in the Federal Democratic Republic of Ethiopia as one of the heat sources for cooking. They selected three communities in Jijiga refugee camp and one local village near Mekelle University, which was their counterpart. To improve the durability and reflection rate, new laminated film consisting of aluminum-metallized PET film and aluminum foil developed especially for their solar cooker. They conducted two field researches its outcomes revealed that almost all of the local typical food can be cooked with solar cooker and 80% of the refugees give positive feedback on the product. The main reason is “Can save precious fuel”, others are “No smoke” and “Safe to use”. As seen from the graph temperature of 500ml of water raised to about 85°C at 90 minutes.

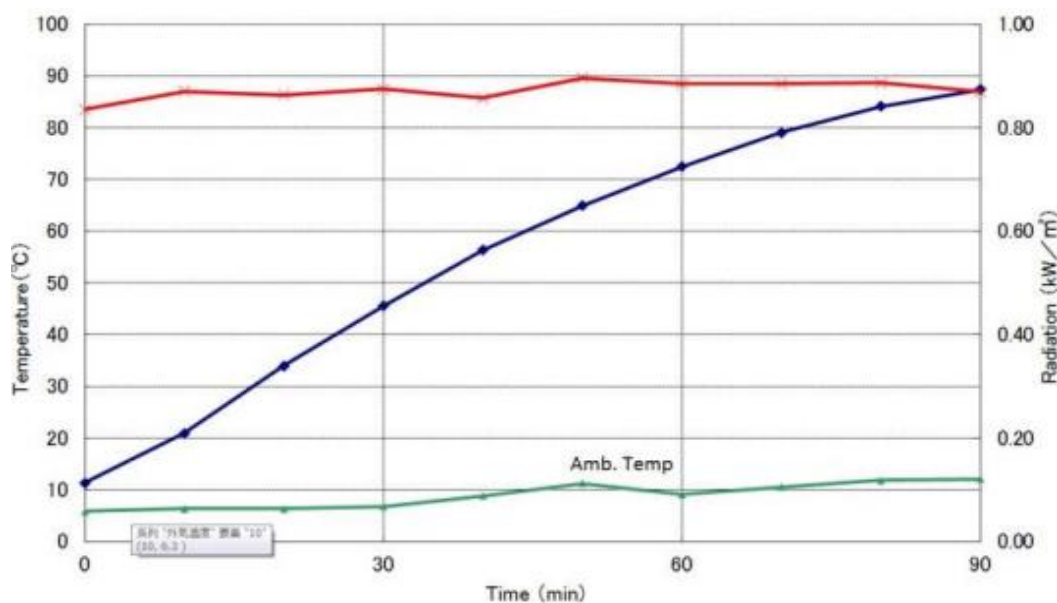


FIGURE 2-8: Temperature rise on Dec 24 around noon. [8].

2.2.3. Parabolic type solar cooker

Unlike in panel type solar cooker, solar rays focused at a single area, in parabolic type solar cooker all the solar rays are direct to single focal point. Therefore in parabolic type solar cooker concentration ratio is very high for the same aperture area, because of this it reaches higher temperatures, over 150 °C, much faster than any other type of solar cookers. But this can be possible only when the cooker is well positioned at the sun and it needs to change the position with the sun regularly, at least every 15 minutes [4]. All the reflected sun's rays concentrates to a focal point where the pan is placed.

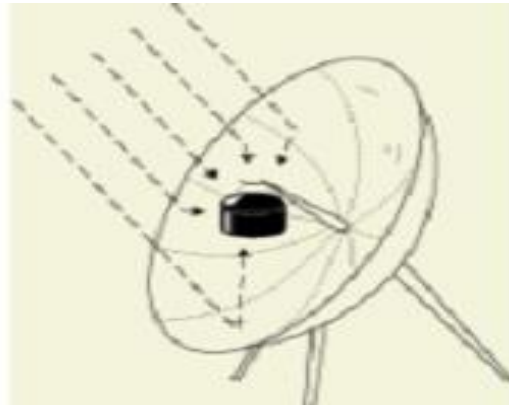


FIGURE 2-9: Solar parabolic cooker (source: SCI)

The disadvantages of parabolic concentrator type solar cooker are:

- It needs specific parabola design parameters
- Often it is not easy to construct with available materials in locally
- Risk of fire and burning due to its high temperature
- Sensitive to the slightest changes in sun position(O. Craig(2015))
- Unstable at wind speeds exceeding 10km/h (M. Abbker(1999))

2.3. Indirect solar cookers

Indirect solar cooker has no direct contact between solar incidence and cooker. In indirect type solar cookers, the pot is physically displaced from the collector and a heat transferring medium is required to convey the heat to the cooking pan. Solar cookers with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category (Haftom, 2014).

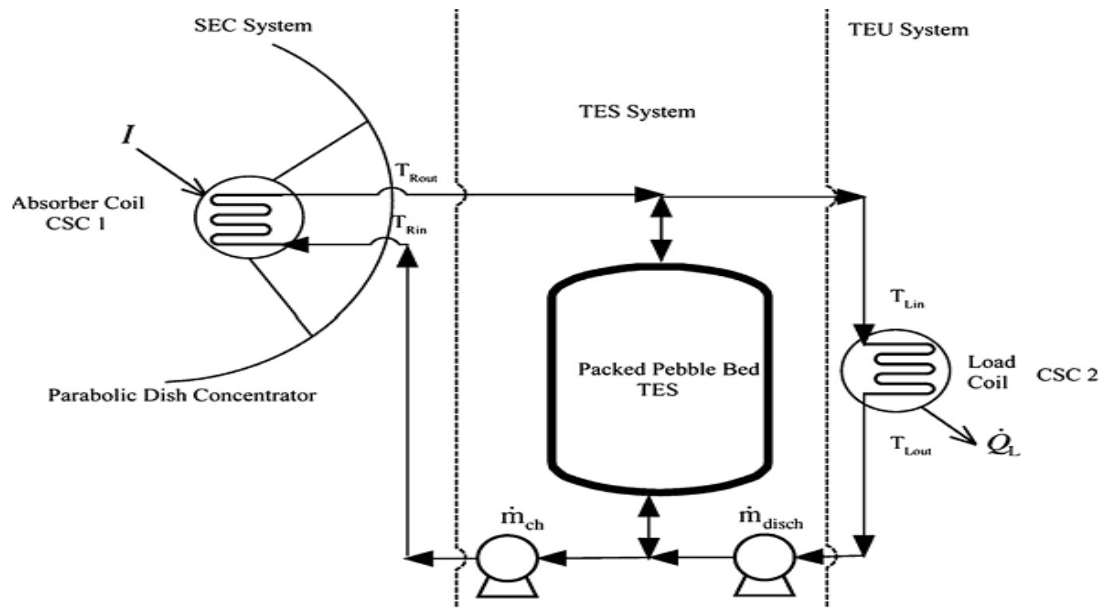


FIGURE 2-10: Conceptual diagram of the incident solar thermal energy storage and cooking system proposed and tested by Mawire et al.(2014)

Mawire et al (2014) presented Charging experiments to evaluate the thermal performance of three thermal energy storage oils for solar cookers. Energy and Exergy based thermal performance parameters are evaluated for the three thermal oils such as Sunflower Oil, Shell Thermia C and Shell Thermia B. They confirmed Sunflower oil performs better than the other thermal oils under different flow charging.

2.4. Solar Cookers with Thermal Storage

All solar cookers, as any solar powered system, can use thermal energy storage material to increase system performance. Specially, an indirect type solar cooker uses thermal storage as a common unit of the system. TES is also used in box type and other concentrator type solar cookers. The main objective of thermal storage usage for solar cooker is to hold extra amount of solar heat and to balance the heat usage over the day in daily variation or over the year for seasonally varying incident. That is by using storage materials which can hold large amounts of heat and radiate it slowly.

Many research works have been conducted with experiment by using different thermal heat storage materials. Cuce (2018) experimentally analyzed box type solar cookers with and without thermal energy storage within the scope of his research for characteristic continental climatic conditions of Bayburt, Turkey. He used bayburt stone, a special natural stone with low density and notably high specific heat capacity, to utilize as a sensible thermal energy storage medium in a cylindrical box type solar cooker and compared thermal performance

assessment of Bayburt stone cooker with a conventional cooker without thermal energy storage through a comprehensive experimental research and thermodynamic analysis. Energy efficiency of Bayburt stone cooker is found to be in the range of 35.3 –21.7% while it is 27.6 –16.9% for conventional solar cooker. Exergy efficiency of Bayburt stone cooker is calculated to be 21.2 –14.1% whereas it is 18.0 –11.6% for conventional cooker. Finally, he concluded from the results that Bayburt stone as a thermal energy storage medium remarkably improves the thermal performance figures of box type solar cookers.

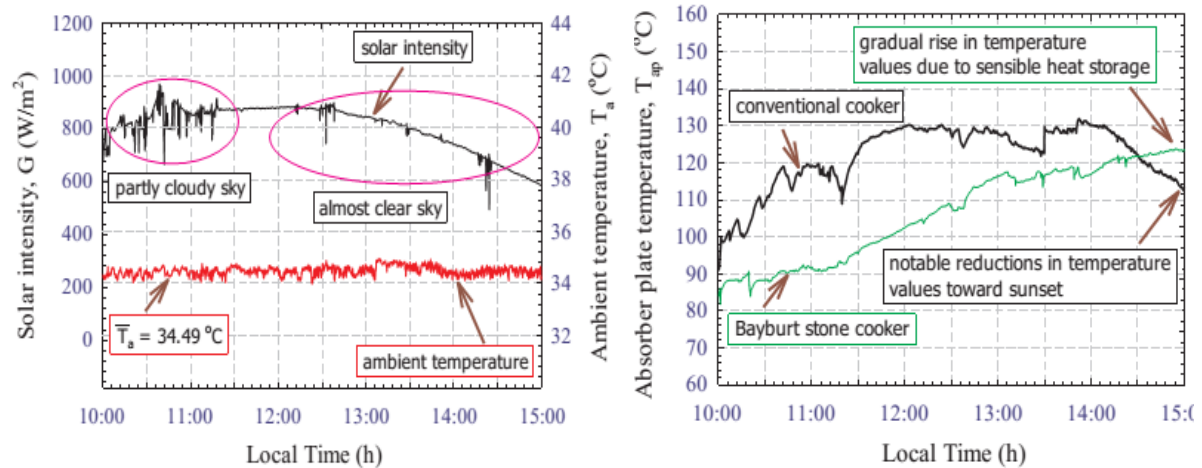


FIGURE 2-11: Absorber temperatures of conventional and Bayburt stone solar cooker. [19]

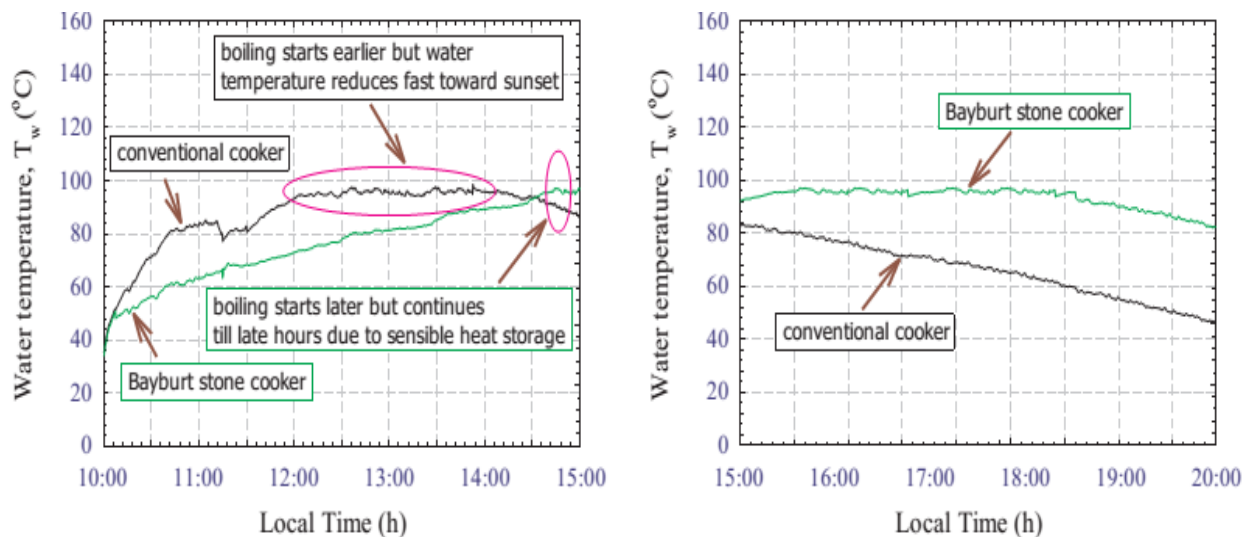


FIGURE 2-12 Water temperatures of conventional and Bayburt stone SC. [19]

Shrestha et al. (2007) investigated the effect of using stone pebbles as thermal energy storage. A thermal performance of box type solar cooker with stone pebbles inside the cooker was tested with methodology described in ASAE international test standard. For the comparison, the cooker was put to test without stone pebbles, with un-coated stone pebbles and with black

coated stone pebbles. The first figure of merit is higher when cooker is loaded with stone pebbles showing decreased heat loss. Further this figure is found larger for the test with black coated stone pebbles. Conversely, the second figure of merit is found to be smaller for the test with stone pebbles which describes the slower rate of increase of temperature. However, the temperature profile of water and stone pebbles indicated that the cooked food can be kept warm for long time with stone pebbles inside the cooker.

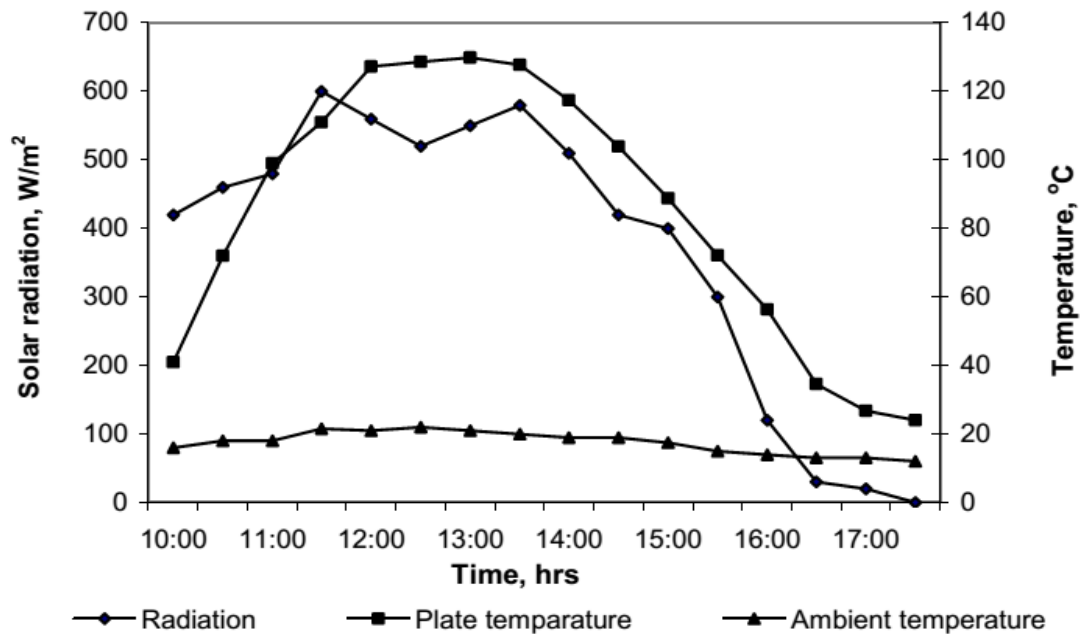


FIGURE 2-13 Plate Temperature without stone pebbles during no-load test [37]

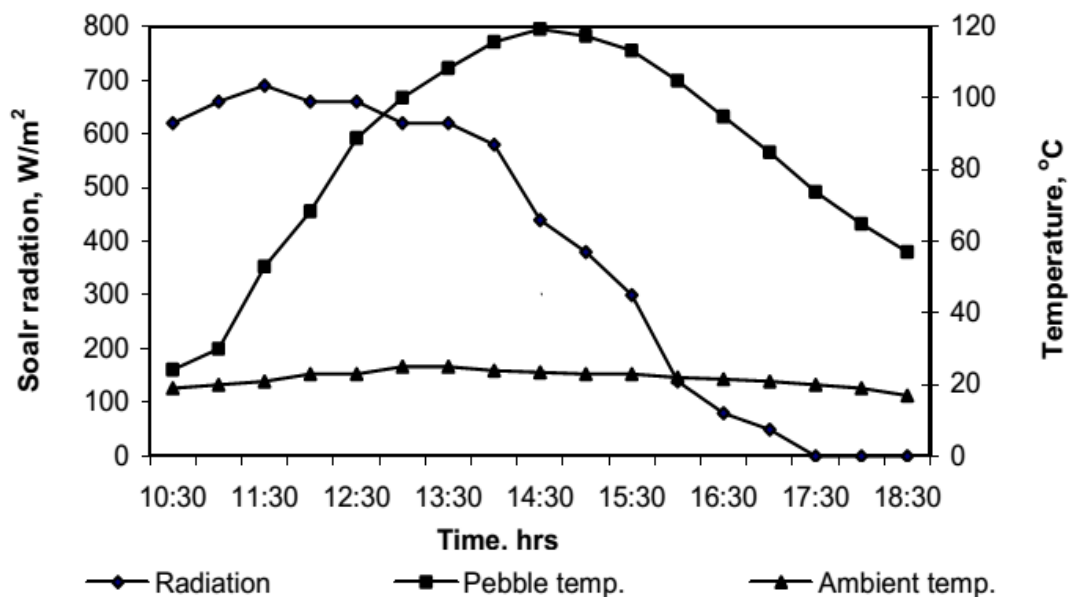


FIGURE 2-14: Temperature profile of black coated stone pebbles in no-load test [37]

2.5. Summary of Literature Review

In developing countries, like Ethiopia sunlight is unrivaled source of energy. In this thesis providing new design of solar cooker with locally available and low cost thermal heat storage material and finding out how it affect the solar cooker performance and for how long it can maintain a higher temperature inside a solar cooker using solar radiation are mainly focused area. That is aimed to divert people, living in remote location, from fire-wood powered oven to solar powered cooker. As explained in literature reviews above many researches have been taken with an intensive experimental and numerical investigation of box type solar cooker. However, still there is a wide research gap to fulfill societies need and to design socially acceptable solar cooker. One of those gaps concentrating box type solar cooker with integrated thermal energy storage for solar remote areas like daassanech is not studied numerically or experimentally; and using locally available insulations and construction materials are focused area in this study. Generally, in this thesis by starting from solar potential assessments, socially acceptable new box type solar cooker is designed, it is internally and externally concentrating type with sensible thermal heat storage, and experimental setup is fabricated for performance testing.

CHAPTER THREE

METHODS AND MATERIALS

To perform this research work four main methodologies have been employed; that are, overview of the prior related works, experimental tests, investigation of performance by using figures of merits then comparing the results of inverted improved box type solar cooker with inner and outer reflector and which has thermal storage, and conventional solar cooker with outer reflector finally surveying. Testing has performed by two ways stagnation testing and load testing (boiling of water and cooking tests). For developing prototype, low cost and locally available materials will be used. For portability confirmation, selected site community members allowed to try it and training carpenters, who can continue to producing in that area.

3.1. Description of the improved solar cooker

There are so many solar cookers have been designed. The construction costs and weights of the box type solar cooker vary widely. For every type of solar cookers, metal pan and absorber should be black. Because black makes sure, the incoming sunlight is absorbed and metal easily conducts the heat to the food inside the pan.

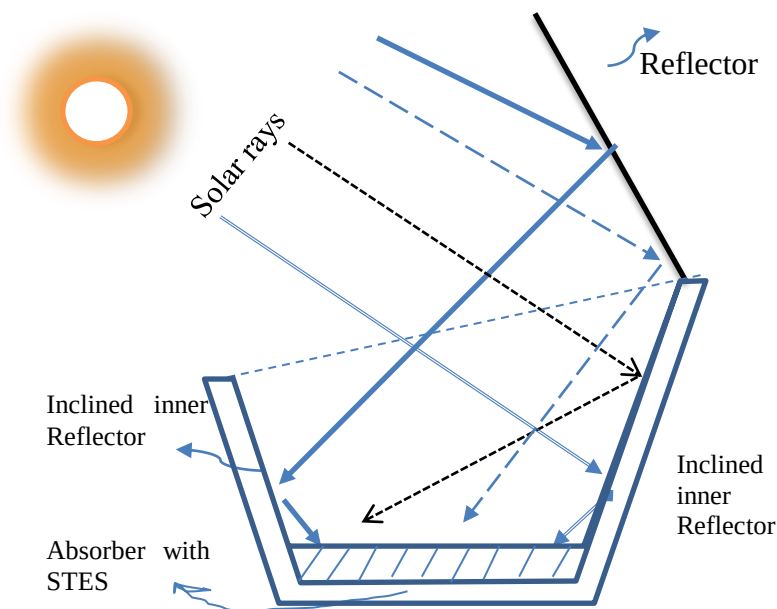


FIGURE 3-1: Schematic description of ISC with Solar rays reaching to absorber

The pretest assumption is improved solar cooker has better performance than commercial square box solar cooker. In addition, it has low cost and portable to cry. Its principle is internal and outer reflectors direct sunrays in addition to beam and diffuse solar energy to

absorber and it convert light energy with short wave length to heat that has large wave length. Then heat will transfer from absorber to the black color painted pan in the box. Thermal energy storage stores excess energy to discharge at evening.

3.2. Data collection

Solar energy data was collected from different websites and from National meteorology Agency of Ethiopia from South Nation Nationality Station (NMAE).

Website based solar radiation data were collected from:

1. Travel weather averages, <https://www.weatherbase.com/weather> ,
2. HelioClim-1 Database, <http://www.soda-is.com> , data provider is MINES ParisTech -Armines (France)
3. MERRA-2 meteorological data, <http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2> , data provider is National Aeronautics and Space Administration (NASA)/ Goddard Space Flight Center
4. HOMER energy, <http://www.homerpro.com>, as a resource of National Solar Radiation Database

Thermal property of thermal energy storage (TES) material was collected from review papers and density and specific heat capacity both are tested. Then the best material selection is based on its cost, availability and tested thermal properties.

3.3. Experimental Setup

Schematic figure described in FIGURE 3-2 is drawn by using SOLIDs work software.

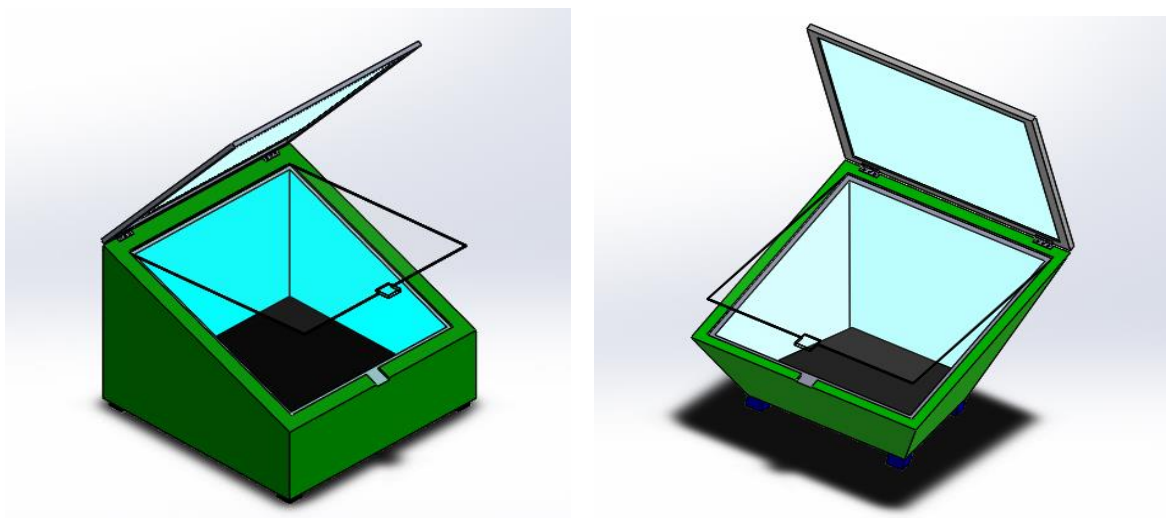


FIGURE 3-2: Conventional and Improved Solar cookers with equal aperture area



FIGURE 3-3: Experimental setup and during testing

As shown in figures above (FIGURE 3-2 and 3-3) both cookers have the same collector area but improved solar cooker has 5cm additional height to hold TES material and its absorber area is smaller than the conventional solar cooker.

In FIGURE 3-4 (a) four channel digital k-type thermocouple which is imported from India, and glass type mercury thermometer to measure ambient temperature (b) weight measuring instrument for TES and (c) two aluminum cooking pans that painted black color are described below. Thermocouple calibrated with lab standard K-type thermocouple as described in Appendix B.



FIGURE 3-4: Instruments used for measuring and two cooking pans

Performance of Conventional solar cooker both with the same absorber area and glazing (collector area) area with improved solar cooker has been analyzed numerically by Excel Microsoft software.

3.4. Testing Methodology

The frequently used and well accepted standard procedures for testing thermal performance of solar cookers are Indian standard which is based on test procedure proposed by Mullick et al. (1987) and American Society of Agricultural and Biological Engineers standards (ASAE S580 and S580.1) described by Funk (2013).

Indian Test procedure standard which is proposed by Mullick et al. (1987) and approved by BIS provides two figures of merit (F_1 and F_2) as thermal performance parameters for one specific design of solar cooker.

American Society of Agricultural and Biological Engineers standard (ASAE S580) is not as much as technically related to single design as BIS standard. ASAE S580 standard is dependent on uncontrolled variables like weather condition. Cooking power and standardized cooking power are the most important parameters in this standard. Cooking power is used to measure the cooker's ability for effectively heat food and standard cooking power is used for comparison of dates and locations. These parameters can be calculated as follows:

$$P = \frac{(mc_p)_w \Delta T_w}{600} \dots\dots\dots 3.1$$

$$P_S = \frac{P \cdot 700}{I_a} \dots\dots\dots 3.2$$

Where: (mc_p) the product of mass and specific heat of water (4186 J/kg K)

ΔT_w water temperature difference in 10 minute interval

I_a is average solar radiation during testing interval

3.5. Box type solar cooker model

The top loss coefficient $U_{t,j}$ can be calculated from the empirical equation by following the basic procedures of Hottel and woertz (1942), and klein (1975).

$$U_t = \left(\frac{N}{\frac{C(T_p - T_a)^e}{N+f} + \frac{1}{h_v}} \right)^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{(\varepsilon_p + 0.005591 \cdot N \cdot h_v)^{-1} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \dots\dots\dots 3.3$$

Where: $f = (1 + 0.089hw - 0.11 * hw * \varepsilon_p)(1 + 0.07866 * N)$

$$C = 520(1 - 0.000051 * \beta^2)$$

$$e = 0.430(1 - 100/T_{pm})$$

$$\varepsilon_g = 0.88(\text{Emittance of glass})$$

$$hv = 2.8 + (3 * V_{wind})$$

ε_p is Emittance of plate, v_w speed of wind,

N is number of glazing, β is absorber slope

The plate temperature at any time $(t+\Delta t)$ can be obtained from energy balance of absorbed by and loss from the cooker chamber.

$$mC_p \frac{dT_p}{dt} = A_c I_c - A_c U_t(T_p - T_a) - A_e U_{pae}(T_p - T_a) - A_{pot} U_{pw}(T_p - T_w) - A_b U_{pb}(T_p - T_a)$$

$$T_p = \frac{A_c I_c \Delta t}{mC_p} + \left[1 - \left(\frac{A_c U_{pt} + A_e U_{pae} + A_b U_{pb}}{mC_p} \right) \Delta t \right] T_p^0 + \left[\frac{A_b U_{pab} + A_e U_{pae} + A_c U_{pa}}{mC_p} \right] T_a \Delta t \dots\dots\dots 3.4$$

Steady state Water temperature profile can be calculated from energy balance of water in the pot.

$$A_c I_c = A_c U_t(T_p - T_a) + A_b U_{pb}(T_p - T_a) + A_e U_{pae}(T_p - T_a) + A_w U_{pw}(T_p - T_w)$$

$$T_w = \frac{A_c I_c \Delta t}{A_w U_{pw}} + \left[\frac{A_c U_{pt}}{A_w U_{pw}} + \frac{A_e U_{pae}}{A_w U_{pw}} + \frac{A_b U_{pb}}{A_w U_{pw}} \right] (T_{pm} - T_a) + T_{pm} \dots\dots\dots 3.5$$

3.6. Performance Analysis

3.6.1. Figures of Merit

Two figures of merit (First and second figures of merit) are provided from Indian standard.

First figure of merit is based on a stagnation test cooker box without any load.

$$F_1 = \frac{T_p - T_a}{H_s} \dots\dots\dots 3.6$$

Second figure of merit is computes from a load test that follow water boiling test procedure for the thermal performance evaluation of a solar cooker.

$$F_2 = \frac{F_1(mc)_w}{A \cdot t} \ln \frac{1 - \frac{1}{F_1} \left[\frac{T_{w1} - T_a}{H} \right]}{1 - \frac{1}{F_1} \left[\frac{T_{w2} - T_a}{H} \right]} \dots\dots\dots 3.7$$

According to (Jagan and Madhu, 2007) for a good design solar box cooker, the first figure of merit (F1) should be at the range of 0.12 – 0.16 and the second figure of merit (F2) should be above 0.254.

For a known value of average F_2 , the time required for a temperature rise from ambient to boiling or specific temperature in this case 95°C, T_{w2} , may be evaluated (Mullick et al., 1987) assuming quasi-steady-state conditions by the following equation:

$$\Delta\tau = \frac{(MC)_w(T_{w2} - T_a)}{AF_2 \left(H - \frac{1}{F_1} (T_{w1} - T_a) \right)} \dots\dots\dots 3.8$$

3.6.2. Based on Thermodynamics

Thermodynamic analyses provide another way to evaluating and comparing solar cooker. Such as by calculating efficiencies of solar cooker based on law of thermodynamics.

1) Based on first law of thermodynamics

Energy efficiency of the solar cooker can be defined as the ratio of the output Energy (gained by solar cooker) to the input solar radiation Energy. Energy efficiency is given as:

$$\eta = \frac{\text{Energy output}}{\text{Energy input}} = \frac{(mc_p)_w [T_{wf} - T_{wi}]}{I \cdot \Delta t \cdot A_{sc}} \dots\dots\dots 3.9$$

2) Based on second law of thermodynamics

Yettou et al. (2013) have discussed about second law analysis to assess the thermal performances of solar cookers. And he provided one additional parameter that is Exergy efficiency. Exergy efficiency of the solar cooker is defined as the ratio of the output Exergy (gained by solar cooker) to the input Exergy (Exergy of the solar radiation). It is given as:

$$\Psi = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{(mc_p)_w [(T_{wf} - T_{wi}) - T_{ra} \ln(T_{wf}/T_{wi})]}{I_b \cdot \Delta t \left[1 - \left(\frac{T_a}{3T_s} \right) \right] A_{sc}} \dots\dots\dots 3.10$$

Where: T_{ra} is the reference-ambient temperature during the given time interval.

T_s is Surface temperature of the sun (K)

T_o is Output temperature

A_{sc} is the incident area of the solar cooker

3.7. Solar Potential Estimation

Detail data about solar radiation is the main input in designing of photovoltaic and solar collector thermal systems, even in building designing and agroindustry processes solar radiation data is very important (Dlamini et al., 2017). Unfortunately in developing countries like Ethiopia there are no as much as enough technological instruments to conduct detail meteorology related measurements including solar radiation. So to overcome this problem, different analytical models have been assessed and developed to estimate solar radiation in different parts of the world by using geographical data and simple meteorological data by using air Temperature such as in Swaziland (Dlamini et al., 2017), by using sunshine hour such as in USA (Allen, 1997), Nigeria (Umoh, 2013) and etc. In fully organized meteorological agencies all meteorological parameters such as temperature, atmospheric pressure, relative humidity, the number of sunshine hours, wind speed, cloud cover, and rainfall are available. But in developing countries some of meteorological parameters may not be available for specific locations.

As an initial point in solar energy estimation for thermal system designing, one should have knowledge about extraterrestrial solar radiation; it depends on solar constant, geographical location, solar hour angle and day of the year. Solar constant is solar insolation outside the earth atmosphere. After many revised measurements NASA was indicated the value of the solar constant to be 1353 W/m^2 , recently well-known frequently used value of solar constant is 1367 W/m^2 .

Since the earth's orbit is elliptical, the earth–sun distance varies during a year, Therefore, the extraterrestrial radiation, I_o , also varies by the inverse square law, ^[27]

$$I_o = I_{sc} \left(\frac{D_o}{D} \right)^2$$

$$\begin{aligned} (D_o/D)^2 = & 1.00011 + 0.034221\cos X + 0.00128\sin X + 0.000719\cos 2X \\ & + 0.000077\sin 2X \end{aligned}$$

Where, $X = 360(n - 1)/365$, n is day number

Then it is approximated without significant accuracy loss to: ^[27]

$$I_N = I_{sc} \left[1 + 0.034 \cos \left(\frac{360n}{365.25} \right)^0 \right]$$

Extraterrestrial radiation incident on horizontal surface is the product of extraterrestrial radiation incident normal to horizontal surface and zenith angle.

$$I_o = I_{sc} \left[1 + 0.034 \cos \left(\frac{360n}{365.25} \right)^o \right] (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) \dots\dots 3.11$$

By integrating the above equation in terms of solar time angle, daily extraterrestrial solar radiation outside the atmosphere (H_o) can be derived that is known as Klein relationship:

$$H_o = \frac{24 \times 3600 I_{sc}}{365} \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \left(\cos \phi \cos \delta \sin \omega_s + \frac{\pi \omega_s}{180} \sin \phi \sin \delta \right) \dots\dots\dots 3.12$$

3.7.1. Fundamental angles of sun with earth

Fundamental angles of sun are hour angle, latitude, and declination. Other angles like solar incidence, azimuth and etc. must be related to these fundamental angular quantities ^[28].

Latitude (ϕ) is the angular geographical location that made in between the line joining location with center of the earth and its projection equatorial plane. Northern hemisphere is positive $-90^\circ \leq \phi \leq 90^\circ$ ^[25].

Declination (δ): The declination (δ) for each day of the year can be found from the equation of Cooper (1969) as cited by Duffie (2006): ^[28]

$$\delta = 23.45 \sin \left(\frac{360}{365} (284 + n) \right) \dots\dots\dots 3.13$$

Where, n is number of the day between (1 to 365)

Equation Spencer (1971) as cited by Duffie (2006):

$$\delta = \left(\frac{180}{\pi} \right) (0.006918 - 0.399912 \cos B + 0.070257 \sin B - 0.006758 \cos 2B + 0.000907 \sin 2B - 0.002697 \cos 3B + 0.00148 \sin 3B) \dots\dots\dots 3.14$$

The value of B given by, $B = (n - 1) \frac{360}{365}$

But for engineering calculation, simple equation with sufficient accuracy can be chosen. The maximum rate of change of declination is about 0.4° per day [28].

Sunset hour angle (ω_s) is a solar hour angle at zenith angle of 90° that is corresponding to a sunset solar time. By substituting $\omega = \omega_s = 90^\circ$ in to equation of $(\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta)$,

$$\cos \omega s = -\tan \varphi \tan \delta \dots\dots\dots 3.15$$

Solar time: - is a reckoning of the passage of time with reference to the position of the Sun in the sky, which has the fundamental unit of a day [25].

$$\text{Solar time} - \text{standard time} = 4(L_{st} - L_{loc}) + E$$

$$E = 229.2 (0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B)$$

The value of B given by, $B = (n - 1) \frac{360}{365}$

Where, n is the number of the given day in the year.

3.7.2. Geographic coordinates of selected site

Latitude: 4°49'59" or 4.83333° N

Longitude: 36°06'00" or 36.10° E

Elevation above sea level: 367 m or 1204 ft.

Geographical Location of Nairobi: -1°17'S, 36°49'E (To use this for solar time determination. Solar time in Daassanech (Omorate) and local time based on Nairobi location has 0.07 up to 17.9 minute differences depending on the day number of the year.)

3.7.3. Monthly average Daily solar radiation estimation

3.7.3.1. Global monthly average daily radiation

In Ethiopia sunshine data based solar energy estimation has been used frequently in different researches for solar radiation energy estimation and for designing purpose of solar system.

Neway (1996) estimated solar radiation energy on a horizontal surface, for nine meteorological stations in Ethiopia. He computed solar radiation by using sunshine data based on Ångström relations and compared with their corresponding global solar radiation on a horizontal surface values; he also obtained Regression coefficients and determined correlation equations to predict the global solar radiation. He explained based on the results, Ångström relations are valid for Ethiopian locations, and the correlation equations can be used to predict the monthly mean daily global solar radiation in the locations considered in the study.

Addisu et al (2013) was estimated solar radiation by using sunshine data of the different sites based on well-known Angström model which was modified latter by Prescott (1940) and Page (1961) for his successfully designed large scale solar water heating system in Ethiopia.

The Angström-prescott model between sunshine duration and the amount of global solar radiation is as follows:

$$\frac{H}{H_o} = a + b \frac{n_s}{N} \dots\dots\dots 3.16$$

Where H is the daily total amount of global solar radiation at the ground surface, H_o is the daily total amount of global solar radiation outside the atmosphere, n is the sunshine duration, N is the maximum possible sunshine duration, and a and b are constants

$$a = -0.110 + 0.235 \cos \varphi + 0.323 \left[\frac{n_s}{N} \right]$$

$$b = 1.449 - 0.533 \cos \varphi - 0.694 \left[\frac{n_s}{N} \right]$$

Average days for each month are January 17, February 16, March 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14 and December 10

3.7.3.2. Diffuse monthly average daily radiation

Diffuse solar radiation is solar radiation which reaching the earths' surface after scattered in the atmosphere. Prediction of monthly average daily diffuse radiation on a horizontal surface (H_d) can be given as

$$H_d = H \left[0.931 - 0.814 \left(\frac{n_s}{N_s} \right) \right]$$

3.7.3.3. Beam monthly average daily radiation

Beam solar radiation is direct solar radiation which reaching the earths' surface without scattering in the atmosphere. Monthly average daily beam radiation on a horizontal surface (H_b) is the difference between global and diffuse monthly daily average radiation.

$$H_b = H - H_d$$

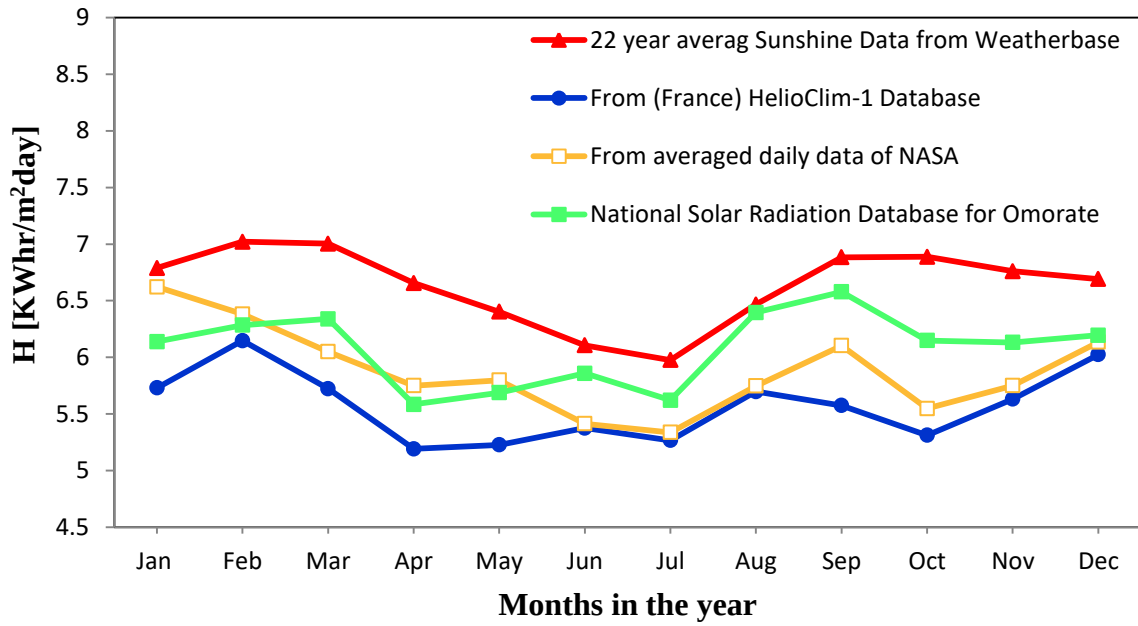


FIGURE 3-5: solar radiation obtained from different data sources

Sunshine data is used to single out the radiation components in the global solar radiation, so it should be calculated from averaged solar radiation. From averaged global solar radiation, the ratio of measured average sunshine to possible maximum sunshine (n_s/N) can be calculated as follows:

Let us assume, ($x = \frac{n_s}{N}$) to substitute in the Ångström relations.

$$\frac{H}{H_o} = [-0.11 + 0.235 \cos(\varphi) + 0.323x] + [1.449 - 0.533 \cos(\varphi) - 0.694x]x$$

$$\frac{H}{H_o} = [-0.11 + 0.235 \cos(\varphi)] + [0.323 + 1.449 - 0.533 \cos(\varphi)]x - 0.694x^2$$

$$-0.694x^2 + [0.323 + 1.449 - 0.533 \cos(\varphi)]x + \left[0.235 \cos(\varphi) - \frac{Ha}{H_o} - 0.11\right] = 0$$

$$-0.694x^2 + 1.241x + \left[0.1242 - \frac{Ha}{H_o}\right] = 0$$

In Quadratic equation form: $ax^2 + bx + c = 0$

The solution for quadratic equation: $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

3.7.4. Monthly average hourly solar radiation estimation

3.7.4.1. Global hourly solar radiation estimation

Prediction of monthly average hourly global radiation on a horizontal surfaces (I)

$$I = \frac{H\pi}{24} (a + b\cos\omega) \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s \cos\omega_s} \dots\dots\dots 3.17$$

$$\text{Where, } a = 0.409 + 0.5016 \sin(\omega_s - 60)$$

$$b = 0.6609 - 0.4767 \sin(\omega_s - 60)$$

3.7.4.2. Diffuse hourly solar radiation estimation

Prediction of monthly average hourly diffuse radiation on a horizontal surfaces (I_d)

$$I_d = \frac{H_d\pi}{24} \frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi}{180}\omega_s \cos\omega_s} \dots\dots\dots 3.18$$

3.7.4.3. Beam hourly solar radiation estimation

Estimation of monthly average hourly beam radiation on a horizontal surfaces (I_b)

$$I_b = I - I_d \dots\dots\dots 3.19$$

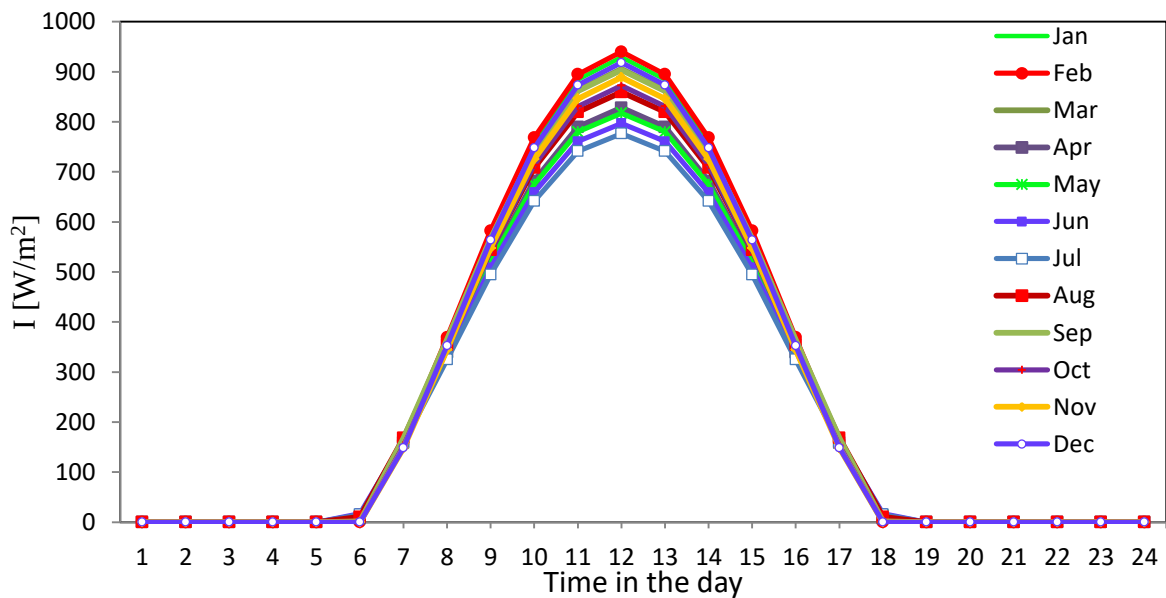


FIGURE 3-6: Monthly Average Hourly Global Radiation on Horizontal surface

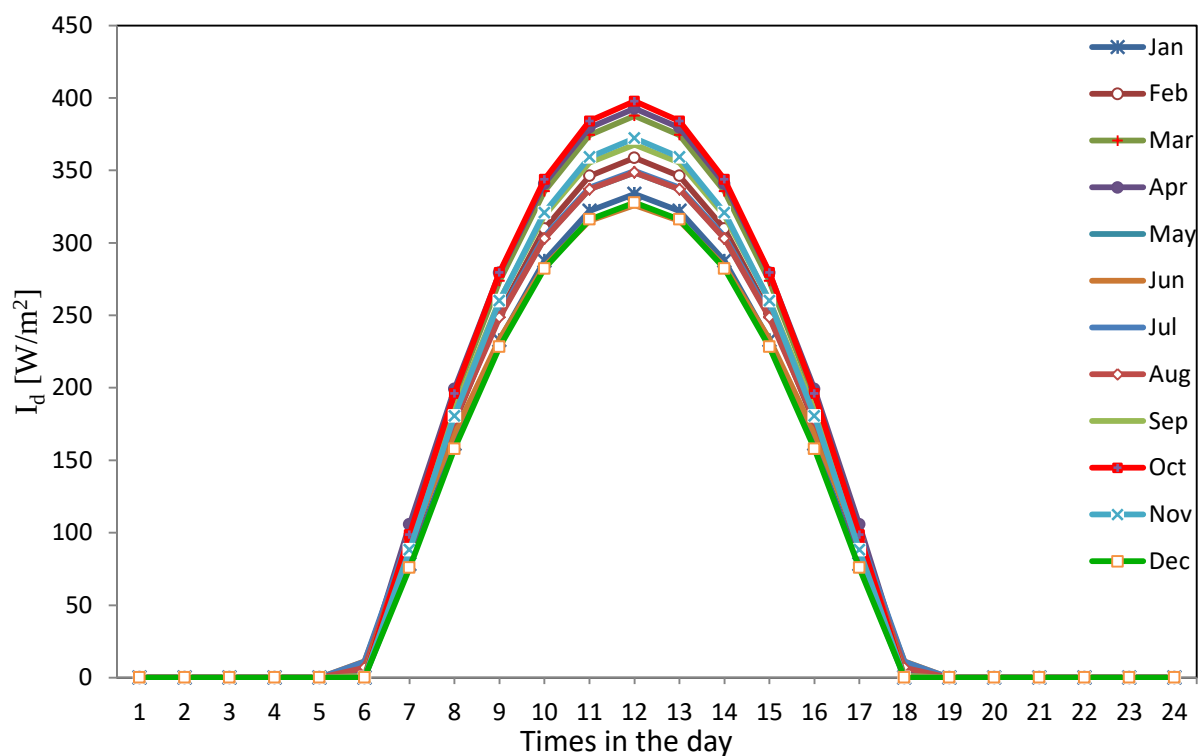


FIGURE 3-7: Monthly Average Hourly Diffuse Radiation on Horizontal surface

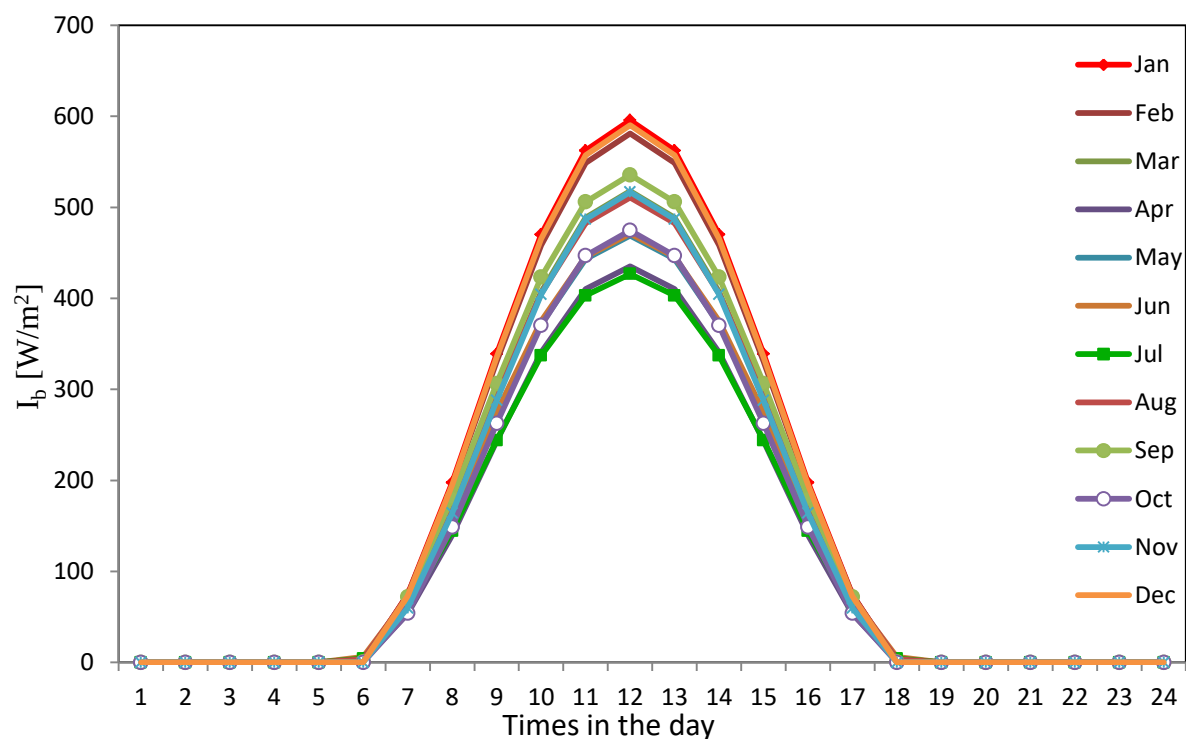
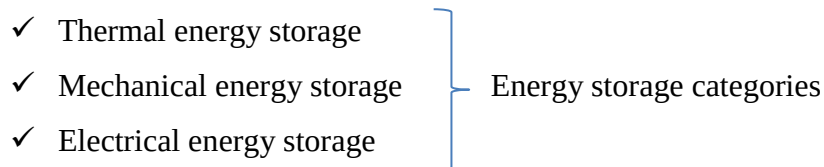


FIGURE 3-8: Monthly Average Hourly Direct Radiation on Horizontal surface

3.8. Thermal Energy storage

Thermal energy storage is one of energy storage categories such as mechanical energy storage and electrical energy storage, it store thermal energy by raising or lowering the temperature of a substance (i.e., altering its sensible heat), by changing the phase of a substance (i.e., altering its latent heat) or by reversible chemical reactions. [25, 26] As thousands of different TES materials are known and are developing every year, researchers recommend that developed materials should be looked at, to better efficiency if it used in thermal energy storage. The number of available materials is more than 150,000 with more appearing every year [Fernández et al. (2018)].



Today solar energy as an energy source had become a most promising alternative renewable energy to meet highly developing energy need in the world. It is clean (no air pollution issue), cheap, abundant, no noise problem, no transportation need and easy to be obtained anywhere in the earth.^[25,26] Inside the core of the Sun, hydrogen fuses into helium with a rate of 7×10^{11} kg/s and generates very powerful nucleation power. This type of nucleation explosion creates ultra-high temperature in the core of the Sun, which reaches approximately 16 million Kelvin degrees. Although the Sun is not perfectly black body, it still radiates abundant power with the energy density as 1.6×10^7 watts/m². Out of this high power only 1360W/m² finally reaches the upmost surface of the earth.

However solar energy is clean high potential energy, its supply is dependent on time of the day and season through the year. To overcome this limitation, absorbed energy can be stored in the thermal energy storage materials. This improves also thermal energy systems performance by smoothing supply and increasing reliability. Thermal energy storage that is possible to store solar energy is classified as sensible, latent and thermo-chemical thermal energy storage.

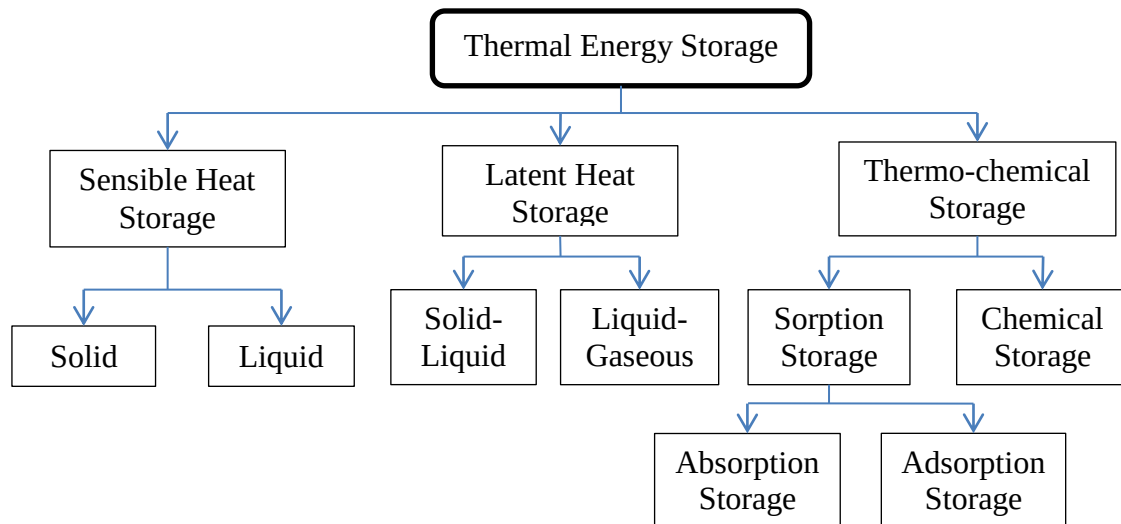


FIGURE 3-9: Classification Thermal energy storage [26]

3.8.1. Sensible thermal energy storage

Sensible thermal energy storage stores thermal energy by raising material temperature, so stored sensible heat amount is dependent on material density, its specific heat capacity and temperature difference.

$$Q_{sensible} = m \int_{T_L}^{T_H} C_p(T) dT \dots\dots\dots 3.20$$

Where m is the mass of storage material, T_L and T_H are low temperature and high temperature in the same phase, respectively, $C_p(T)$ is the specific heat capacity at different temperature.

So many sensible storage materials have been studied in different countries. Out of those frequently used low cost sensible thermal storage materials are stone, sand, clay, solid salt, water, molten salt, used engine oil and etc.

Water as a thermal energy storage medium has high heat capacity and good thermal conductivity it is available everywhere and cheap in cost. But its limitation is it can't be applicable as sensible storage for more than 100°C temperature and it need to be pressurized.

Rock also can be a good thermal energy storage material although it has low specific heat capacity relative to water, its cheap cost and availability in everywhere made it practical in thermal storage system. Stones can be easily applicable for above 100°C. water with rock and air with rock is common thermal storage system in solar water heating and solar space heating systems.

3.8.2. Latent thermal energy storage

Latent thermal energy storage stores thermal energy by changing the phase of a substance from solid to liquid or from liquid to gaseous state.

$$Q_{latent} = m \int_T^{T_{mp}} C_p(T) dT + m \Delta H_{fusion} + m \int_{T_{mp}}^{T_h} C_p(T) dT \quad \dots\dots\dots 3.21$$

Where T is temperature in solid state, T_{mp} is melting point of storage material, T_h is the high temperature in liquid state and ΔH_{fusion} is enthalpy of fusion.

So many solar cookers have been experimentally and theoretically studied with latent heat storage material in the world such as Stearic acid or magnesium nitrate hexa-hydrate (Domaski, Elsebaim and Jeworki, (1995)), commercial grade acetamide (Sharma et al. 2000, Buddhi, Sharma and Sharma (2003)), paraffin wax (Arabacigil, , et al.(2015)) and so on.

3.8.3. Thermo-chemical energy storage

Thermo-chemical energy storage stores energy as the heat of reaction in reversible chemical reactions. When storage material absorbs heat energy, endothermic reaction begins to occur then stores the heat and in the reverse action it releases the heat by exothermic reaction. [27]

$$Q_{tc} = m \int_{T_L}^{T_R} C_p(T) dT + m \Delta H_{Reaction} + m \int_{T_R}^{T_H} C_p(T) dT \quad \dots\dots\dots 3.22$$

Where T_R is the reaction temperature and $\Delta H_{reaction}$ is the enthalpy of chemical reaction.

3.8.4. Thermal performances of thermal energy storage

Thermal performances of thermal energy storage such as charging and discharging times, thermal distribution, energy storage capacity and energy efficiency have studied experimentally and the best one have been selected.

3.8.4.1. Charging and discharging time

Charging time is the time taken to store enough thermal energy from sun available time to cook or warm food at evening. The amount of stored energy is dependent on the capacity and volume of the material, and charging rate is depends on thermal distribution of the storage volume. Charging rate of low conductivity material is slow, due to small thermal diffusivity.

Discharging time is time taken to release complete stored energy from storage medium. That is by achieving a volume average temperature of T_{inlet} . But after a certain time, the decrease

in storage medium, temperature is not significant particularly when its temperature becoming near to T_{inlet} . In this way, effective discharging time of storage material is taken as the time till the temperature drop is significant.

3.8.4.2. Porosity of the rocks

The porosity of the material, ε , is the free space that is filling with air in a solid storage material. It can be given as the ratio of the volume of space gap (V_f) to the total volume of storage material (V_o).

$$\varepsilon = \frac{V_f}{V_o}3.23$$

3.8.4.3. Thermal distribution

Thermal diffusivity is the rate of thermal conductivity to the thermal storing capacity of the storing material. Thermal distribution is highly dependent on the material thermal diffusivity. The large value of the thermal diffusivity represents the faster the propagation of heat into the medium. A small value of thermal diffusivity means that most of heat is absorbed by the storage material and a small amount of heat will be conducted further (Cengel, 2003, pp 382).

$$\alpha = \frac{\text{heat conducted}}{\text{heat stored}} = \frac{k}{\rho \cdot c_p}3.24$$

3.8.5. Specific heat storage capacity

Sensible thermal storage stores sensible thermal energy only by temperature difference. Its storing capacity is dependent on thermal heat capacity ($\rho \cdot c_p$) of the volume of storing material.

$$Q = mc_p\Delta T = \rho c_p V \Delta T3.25$$

Where, c_p is the specific heat of the material, ΔT is the temperature difference,

V is the total volume of the storage material, and

ρ is the density of the storage material.

Specific heat capacity of storage material can be calculated easily, since the specific heat capacity of water (C_p), the mass of storage material (m_s), the mass of water (m), and the temperature differences (ΔT , ΔT_s), are all known or can be measurable. The energy lost from the water to storage material can be calculated and it must be equal to the energy gained by

the storage material, if there are inconsiderable losses to the environment (water and storage should be in well insulated pot). So the specific heat capacity of the storage material can be calculated from:

$$(m * Cp)_w * \Delta T = (m * Cp)_s * \Delta T_s$$
$$Cp_s = \frac{(m * Cp)_w * \Delta T}{m * \Delta T_s} \dots\dots\dots 3.26$$

3.8.6. Energy efficiency

Storage efficiency is the ratio of energy output to energy input. It represents the heat losses to the surroundings.

$$\eta = \frac{E_{dis}}{E_{char}} \dots\dots\dots 3.27$$

3.8.7. Thermal energy storage material selection

TABLE 3-1: Thermal property of some of engineering materials

Material	Temperature Range (°C)	Density ρ (kg/m ³)	Specific Heat c_p (J/kg°C)	Energy Density (kJ/m °C)
Aluminum	Max. 660 (melting pt)	2700	920	2484
Brick	-	1969	921	1813
Concrete	-	2305	920	2122
Fireclay	-	2200	1000	2200
Granite	-	2400	790	1896
Oak	-	769	2385	1833
Pine	-	496	2803	1391
Taconite		3200	800	2560
Water	0 – 100	1000	4190	4190

(Source: Engineering toolbox website)

So many types of materials have been studied before this study in many different countries some of those materials have described in above table. But to make solar cooker with storage familiar to developing countries rural community, it should be made of locally available materials, low cost and should be safe to use. So by considering the above, storage material and construction material should be select.

3.8.8. Selection criteria

There are important selection methodologies to select storage materials for large scale thermal storage materials. Those studied methodologies can also be applicable for small scale storage materials selection. The material must be inexpensive and have a good thermal capacity factor. Another important parameter in TES is the rate at which heat can be released and extracted. [Gunerhan, 2005]

The size of the storage material is one important parameter within the design of the thermal storage system ^[36]. For this thesis amount of the storage material is must be enough to store the energy greater than the amount of energy that is required to raise or keep warm 2kg of water above 60°C at least once after charging.

$$Q = m_w * C_{p_w} * \Delta T_{\infty-95^\circ C} = m_s * C_{p_s} * \Delta T_{max-min}$$

The size is dependent on the volume of storage material and volume can be determined from mass of storage material and its density. Mass of storage material can be obtained from required energy by using energy balance equation.

$$m_s = \frac{Q}{(C_{p_s} * \Delta T_{max})} = \frac{m_w * C_{p_w} * \Delta T_{\infty-95^\circ C}}{(C_{p_s} * \Delta T_{max})}$$

Where: m_w = mass of water, C_p = specific heat capacity of water

In this research paper five inexpensive, easy to use and locally available solid and liquid materials have been selected. Such as sand, concrete, clay (rammed soil), black stone and used engine oil the best storage material will select after study with relatively higher heat capacity, good thermal conductivity and relatively low cost.

Very important properties of the storage materials that should be tested are the thermal conductivity k , the specific heat capacity C_p , and the density ρ . Good thermal conductivity for storage material is higher than 0.3 W/m·K [Fernández et al., (2018)].

3.8.8.1. Desert Sand

TABLE 3-2: physical properties of desert sand

Properties	Literature (Saxena, 2017)	Water property
Density(kg/m ³)	1450	1000
Thermal conductivity (W/m K)	0.26	0.6
Specific heat (J/kg K)	800	4.20
Thermal diffusivity (10 ⁶ m ² /s)	0.35	0.143

3.8.8.2. Shiny basalt stone (Black Stone)

Gunerhan et al. (2005) studied thermal property of the Basalt stone at 20°C in Dokuz Eylul University, Izmir, Turkey. After testing he got the following results.

TABLE 3-3: physical properties of Shiny basalt stone

Properties	Literature (Gunerhan et al., 2005)	Tested
Density(kg/m ³)	2800	2660
Thermal conductivity (W/m K)	1.513	-
Specific heat (J/kg K)	1500	1534
Thermal diffusivity (10 ⁶ m ² /s)	0.36	-

3.8.8.3. Clay (rammed soil)

According to Melkamu (2013) thermal properties of fire clay that is pressed to make Ethiopian clay plate ‘mitad’ are:

TABLE 3-4: Physical properties of clay

Properties	Literature (Melkamu (2013))	Tested
Density(kg/m ³)	2400	2300
Thermal conductivity (W/m K)	1.32	-
Specific heat (J/kg K)	800	856
Thermal diffusivity (10 ⁶ m ² /s)	0.6875	-

3.8.8.4. Used engine oil

This fluid has been used in small scale thermal storage system in the different countries [24]. But in Ethiopia it has no more significant use after removed from the engine. So it can be easily got in urban area.

TABLE 3-5: Engine oil property at 300K

Properties	Literature (Kakaç and Yener, 1995)
Density(kg/m ³)	884.2
Thermal conductivity (W/m K)	0.144
Specific heat (J/kg K)	1910
Thermal diffusivity (10 ⁸ m ² /s)	8.53

3.8.8.5. Concrete

TABLE 3-6: physical properties of concrete

Properties	Literature (ACI Committee Report)	Tested
Density(kg/m ³)	2305	2350
Thermal conductivity (W/m K)	1.2	-
Specific heat (J/kg K)	920	894

Thermal conductivity has not tested for all storage materials only density and specific heat capacity had been tested. Storage materials which have thermal conductivity value less than 0.3 W/m k such as sand and engine oil are not good enough for thermal storage purpose. So they were not selected to test experimentally. 6.25 kg black stone 7.1 kg concrete have been used as storage materials. Specific heat capacity and density were calculated as described in section 3.8.4.

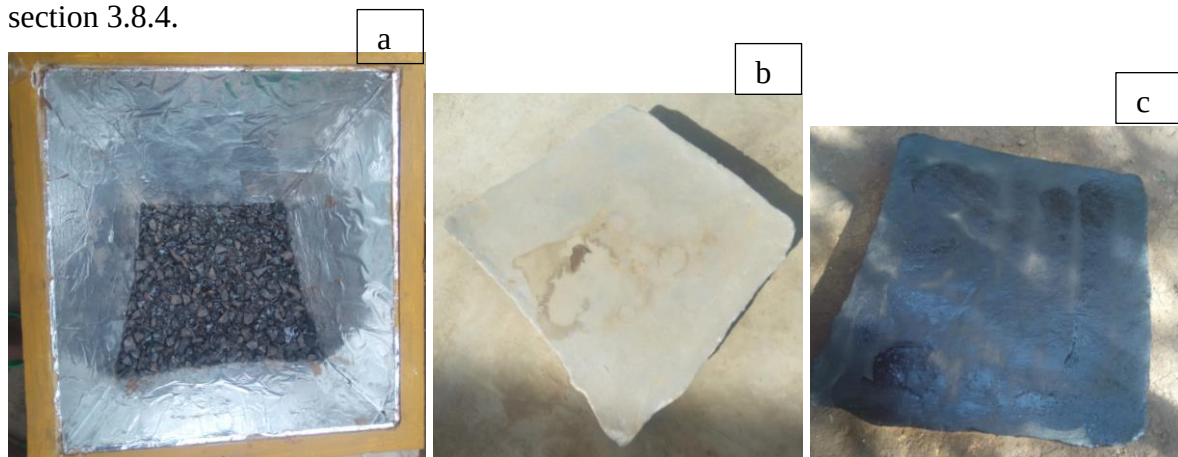


FIGURE 3-10: Storage materials a) Black stone b) concrete c) black painted concrete

3.9. Design of Box Type Solar Cooker

To design solar box cooker, different solar angles must be considered well. Sunset and sunrise solar time angle and incidence angle specially the most important angles in designing solar thermal systems, to obtain adequate Energy to cook traditional foods.

Angle of incidence, θ , is the angle which sunrays (incident radiation) makes with the vertical to inclined solar receiver surface at a given latitude, φ , Incidence angle, θ , is given by: [25, 26]

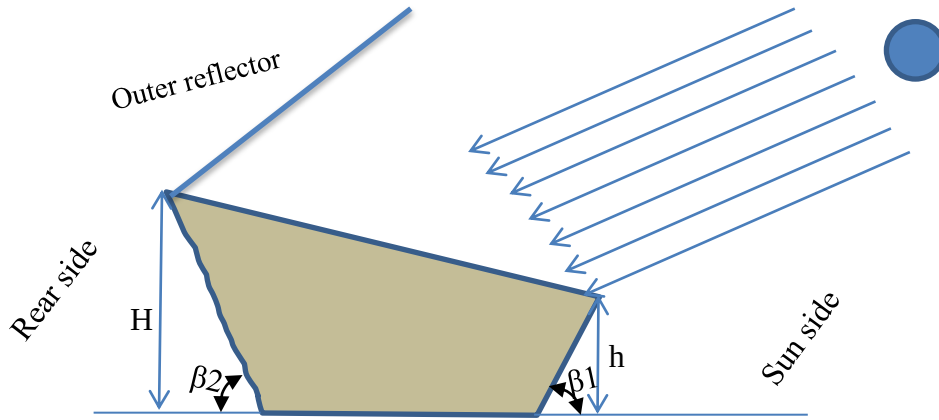
$$\cos \theta = (\cos \varphi \cos \beta + \sin \varphi \sin \beta \cos \delta) \cos \delta \cos \omega + \cos \delta \sin \omega \sin \beta \sin \gamma + \sin \delta (\sin \varphi \cos \beta - \cos \varphi \sin \beta \cos \gamma)$$

Zenith angle, θ_z , is angle of incidence in the horizontal plane $\beta=0$, it can be written as:

$$\cos \theta_z = \cos \varphi \cos \delta \cos \omega + \sin \delta \sin \varphi$$

Where, β is the angle of surface inclination

δ is an angle of declination of the sun



The main advantages of utilizing inclined cover in a sunlight based box cooker is the absorption of a higher portion of incident solar radiation falling on the aperture at larger incidence angles, because of an increasingly a more exposed surface region. To reduce the blocking effect of sun rays by the sun side inclined surface, the inclination angles should be related with angle of incidence and its height should be considered.

Outer reflector

- Is flexible to track with sun ray
- Its area is equal with glazing cover area

As Claude *et al.* (2012) explained box solar cookers with reflectors can be positioned toward the morning or afternoon sun to do the cooking at those times of day. Solar box cookers used with reflectors in the temperate zones do operate at higher temperatures if the box is repositioned to face the sun at short time interval.

Fixed inner reflector angle

- ✓ Direct all the rays that passed through cover glass from sun and outer mirror to the absorber plate.

Collector area and intercept area of conventional cooker should be the same. So it can be calculated by using conventional box solar cooker with sun facing reflector.

3.9.1. Adequate Energy to cook traditional foods

In Daassanech frequently preparing traditional foods are possible to prepare by using solar cooker. Just to introduce some of them, Shoforo is well known traditional drink and ‘Curcufa’ is food preparing for daily consumption.

‘Shoforo’ is a marvelous cultural hot drink in daassanech; it is a broth of coffee husk, made by infusing coffee husk in boiling water to cook it, then by extracting its broth. It is very important hot drink, as literate tribe members told, without shoforo no one can survive long time in daassanech. In daassanech there is no clean water, to overcome this problem since years ago as a cultural trend they use shoforo coffee to meet drinking water need also. The main advantages of shoforo are anyone can drink shoforo as much as he can drink and it is free from any pathogens. Its principle is just as pasteurizing water to clean but is boiled water with coffee husk. In daassanech shoforo coffee boil at least twice per day in each family, one person drinks up to 2 liter shoforo per day.

However, coffee husk is used in daassanech since many years ago; today developed countries are turning to study about it and began to use it instead of coffee bean. M.G Perez and L.Patton reported in Bloomberg BusinessWeek (2018), as coffee husk is now fetching a

higher price, 480% Premium over coffee bean in USA. The reporters described that the hot drink is discovered, tested and now providing to market in Chicago by Aida Batlle.



FIGURE 3-11: Shoforo hot drink by 'shorka' and coffee husk

'Curcufa' is also a common staple food, it is made from cabbage or Moringa leaf and griped maize or sorghum powder; it may cook without a cabbage by griped maize or sorghum powder only. In daassanech curcufa is one of the daily preparing food type.

To determine thermal energy and absorber area for conventional cooker required to heat the cooker, assumptions and standards are mentioned below. Such assumptions and standards are:

- ✓ Energy required for cook 2 kg of food (meal + water) is equal to boil 2kg of water
- ✓ Design radiation component, average beam and diffuse radiation in between 10:00 up to 14:00 for July month with minimum solar intensity are 376 W/m^2 and 328 W/m^2 respectively
- ✓ Initial water Temperature is 30°C
- ✓ Mass x heat capacity of 2 kg of (meal + water) is equal with mass x thermal capacity of 2 kg water.
- ✓ Final water temperature required is 93°C .
- ✓ Maximum Time taken to cook should not exceed 150 minutes
- ✓ Standard assumptions of losses of the incoming solar radiation on the cooker glass surface top and side losses are 7%.

- ✓ Water loss by evaporation during cooking process is 10%.
- ✓ Enthalpy of vaporization of water (h_{fg}) at average temperature is 2342 KJ/Kg

3.9.1.1. Solar radiation analysis

Solar radiation which strike cover

Total solar radiation absorbed by the inclined cover surface is

$$I_g = I_b R_b + I_d R_d + I_r R_r$$

Where, I_b , I_d , and I_r are beam, diffused and reflected solar insolation respectively.

The total solar irradiance on the tilted surface I_T ^[28] times inclined glaze area can be applied here:

$$I_g = \left(I_b \frac{\cos \theta_c}{\cos \theta_z} + I_d \frac{1 + \cos \beta}{2} + I_r \frac{1 - \cos \beta}{2} \right)$$

By modifying Jaramillo's proposed model for the radiation per unit of time falling directly onto the inclined cover, by considering both beam and diffused radiation and illuminating reflected radiation, can be given as

$$I_g \approx \left(I_b \frac{\cos \theta_c}{\cos \theta_z} + I_d \frac{1 + \cos \beta}{2} \right) \dots\dots\dots 3.28$$

$$I_{bg} = I_b \frac{\cos \theta_c}{\cos \theta_z} \quad \text{and} \quad I_{dg} = I_d \frac{1 + \cos \beta}{2}$$

Solar radiation from outer reflector

The total radiation reflected from reflector surface area (A_r) to cover surface with area A_c if reflector has a diffuse reflectance of ρ_r is expressed as follows. [28]

$$I_{r \rightarrow c} = [I_b R_{br} + (1 - F_{r-c}) I_d] \rho_r F_{r-c} \frac{A_r}{A_c} \dots\dots\dots 3.29$$

where - I_{br} is beam radiation on the plane reflectors

ρ_r is reflectivity of outer reflector, it is Assumed as 0.89 (Harrison, 2001)

f_{r-c} is view factor, for adjusted reflector it is 1.

A_r , and A_c are outer reflector and cover area respectively, both are the same.

For adjusted reflector which has equal surface area with glazing area, the angle of reflected incidence is always less than 45° to direct all sun rays on the horizontal cover.

Angle of reflected incidence is the angle made between normal to the inclined cover and the solar radiation reflected from outer flexible reflector to the inclined cover/glazing.

3.9.1.2. Thermal energy calculation

Required thermal energy,

$$Q_w = M_w * C_p * \Delta T = 2 * 4200 * (93 - 30)KJ$$

$$Q_w = 2 * 4200 * (93 - 30)J$$

$$Q_w = 529.2KJ$$

Required energy rate for cooking ($\dot{Q}_w$)

$$(\dot{Q}_{wr}) = \frac{529.2 * 10^3 J}{(120 * 60) Sec} = 73.5 W$$

Energy loss by evaporation ($\dot{Q}_w$)

$$\dot{Q}_{wl} = \frac{m_l x h_{fg}}{\Delta t} = \frac{\left(\frac{10}{100} * 2\right) Kg * 2342 * 10^3 \frac{J}{Kg}}{(120 * 60) sec}$$

$$\dot{Q}_w = 65.06 W$$

Energy loss through insulation and glaze ($\dot{Q}_l$)

$$\dot{Q}_l = Ag \left(\frac{7}{100} * I_{av} \right) = Ag \left(0.07 * 600 \frac{W}{m^2} \right) = (42 * Ag) \frac{W}{m^2}$$

Total power required $\dot{Q}_t = 73.5 + 65.06 = 138.56 W$

Minimum aperture area of the cooker (A_g),

$$Ag = \frac{\dot{Q}_w}{I_{av} - 0.07 I_{av}}$$

$$Ag = \frac{138.56}{600 - 42} = 0.248 m^2$$

3.9.2. Dimensioning of conventional solar cooker

Let us assume a full load for a cooker should be 2kg that is by considering for single family. So to cook this much food two pan with 20cm diameter and 6cm height is enough that is available in market. For place these pans the minimum absorber area must be (2*20) cm length, 20 cm width and 6cm height (40*20*6)cm³. This value is less than theoretically obtained value of area for 2kg water by considering its standard losses.

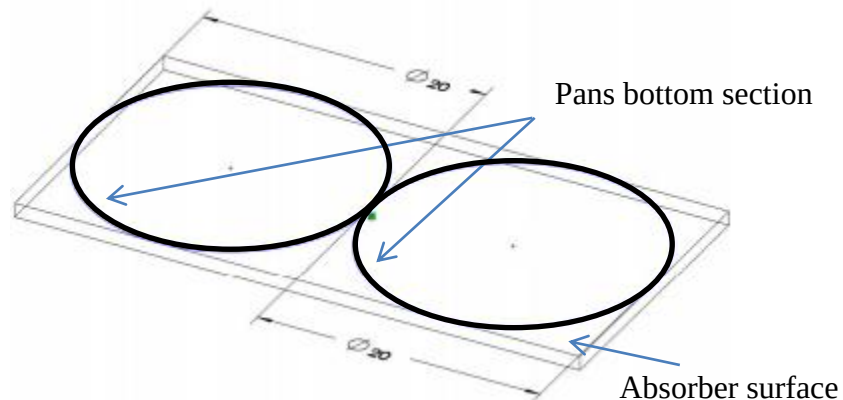


FIGURE 3-12: Minimum possible absorber area for two pans

On the other hand, three things should be considered

- 1) Some part of absorber surface should be exposed to sun rays.
- 2) Calculated area needed to obtain adequate energy in section 3.9.1.2.
- 3) Solar cooker full load testing standard thumb rule that is 8kg/m² collector area (BIS, 2000).

Additionally by considering the cooker weight 0.25m² collecting area for 2 kg load is selected. The absorber area and collector area for convectional solar cooker is the equal. Therefore collector area is 0.25m². As Shringi (2016) described square absorber is better than rectangular one in conventional cooker [9]. Therefore the aperture (Glazing) area can be 0.5m x0.5m.

Kundapur (1998) suggested that the depth of the inner box should not be more than 10 to15 cm. This depth is a critical parameter since a greater depth would introduce a shade effect, but the width and breadth could be of any dimension. Therefore it is selected as heights, H=400 and h=150 mm.

3.9.3. Design of Improved Solar Cooker

3.9.3.1. Preconditions for Designing

Preconditions for the designing of modified solar cooker.

- Whole the system should track the sun only three times a day, but no problem for outer reflector motion with the sun angle frequently.
- The inner reflectors must be at an optimum angle throughout the year because they are fixed surfaces with the system.
- The aperture area must be equal with conventional one for comparison purpose.

Total solar radiation receiving by glazed absorber surface of the solar cooker are global incident $[I(t)]$ and reflected $[\rho I(t)]$ solar radiation.

3.9.3.2. Outer reflector angle

Outer reflector plane mirror angle is vary with solar angle

- Flexible to track with sun ray
- Its Area is equal with aperture area

3.9.3.3. Fixed inner reflector angle

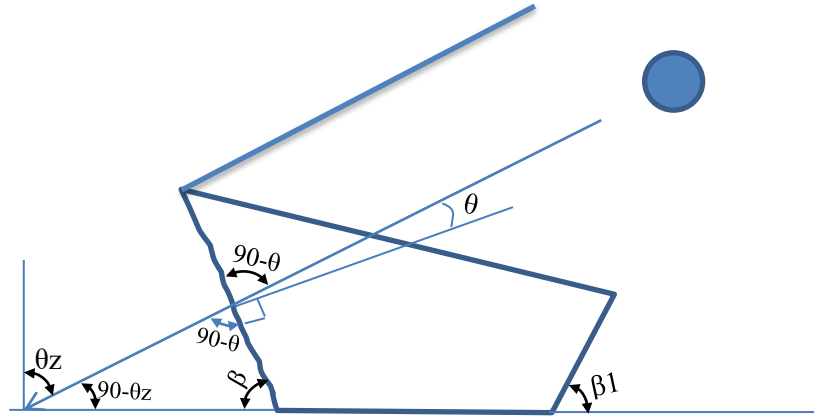
A. Rear and sun side inner reflectors

These reflectors are used to direct all solar rays that come from sun and reflected from outer mirror to the absorber.

Sun side reflector height and angle should be calculated by considering morning or evening solar time to avoid shadow effect on the collector. Sun side inclination, β_1 , must be less than solar altitude angle at a given time.

$$\beta_1 < (90 - \theta_z) = \alpha_s$$

At noon, (12:00), $\alpha_s = 61.7$ degree in the day number with minimum declination angle. For optimum inclination angle β_1 both incidence angle and zenith angle must be determined in between morning 9:00 AM and afternoon 3:00 PM; It is possible to be selected as $\beta_1=51$ degree.



To determine inclination angle of back side inner reflector (β)

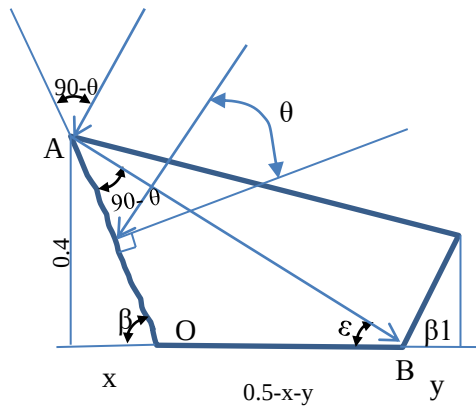
$$\beta + (90 - \theta_z) + (90 - \theta) = 180$$

$$\beta - (\theta + \theta_z) + (90 + 90) = 180$$

$$\beta - (\theta + \theta_z) = 0$$

$$\beta = (\theta + \theta_z) \dots\dots\dots 3.30$$

This should be calculated at minimum declination angle and zero degree surface azimuth angle, symmetrically at maximum declination, that is greater than latitude angle, the cooker will turn toward North.



By using sine law:

$$\frac{\sin(90-\theta)}{0.5-x-y} = \frac{\sin \epsilon}{\frac{0.4}{\sin \beta}} \dots\dots\dots 3.31$$

$$\epsilon = \tan^{-1} \left[\frac{0.4}{(0.5-y)} \right], \text{ and } \beta = \tan^{-1} \left(\frac{0.4}{x} \right) \dots\dots\dots 3.32$$

From triangle AOB,

$$\theta = 90 - \beta + \varepsilon \dots\dots\dots 3.33$$

From equation 3.30 and 3.33,

$$\beta = \frac{1}{2}(90 + \varepsilon + \theta z) \dots\dots\dots 3.34$$

By substituting equation 3.33 in equation 3.31,

$$x = 0.5 - y - \frac{0.4 \sin(\beta - \varepsilon)}{\sin \varepsilon \sin \beta} \dots\dots\dots 3.35$$

If it is assumed at the day of minimum declination angle, December 21, solar time between 10:30 to 13:30 hour and toward south direction, so additionally by considering absorber width, β is calculated as 80.5 degree. Calculated x value is 7.5 cm and the width of absorber becomes 26.5 cm. Therefore, this width is suitable for single pan.

B. Inclination of left and right side inner reflectors

The most direct angle at which the Sun's rays strike the ground (horizontal plane) is at angle $(90 - \varphi)^\circ$ on the days of a vernal and autumnal equinox ($\delta = 0$).

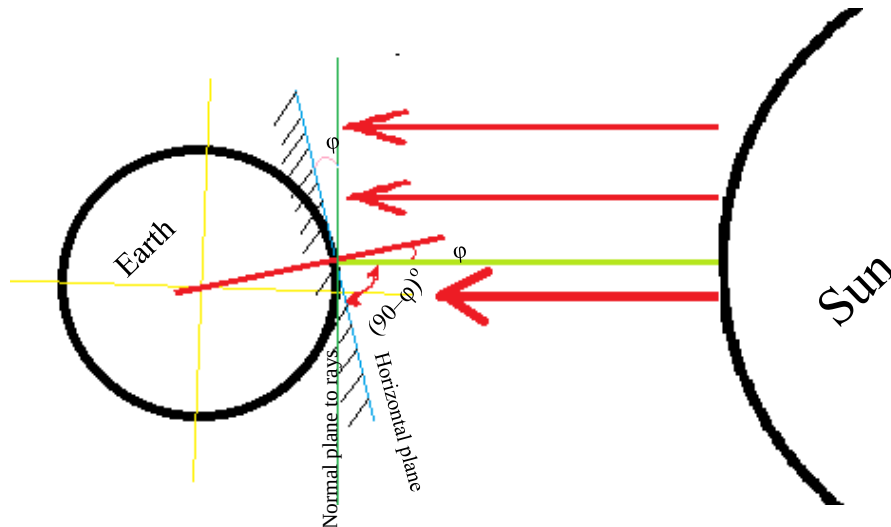
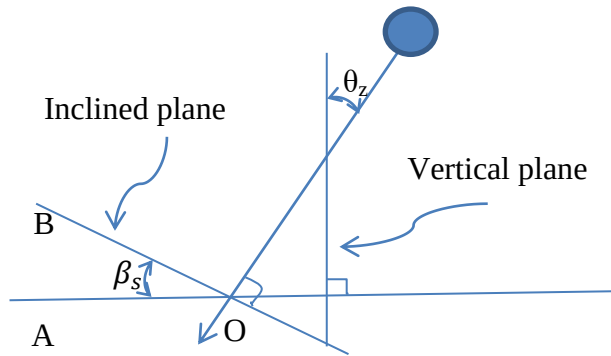


FIGURE 3-13: Earth and sun angle relation

If it is considered as a plane surfaces toward south and north with a single daily adjustment its beam radiation is normal to the surface at noon in different day ($\delta \neq 0$), its slope will be:

$$\beta_s = \varphi - \delta$$



$$\beta_s = \varphi - \delta$$

$$\beta_s = \angle AOB = \varphi - \delta$$
 The plane with inclination of $(90 + (\varphi - \delta))$ is parallel to sun rays at noon each day.

Therefore, the inclination angle of inner left and right side reflectors should be between the inclination of parallel plane to the sun rays and inclination of normal plane to the incident, the values are $(90 + (\varphi - \delta))$ and $(\varphi - \delta)$, respectively. But the inner reflectors are always fixed and its inclination angle is directly relational to cooker size. Therefore the inclination angle, β_s , selected to be 77 degree to preserve absorber area adequate for single pan.

3.9.3.4. Dimensioning of Improved solar cooker

Dimensioning for improved solar cooker is described below in two way (square absorber and square glazing); it has equal glazing area with designed conventional solar cooker.

1. Solar cooker with Square Absorber Area

The conventional box intercept collector area has been calculated as 0.25m^2 .

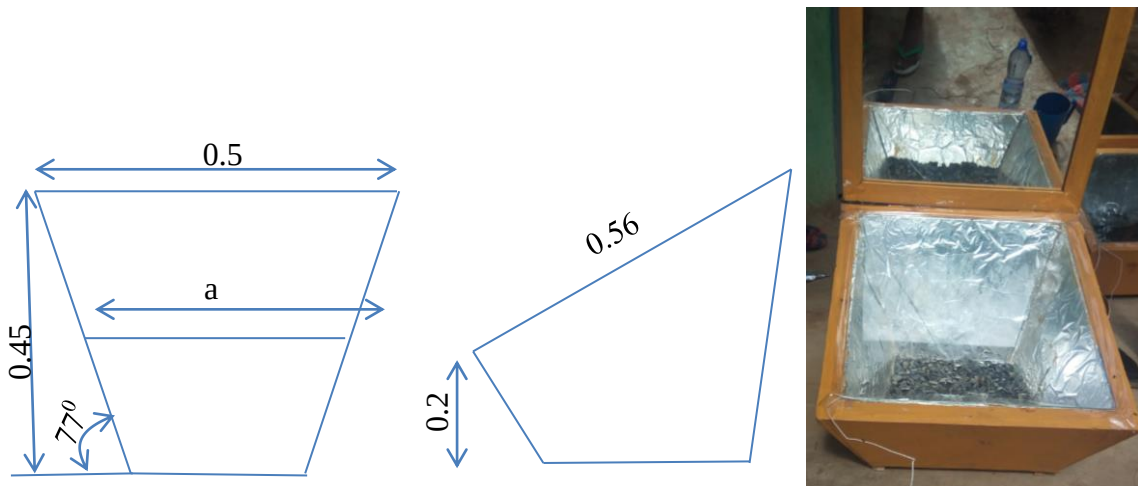


FIGURE 3-14: Side inner reflector inclination and dimension

$$\frac{(0.5 - a)}{2} = 0.25 \tan(90 - 77)$$

$$a = 0.5 - 2(0.25 \tan 13) = 0.385 \text{ m}$$

2. Solar cooker with square glaze or trapezoidal absorber area

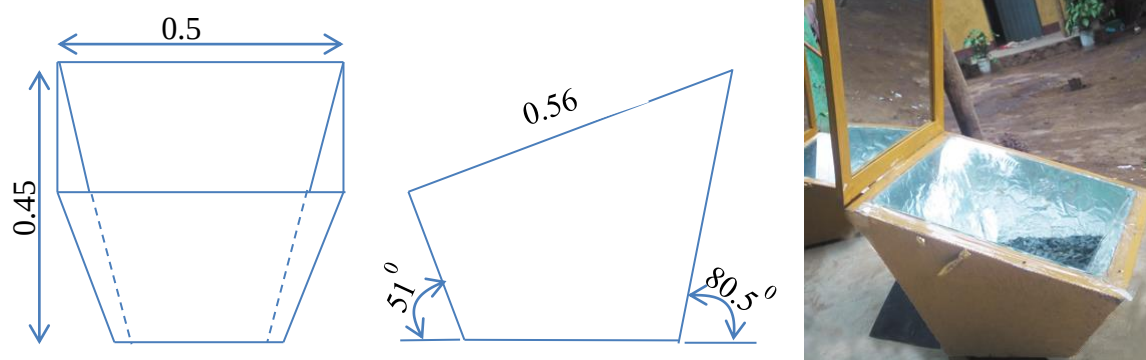


FIGURE 3-15: Front and rear inner reflector inclination

3.9.4. Construction material selection

TABLE 3-7: Construction materials

Part	CSBC	Square glazing with trapezoidal absorber
Absorber	Sheet metal	Sheet metal/Black stone
Insulation	Foam	“Inset” Fiber
Reflectors	Mirror and aluminum foil	Mirror($\rho=0.94$) and Aluminum foil ($\rho=0.86$)
Box	Wood frame	Wood frame
Glazing	Glass ($k=15\text{m}^{-1}$)	Glass ($k=15\text{m}^{-1}$)

3.9.4.1. Insulation

In order for the box to reach interior temperatures high enough for cooking, the walls and the bottom of the box must have good insulation (heat retention) value (Claude et al, 2012). The Second Law of Thermodynamics states that heat always lost from hot to cold, in three fundamental ways: Conduction, Radiation, and Convection.

So to prevent this heat loss insulator must have low heat conductivity and be able to withstand stagnation temperature. Conventionally fiberglass, mineral wool, polyurethane boards, Styrofoam, crumpled newspaper and other organic materials can use as an insulator.

However Styrofoam and Pressed fiberglass are used in conventional solar cooker, they are not recommended because fiberglass is fabricated with chlorofluorocarbons which destroy atmospheric ozone and foam is also made with toxic gases which continue to off gas for long periods.

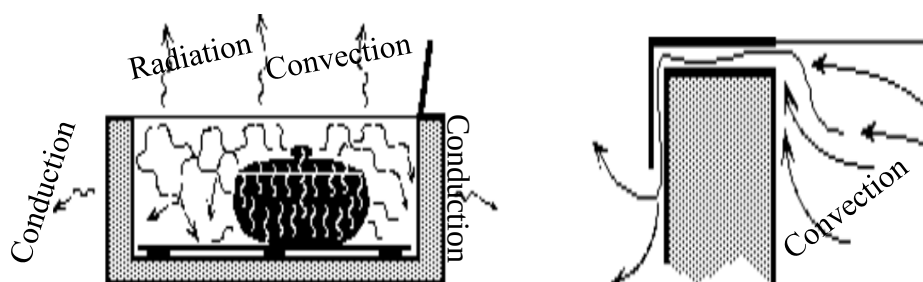


FIGURE 3-16: Heat loss from solar cooker box

Due to its low cost and no effect on environment after usage, natural insulations are very significant insulation materials for low cost solar system. Bhuvaneshwari et al. (2018) has studied the development of Natural Fiber Nonwovens for Thermal Insulation.



FIGURE 3-17: "Inset" fiber used as insulation

Wall insulation thickness can be determined by using fourier's law given by Ekechukwu and Abdussalam (2001) as:

$$x = \frac{KA_l \Delta T_p}{\dot{Q}_l} \dots \dots \dots 3.36$$

Where, K is conductivity of the insulation material, A_l is heat loss area (bottom + side wall)

ΔT_p is difference between plate temperature and ambient temperature

$\dot{Q}_l$ is maximum rate of heat loss

Standard maximum heat loss rate through the cooker walls is 7% of incident insolation (Ekechukwu 2001).

3.9.4.2. Inner Sidewall Reflectors

The inner surfaces of sidewalls of the cooking box are made from aluminum foil reflective material. Design of the box is considered to direct solar rays impinging on the inner sidewalls

to downward that convert to thermal energy by black painted absorber plate at the bottom. The sidewalls are separated from the outer casing by insulation.

3.9.4.3. Absorber

This is very important part of solar cooker to collect or absorb all sun radiation that are reflected from mirrors and direct and diffuse sun rays from the sun. In this research sheet metal and storage material, black stone have been used as absorber plate. Sheet metal is very good absorber due to its high conductivity; black stone can be also a good absorber it can be chosen because of its low cost.

The total inner surface areas including absorber plate for conventional solar cooker and for improved one were calculated as 0.8m² and 0.645 m² respectively for the same glazing area. Therefore, improved solar cooker with square glaze or trapezoidal absorber area which has 5 cm additional height to hold thermal storage material has 20% less size than the conventional solar cooker inner area for the same intercept area of the sun.

3.9.5. Solar energy on the cooker absorber

Solar variables must be calculated for external reflector and glaze individually.

The incident radiation onto the solar oven, I_o , is composed of the direct incidence onto the collector, I_C , and the contribution from each reflector.

$$q_o = q_C + (q_N + q_S + q_E + q_W + q_{ex})$$

Where: q_C , q_N , q_S , q_E , q_W and q_{ex} are the contribution due to the Cover and (North, South, East, West and external) reflectors, respectively, the directions become proper at a noon only.

3.9.5.1. Solar radiation strike cover

Four side reflectors (q_N , q_S , q_E , q_W) are in the box and all are fixed reflectors. So it can be assumed that solar radiation that passed through the glaze can be trapped inside the box by the aid of reflectors, side insulations and due to black plate absorber.

$$q_g = q_C + q_N + q_S + q_E + q_W$$

$$q_g \approx (I_{bg} + I_{dg})A_a \dots\dots\dots 3.37$$

This much energy per unit time will entrap into the cooker from sun to box through the cover.

3.9.5.2. Solar radiation from reflector contribution

Here external flexible reflector considered only because inner reflectors assumed to gain energy passed through the inclined cover then direct it to absorber plate and change remained energy to thermal energy as much as its absorbing ability.

$$q_r \approx I_{or} A_a \dots\dots\dots 3.38$$

The Rate of Total energy entrapped in the cooker can be calculated as

$$q = [(\tau\alpha)_b I_{bg} + (\tau\alpha)_d I_{dg} + (\tau\alpha)_r I_{or}] A_a (1 - D)(1 - S)(1 - Srg) \dots\dots\dots 3.39$$

Where, τ is transmissivity of the glass, α is absorptivity of the absorber

D is the effect due to dust; S is a shading factor due to the cooker walls,

Srg is shading effect due to the reflector on the absorber

According to Grassie and Sheridan (1977), for frequently cleaned glazing, $D = 0.01$, S is a shading factor is assumed to fluctuate sinusoidal with a period equal to day length and with a maximum of 0.1 at sunrise and sunset and zero at solar noon, Srg can be neglected, if the reflector and cooker are so adjusted that the cooker surface is completely exposed to the reflected.

3.9.5.3. Transmittance-Absorbance product

Frequently used cover is glass which can transmit up to 90% of incident short-wavelength radiation, but long-wavelength heat radiation ($\geq 2.6 \mu\text{m}$) emitted by the absorber plate back to cover cannot transmit through glass.

The transmittance of the cover depends on the incidence angle of the solar radiation. The refracted angles are given by snell's law as

$$\frac{\sin \theta_r}{\sin \theta_i} = \frac{n_1}{n_2} = \frac{v_g}{c} = \frac{1}{n}$$

$$\theta_r = \sin^{-1} \left(\frac{\sin \theta_i}{n} \right) \dots\dots\dots 3.40$$

Where, n_1 and n_2 are the refractive indices of glass and air, respectively

v_g is Speed of light in glass which is about 2×10^8 m/s and c is speed of light in air.

So, the refractive index ($n_{\text{air}}/n_{\text{glass}}$) 'n' of glass in solar spectrum is 1.526.

$$\tau_r = \frac{\tau_{r1} + \tau_{r2}}{2} \dots\dots\dots 3.41$$

$$\text{Where, } \rho_1 = \frac{\sin^2(\theta_r - \theta_i)}{\sin^2(\theta_r + \theta_i)} \text{ and } \rho_2 = \frac{\tan^2(\theta_r - \theta_i)}{\tan^2(\theta_r + \theta_i)}$$

$$\tau_{r1} = \frac{1 - \rho_1}{1 + \rho_1} \quad \text{and} \quad \tau_{r2} = \frac{1 - \rho_2}{1 + \rho_2}$$

According to Bouger's Law, transmissivity due to only absorption can be written as:

$$\tau_o = e^{\left[\frac{-k\delta}{\cos \theta_r} \right]} \dots\dots\dots 3.42$$

Where: δ is the thickness of the cover glass; for this Thesis the glass cover used is with plane thickness of 3mm.

k is the extinction coefficient; It varies in between 5 m^{-1} for “white-water” glass to 25 m^{-1} for poor glass (greenish) depending on the glass quality. Assuming the glass cover is of average quality $k=15 \text{ m}^{-1}$. (Idi, 2011)

The transmissivity of the cover is given by (Tiwari, 2016, pp176)

$$\tau = \tau_r \times \tau_o \dots\dots\dots 3.43$$

The absorptivity of a glass cover can be written as:

$$\alpha = 1 - \tau_o \dots\dots\dots 3.44$$

Transmissivity-absorptivity product for diffuse radiation $(\tau\alpha)_d$ is assumed to be equal to that for beam radiation at 60° incidence angle (Supriti, 2015).

Finally the average Rate of energy absorbed by the cooker box can be calculated by using equation 3.37. So the designed solar cooker can entrap 201.12W average rate of energy in between 10:00AM up to 14:00 PM in minimum solar intensity month, July.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Average Solar radiation

Solar radiation data for daassanech (Omorate) has been collected from different sources and its average has been calculated to use as the input for designing of solar powered thermal system. Except nearby data of Jinka city from NMAE, all other solar radiation data are collected from websites and software such are RETScreen and HOMER.

Radiation data from Weatherbase is calculated from twenty two years averaged sunshine data that was obtained from weather averages website (www.weatherbase.com). Radiation data from helioclim-1 database is obtained from HelioClim-1 Database of Daily Solar Irradiance which is derived from satellite data. HelioClim-1 database of Daily Solar Irradiance is provided by MINES ParisTech- Armines (France) and it is available in their website (www.soda-is.com). NASA surface meteorology and solar energy database is one of radiation data sources which provided also twenty two years averaged data (July 1983- June 2005). Its cell midpoint that is near to Omorate city is Latitude 4.5 and Longitude 36.5 with cells dimension of $1^{\circ} \times 1^{\circ}$. National Solar Radiation database (NSRD) is provided averaged data in different cell midpoint in latitude 4.774 and longitude 36.11831 with cell dimension of 40 km x 40 km. Both NASA surface meteorology and solar energy and National Solar Radiation database are available in HOMER software.

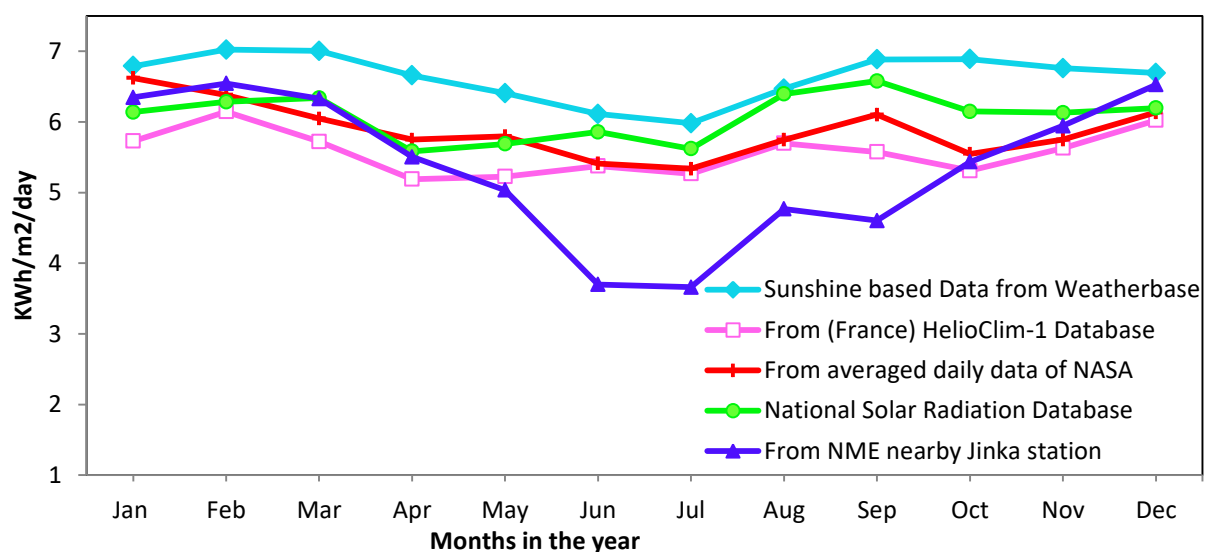


FIGURE 4-1: Comparison of calculated solar radiation with obtained from different data source

The nearby data of National Meteorological Agency (NMA) of Ethiopia from Jinka station was collected from SNNPR, Hawassa NMA branch, but it is measuring only weather condition of the city and nearby areas. Around Jinka city, it is rainy season from May up to September for four months. Except those months the weather condition of Daassanech (Omorate) and Jinka is almost near to each other. Therefore it is possible to take an average solar radiation from different recorded data bases for the selected site except from nearby NMA sunshine based data of Jinka, then averaged result is shown in graph below.

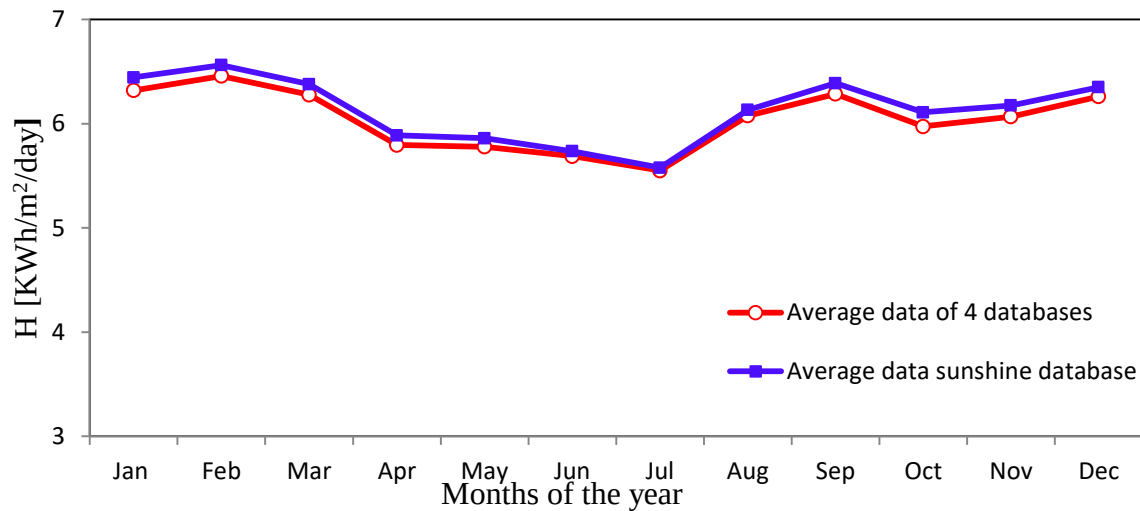


FIGURE 4-2: (Averaged) Monthly average daily solar radiation for Daassanech (Omorate)

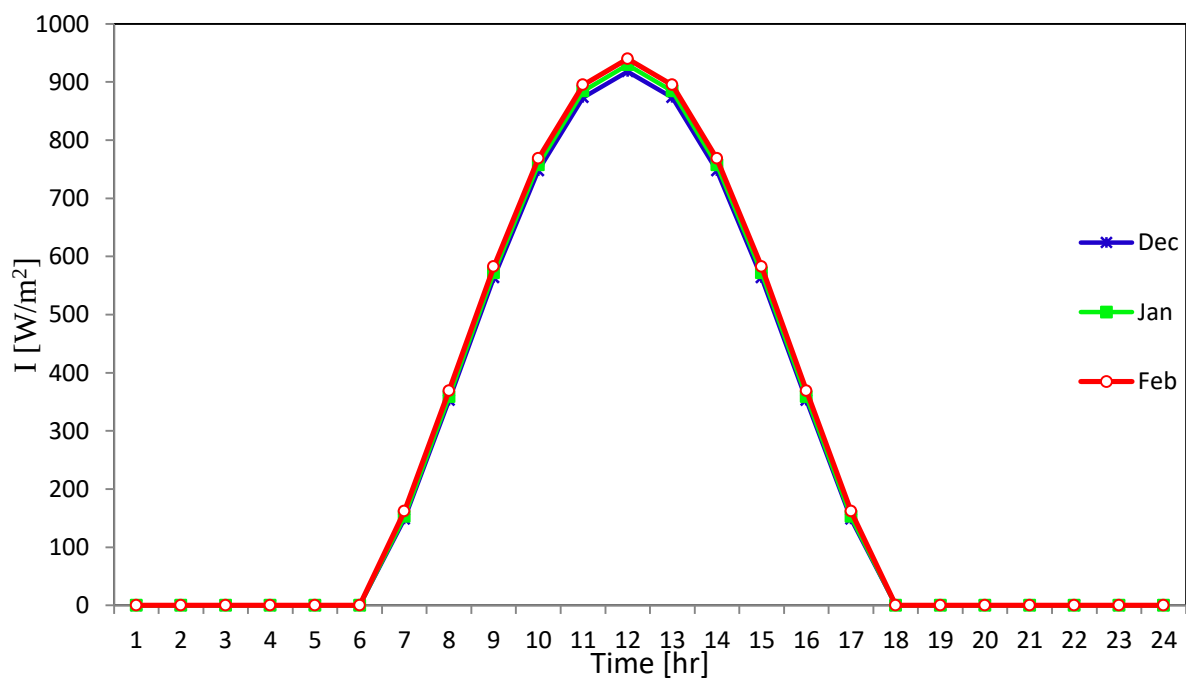


FIGURE 4-3: Monthly average Hourly GSR of Winter Season (Averaged)

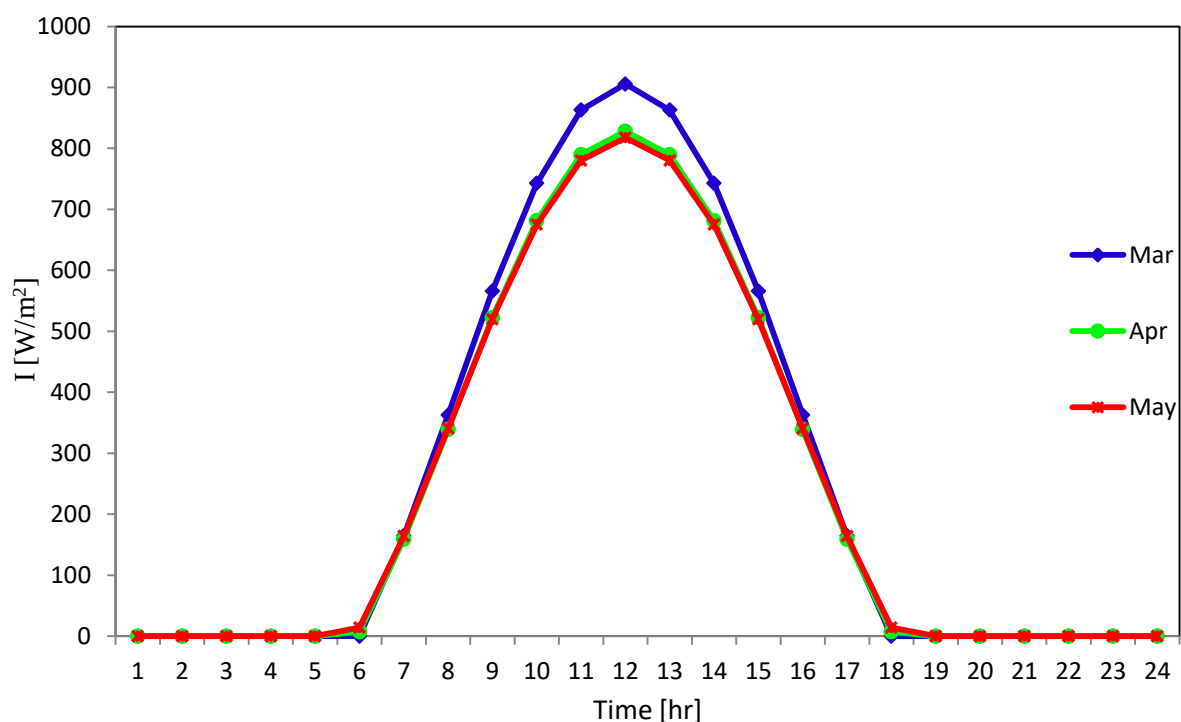


FIGURE 4-4: Monthly average Hourly GSR of Spring season

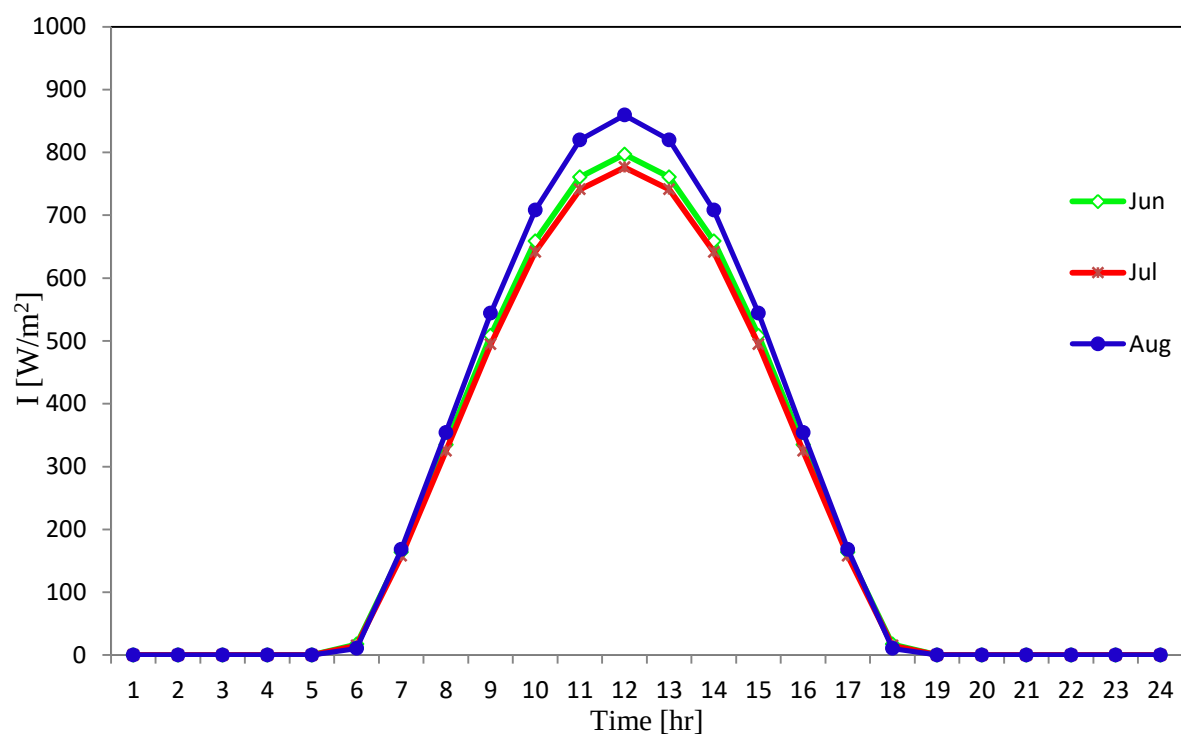


FIGURE 4-5: Monthly average Hourly GSR of Summer season

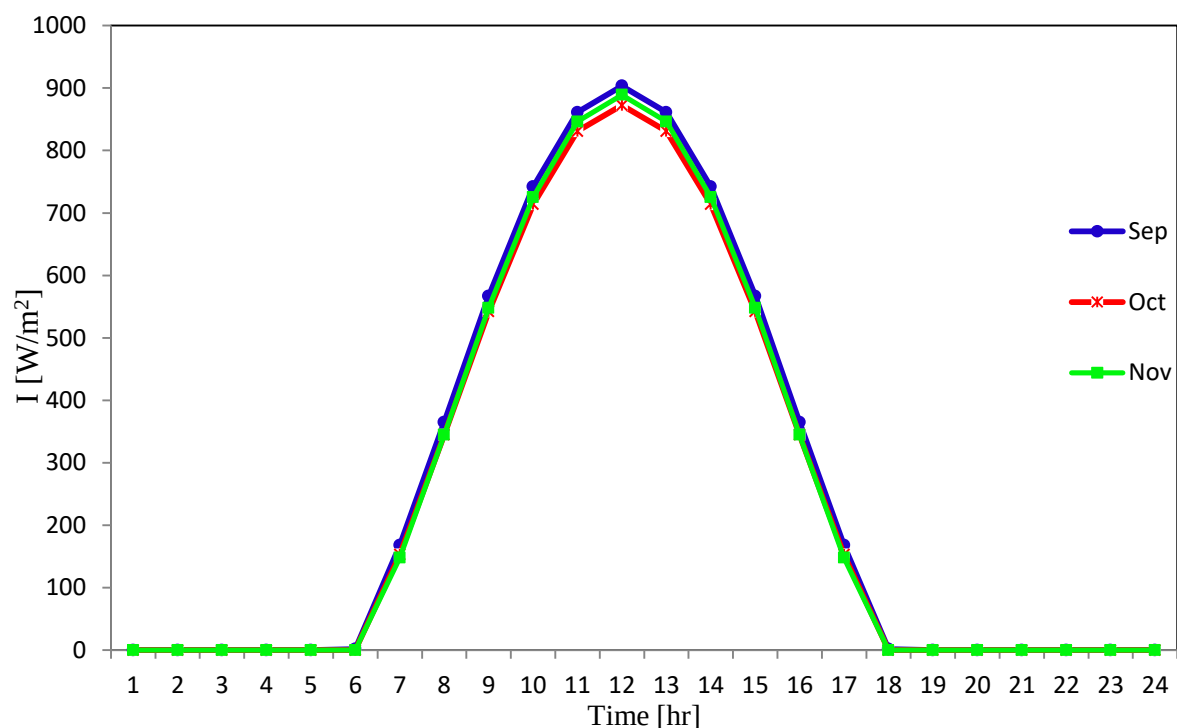


FIGURE 4-6: Monthly average Hourly GSR of Autumn (Fall)

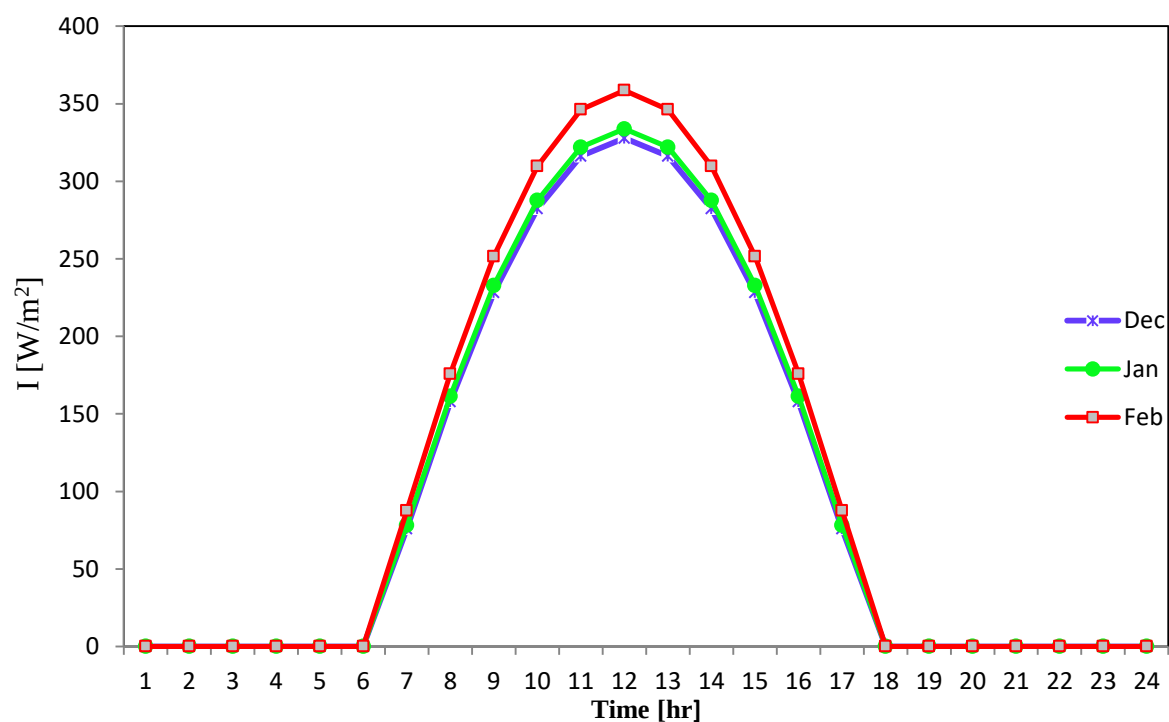


FIGURE 4-7: Monthly average Hourly diffuse solar radiation of Winter Season

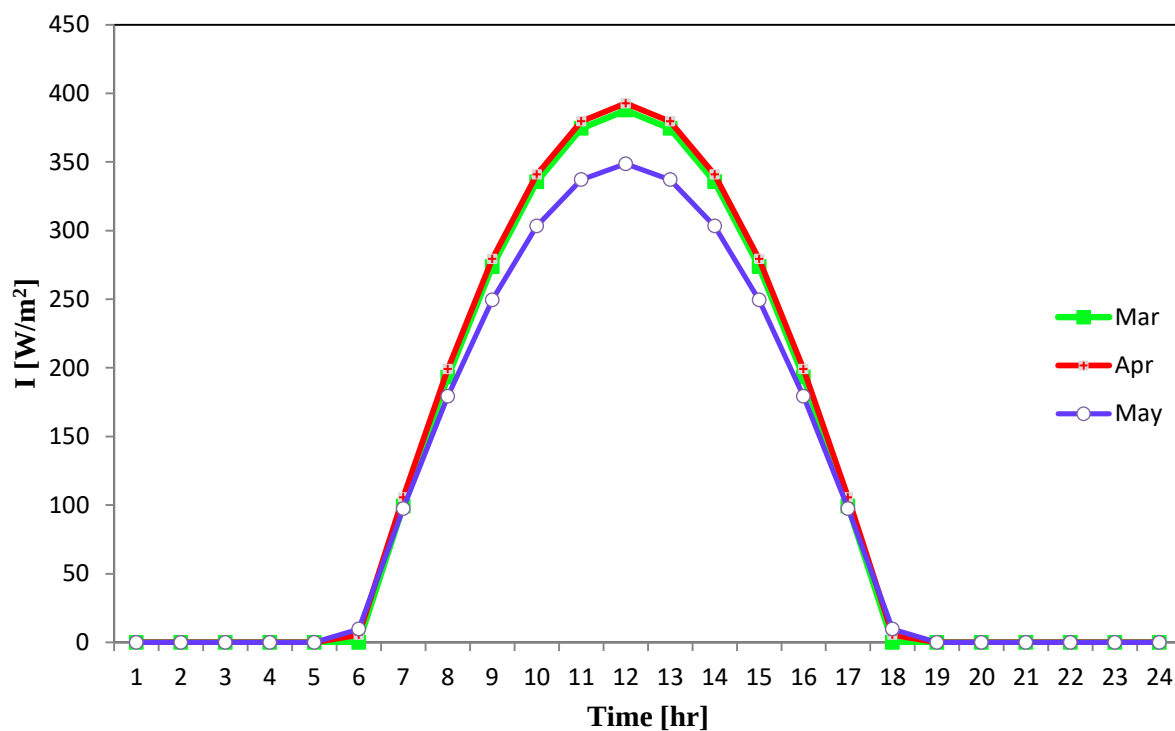


FIGURE 4-8: Monthly average Hourly diffuse solar radiation of Spring Season

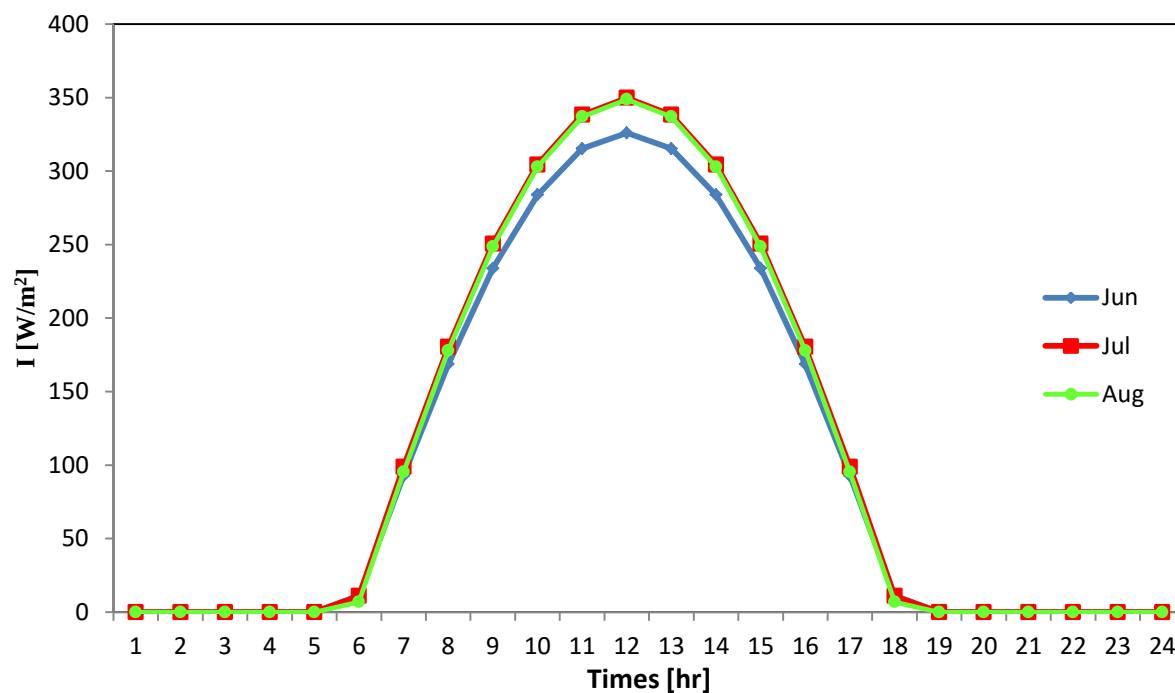


FIGURE 4-9: Monthly average Hourly diffuse solar radiation of Summer Season

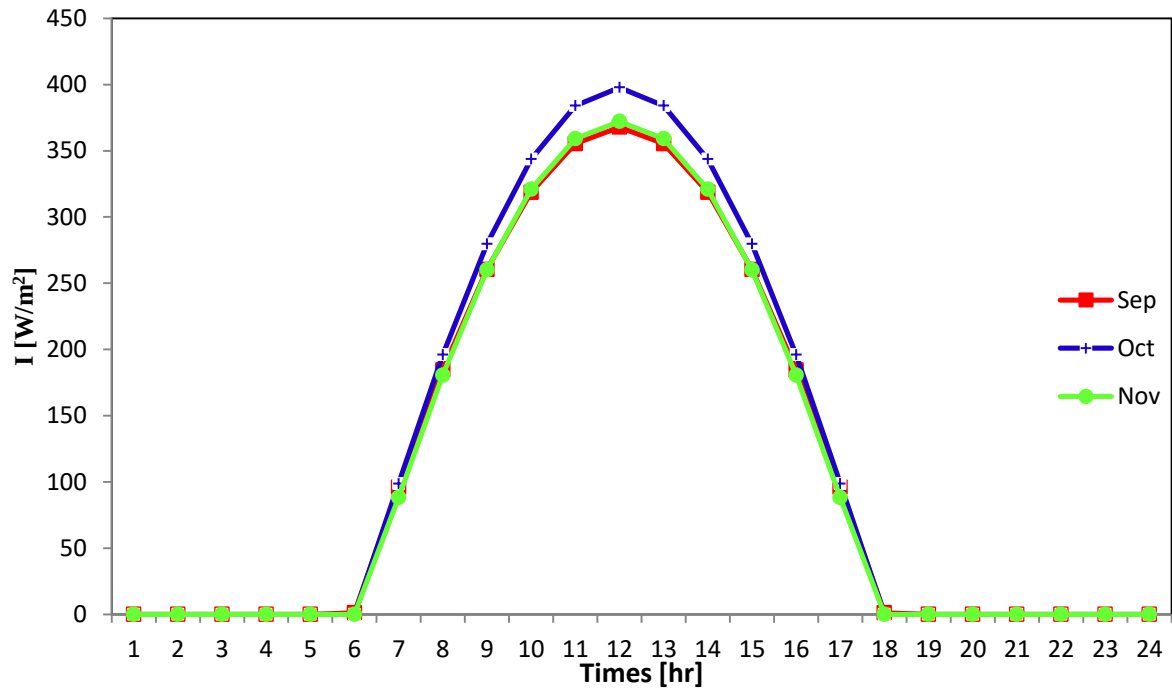


FIGURE 4-10: Monthly average Hourly diffuse solar radiation of autumn (fall) Season

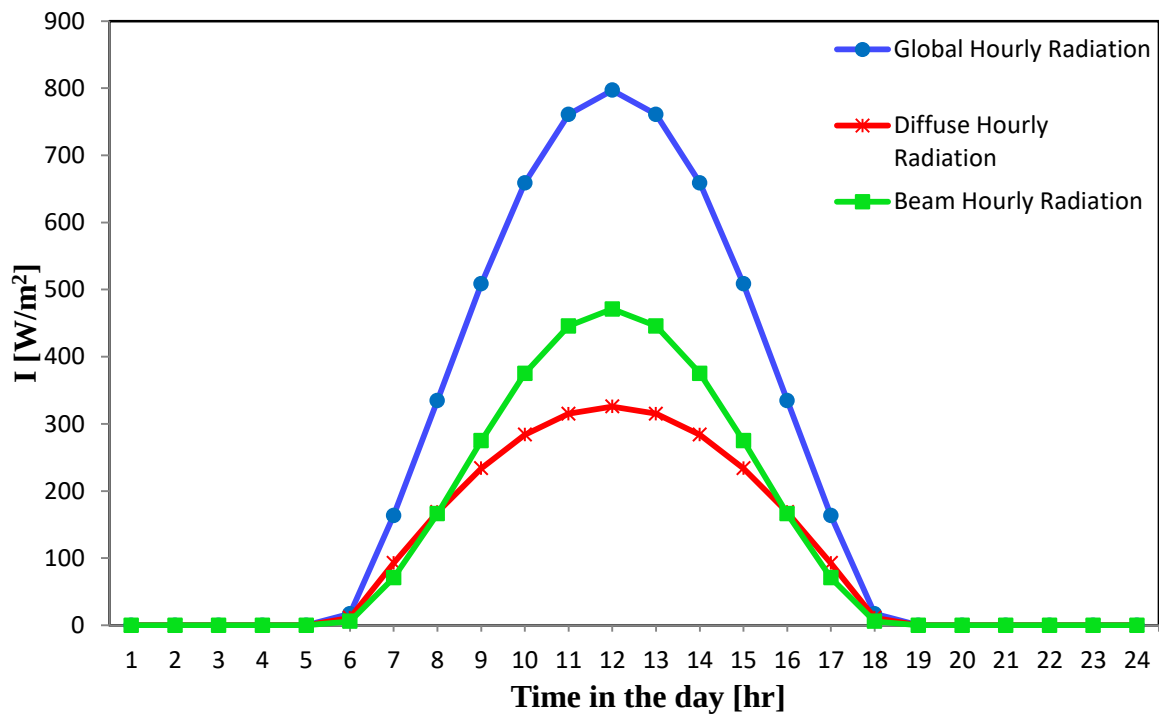


FIGURE 4-11: Monthly Average Hourly Radiation on Horizontal surface for June

An average solar radiation is calculated as maximum in February (6.563 KW/m²/day) and minimum in July Month (5.578 KW/m²/day) and Annual Average daily solar radiation is 6.134 KW/m²/day.

4.2. Temperature distribution

4.2.1. Analytical Results for Temperature distribution

FIGURE 4-12: shows that analytical stagnation plate temperature throughout the day and steady state water temperature for conventional type BSC both with the same absorber area (0.0882 m^2) and glazing area (0.25 m^2) with improved SC for each single hour are calculated by using Microsoft excel software.

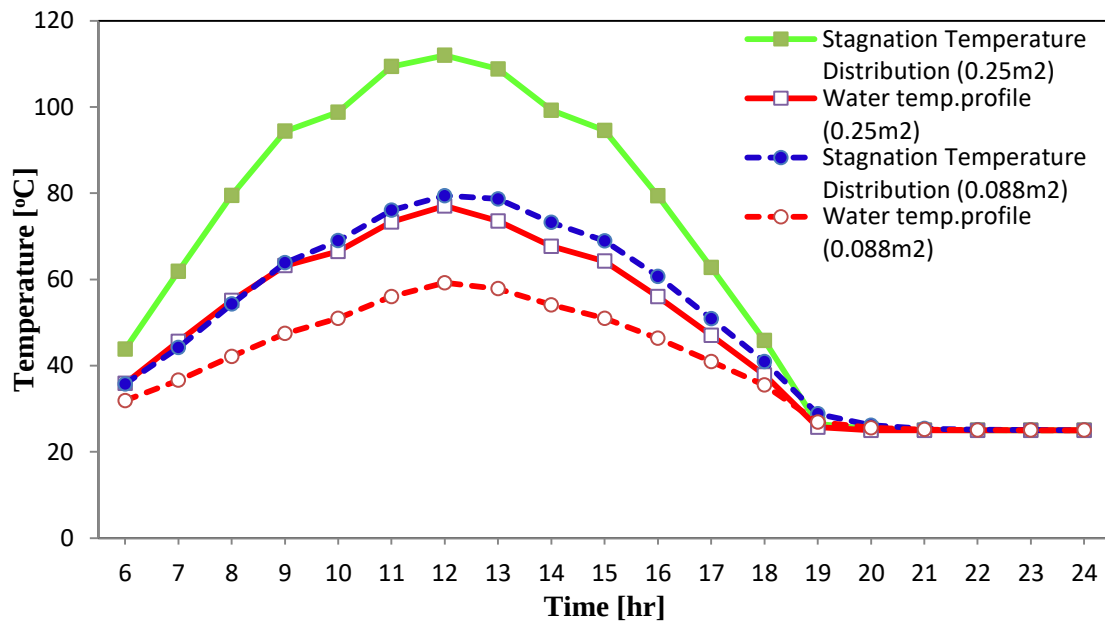


FIGURE 4-12: Simulation results of temperature distribution for each time

In FIGURE 4-13 that analytical result of stagnation plate temperature distribution for 0.25 m^2 absorber area with the time of 20 minutes difference is described. As it is seen in graph of analytical analysis stagnation plate temperature, the maximum absorber plate temperature that can be possible to obtain is 119.5°C .

FIGURE 4-14 shows analytical results of time dependent water and plate temperature distributions for 0.25 m^2 absorber area in each of 10 minutes difference in between 10:00 AM to 2:00 PM (for 240 minutes). The maximum water temperature that can be possible after 240 minutes is about 128°C .

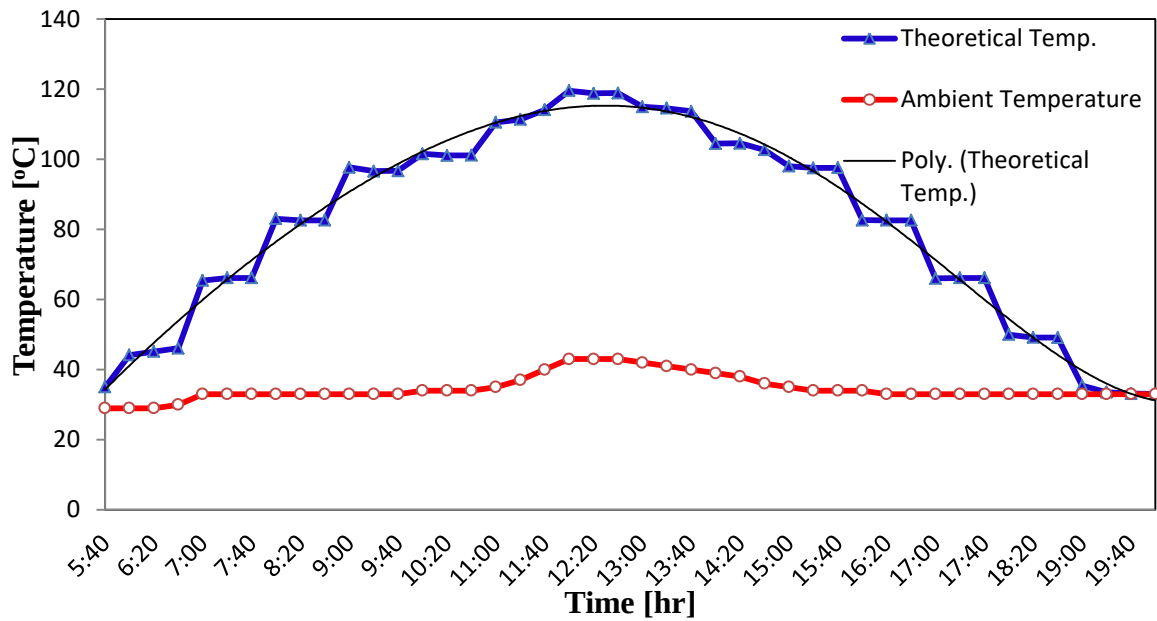


FIGURE 4-13: Analytical results of stagnation plate temperature for 0.25m^2 collector area

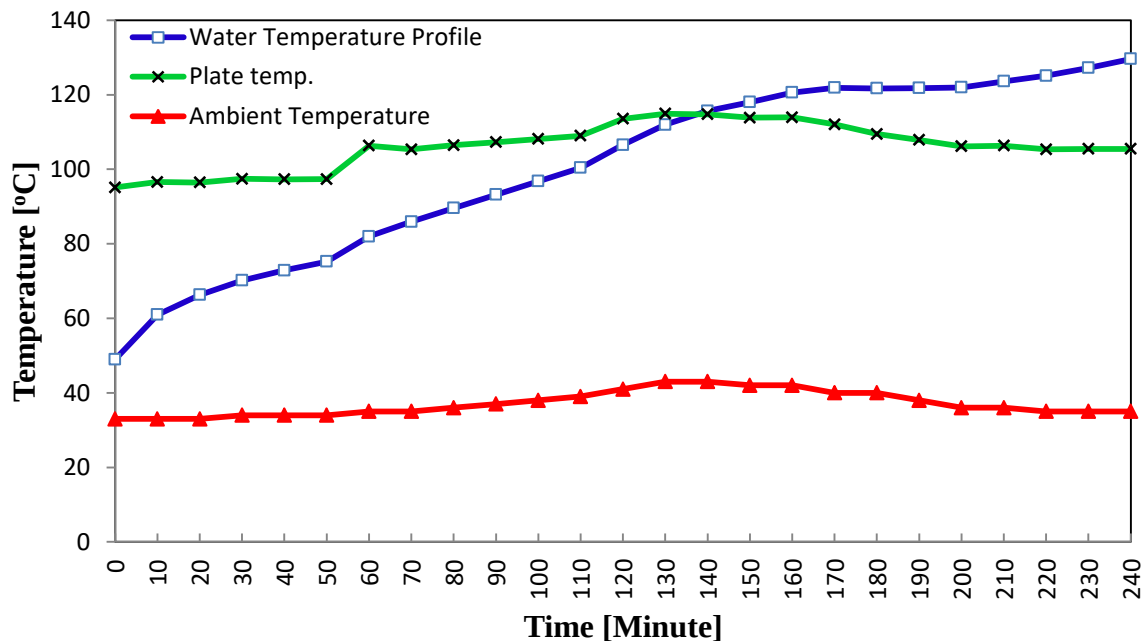


FIGURE 4-14: Analytical results of temperature with full load for 0.25 m^2 collector Area

In FIGURE 4-15 and FIGURE 4-16 analytical results of temperature distribution is described for 0.0882m^2 absorber area which is equal to improved solar cooker absorber Area. The maximum stagnation (no load) absorber plate temperature is 89.25°C . The maximum water temperature that can be attained after 240 minutes is about 104.2°C .

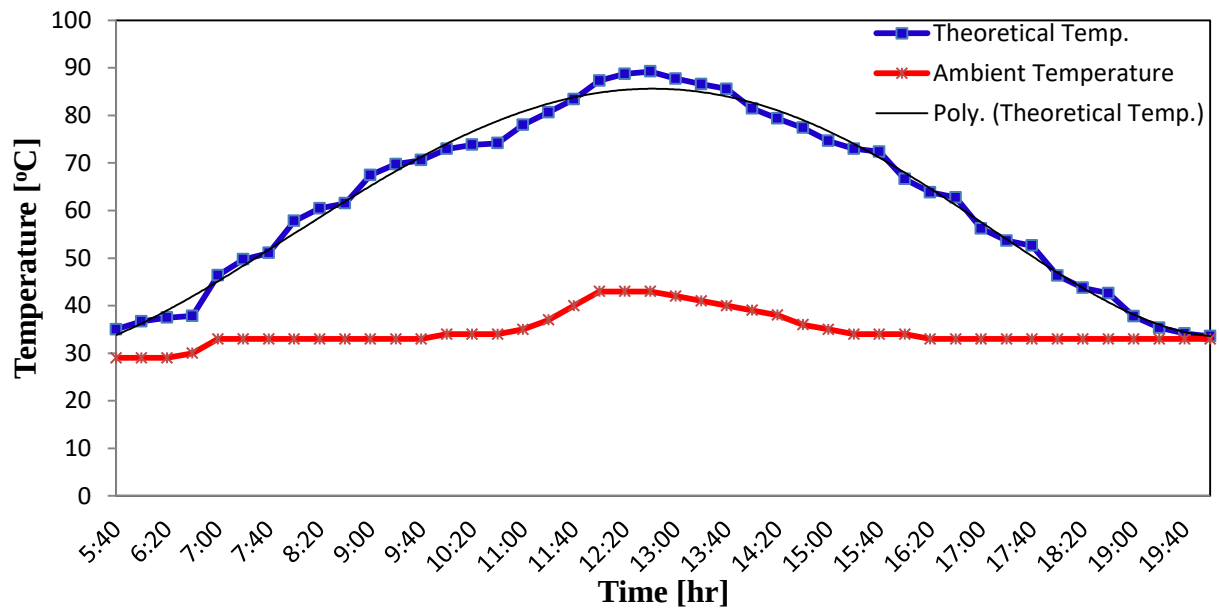


FIGURE 4-15: Analytical results of stagnation plate temperature for 0.0882 m^2 collector area

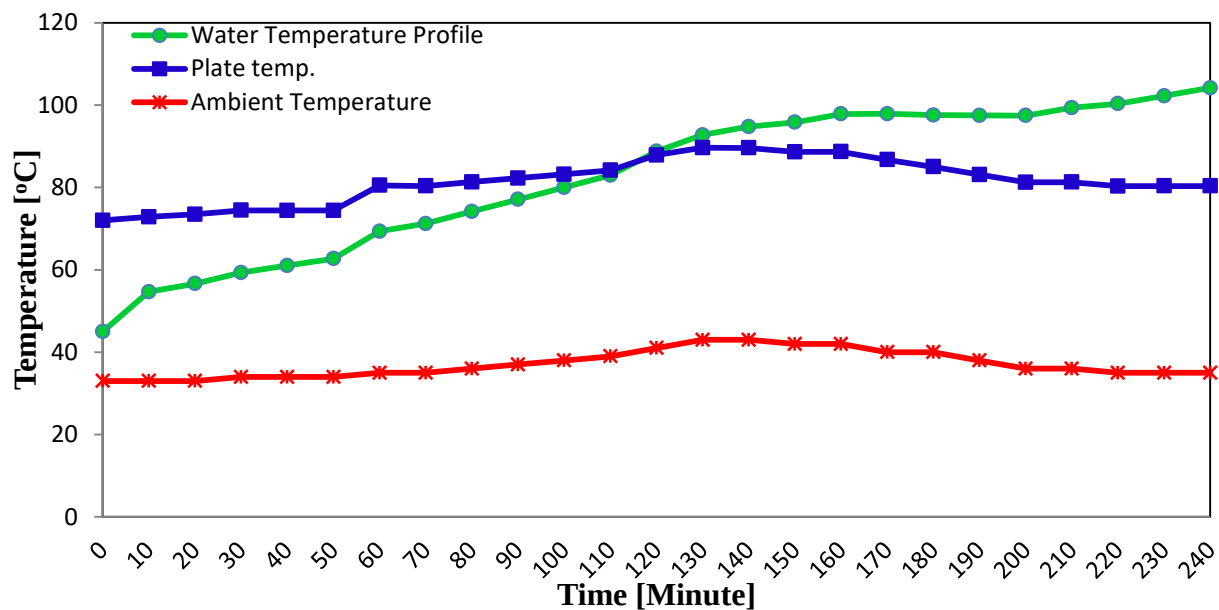


FIGURE 4-16: Analytical results of temperature profile with full load for 0.0882 m^2 collector Area

4.2.2. Experimental Temperature distribution

The data that was collected from the experiment included; ambient temperature (T_a), Plate temperatures (T_p), Water temperatures (T_w) and cooking time were measured at 20 minutes interval for 16 hours (8:00 – 24:40) and 10 minutes interval in load test for 4 hours (10:00 – 14:00) by following standard recommended by the Bureau of Indian Standards.. The raw data was measured by the four channel digital k-type thermocouple and ambient temperature was

measured by mercury glass thermometer, then it was entered into Excel spreadsheet and analyzed.

The load test is described by using graph through FIGURE 4-17 to FIGURE 4-22 and No Load test (stagnation) plate temperature distribution also presented by graphs through FIGURE 4-23 to FIGURE 4-28.

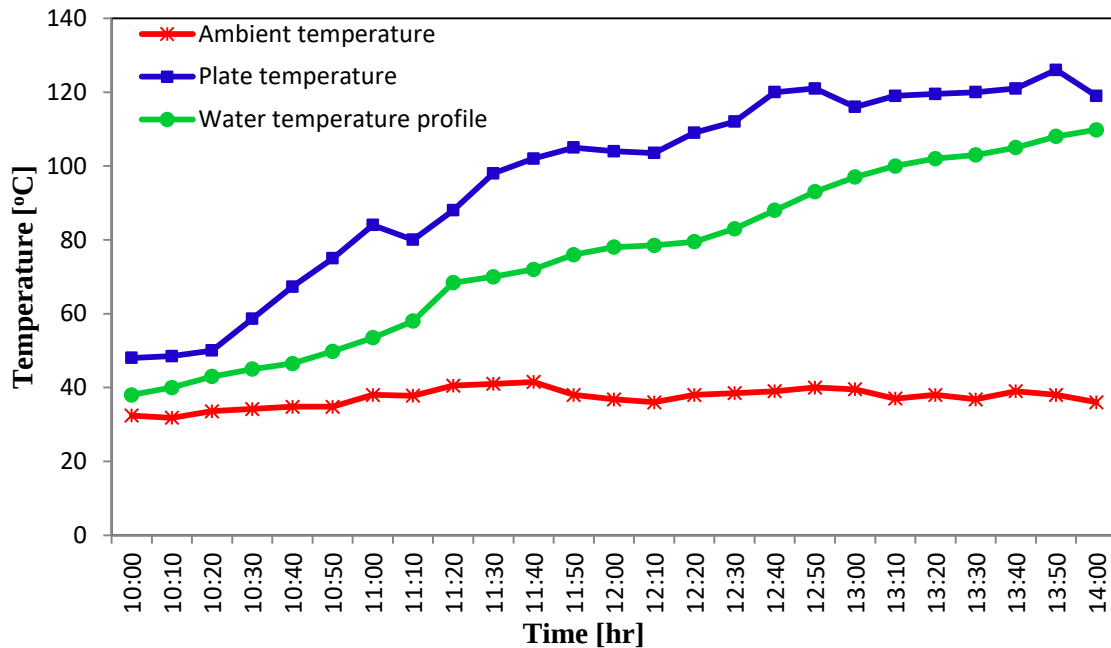


FIGURE 4-17: Load test of Conventional (05/10/2011 E.C)

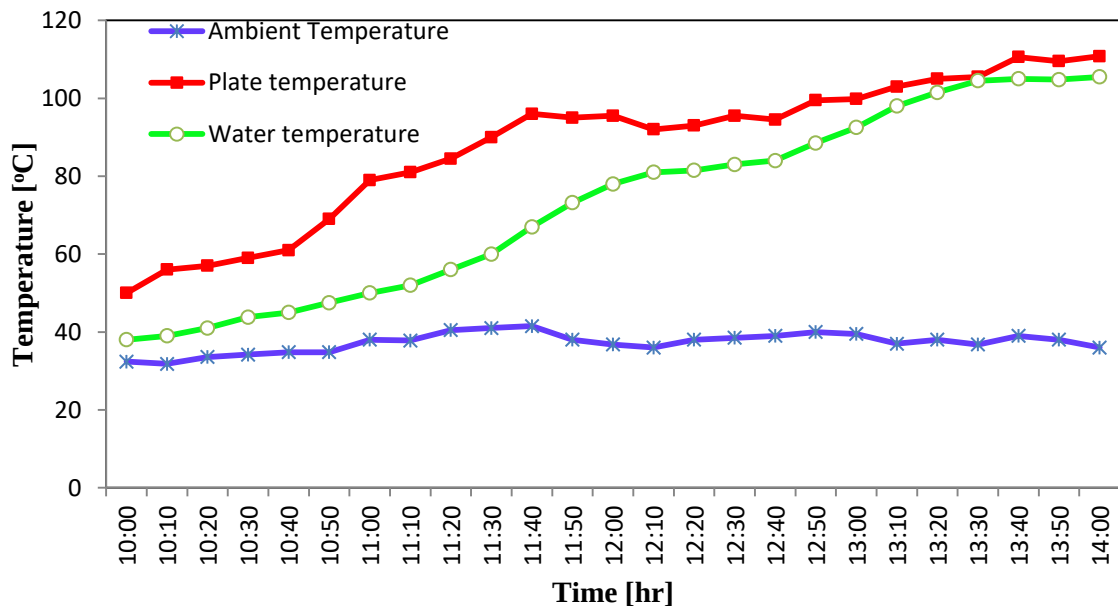


FIGURE 4-18: Load test of improved solar cooker with B.S as TES (05/10/2011 E.C)

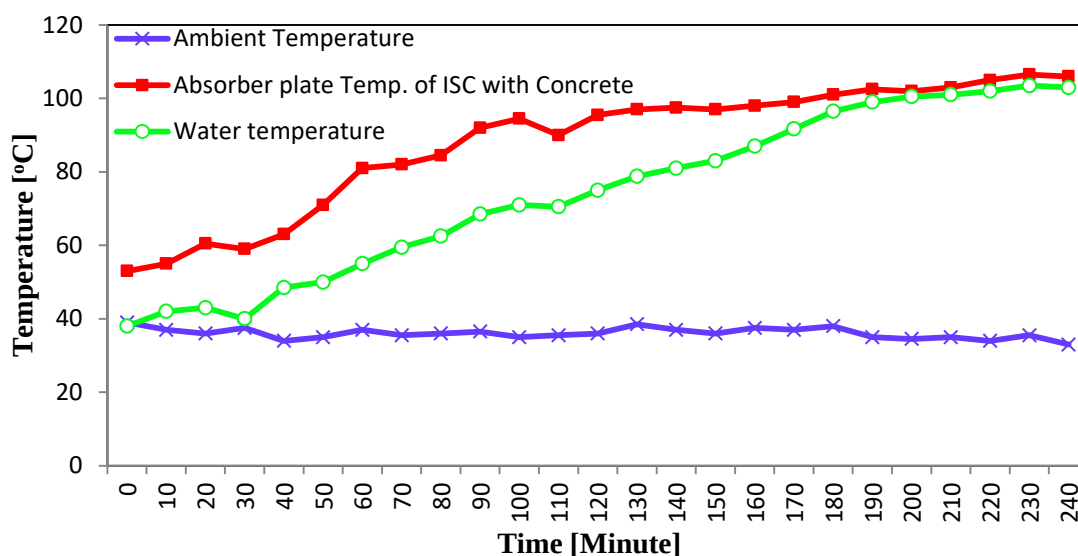


FIGURE 4-19: Load test of improved SC with Concrete as TES (02/10/2011 E.C)

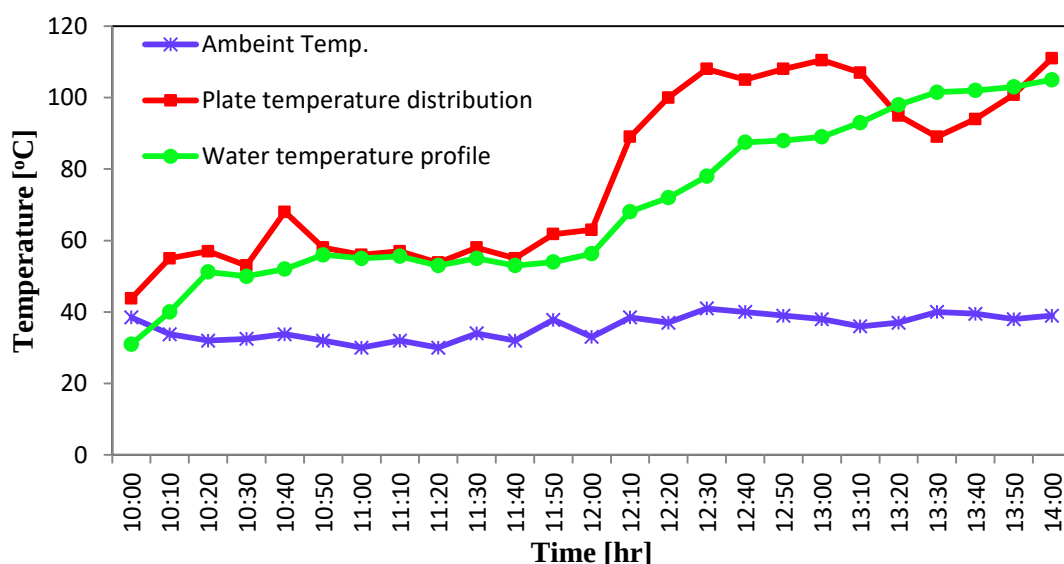


FIGURE 4-20: Load test of Conventional Solar Cooker (06/10/2011 E.C)

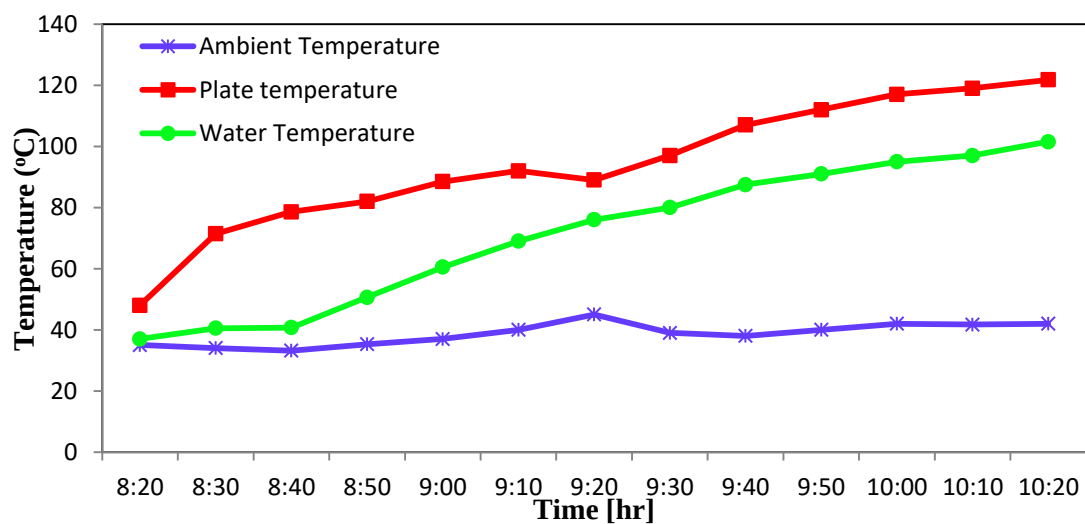


FIGURE 4-21: Cooking test IBSC without storage (08/10/2011)

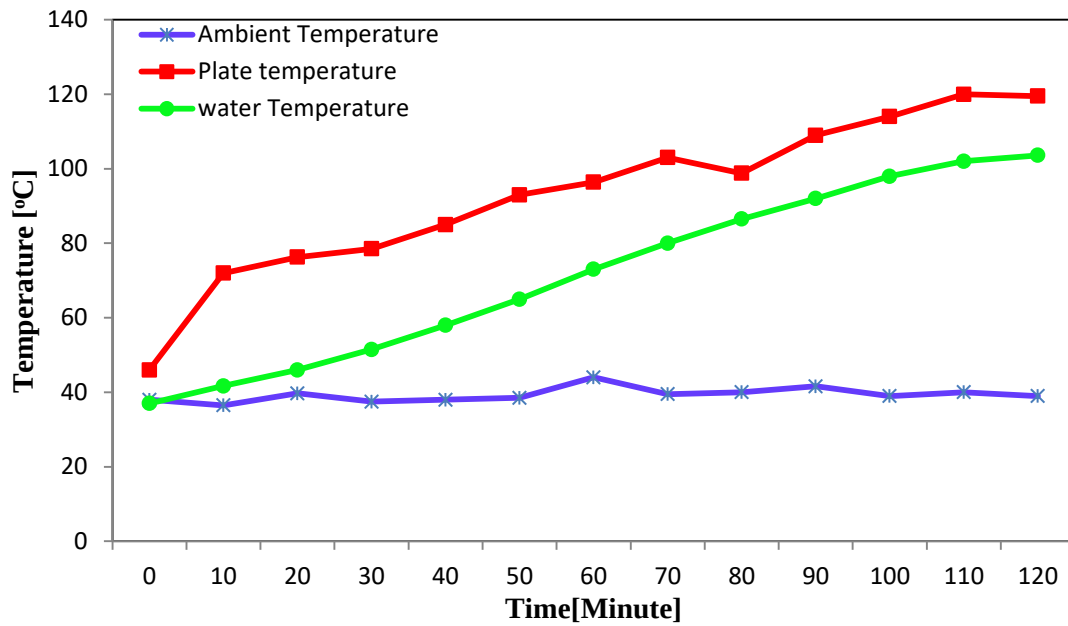


FIGURE 4-22: Water boiling test without storage (08/10/2011 E.C)

As it seen in graphs through FIGURE 4-17 to FIGURE 4-22 the water temperature cannot increase beyond 110°C but as it is seen in theoretical result water temperature reaches about 130°C this much difference has been revealed because at above 95°C water begin to boiling then raised steam was covering the inner surface of transparent glaze (cover Glass).

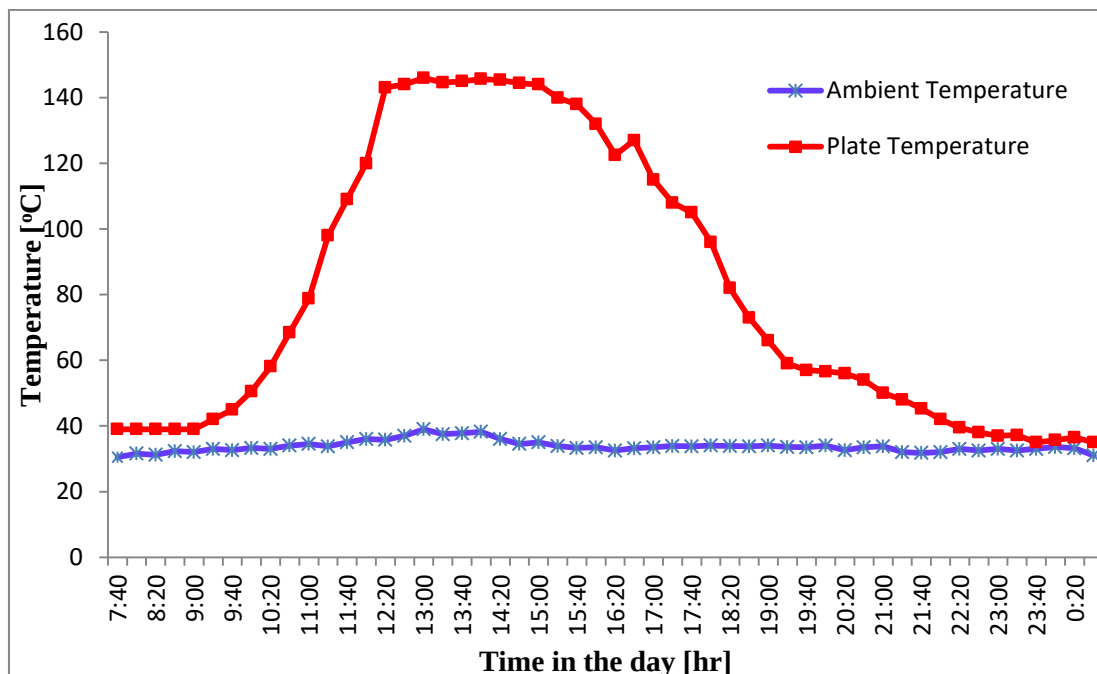


FIGURE 4-23: Stagnation Test of Conventional BSC (03/10/2011 E.C)

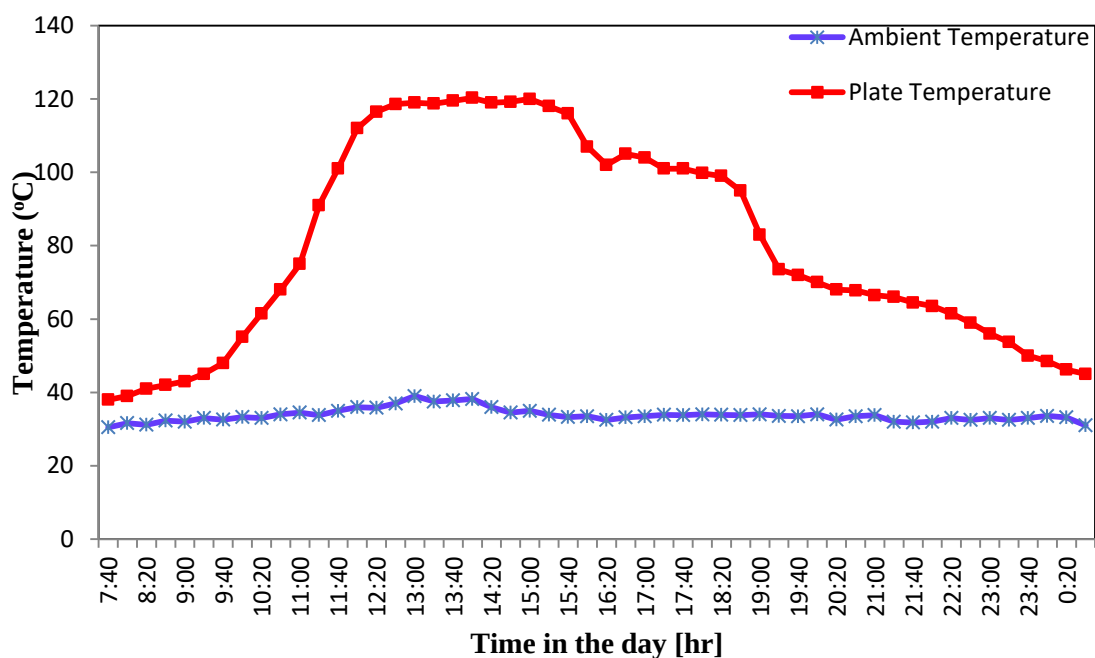


FIGURE 4-24: Stagnation Test IBSC Concrete as thermal Storage (03/10/2011 E.C)

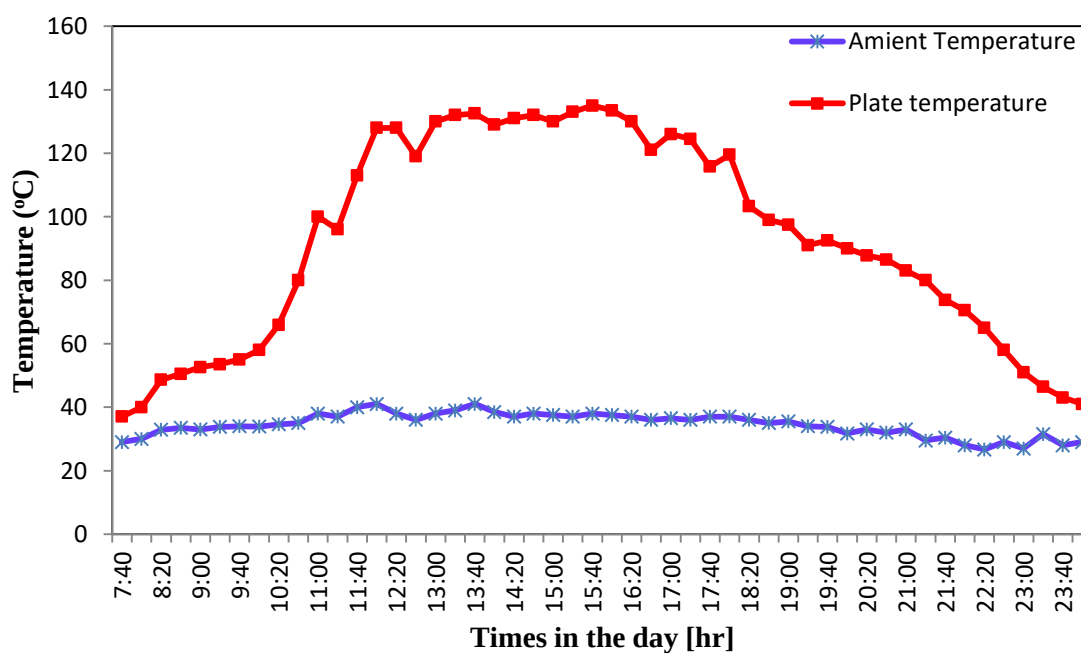


FIGURE 4-25: Stagnation Test of ISC with Black stone as thermal Storage (04/10/2011 E.C)

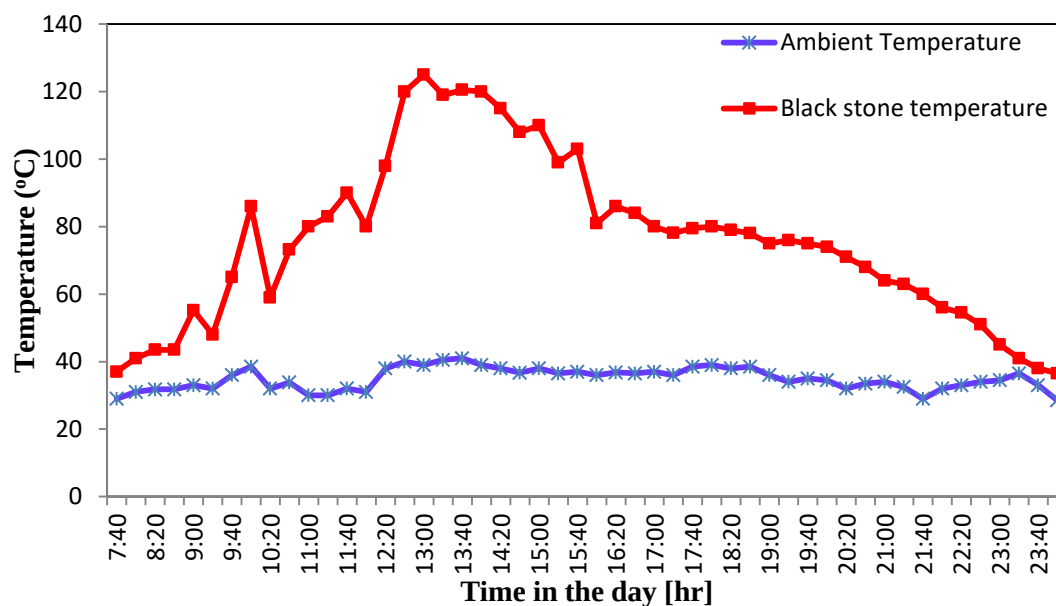


FIGURE 4-26: Stagnation Test of ISC with Black stone as Absorber (06/10/2011 E.C)

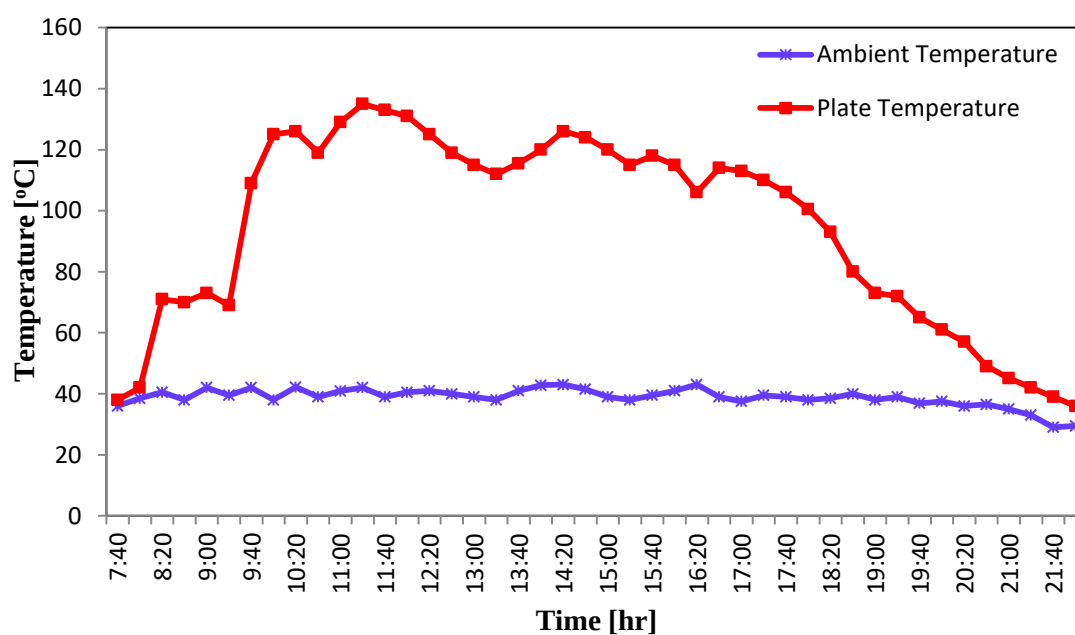


FIGURE 4-27: Second Stagnation Test of conventional (07/10/2011 E.C)

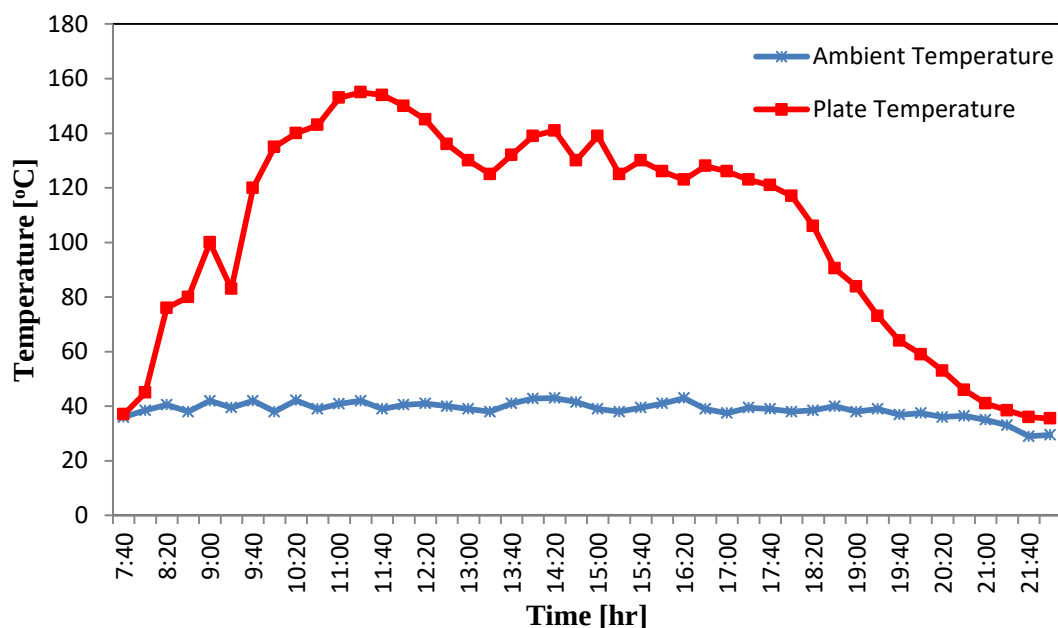


FIGURE 4-28: Second Stagnation Test of IBSC without storage (07/10/2011 E.C)

4.2.2.1. Comparing of Stagnation Temperature profile

In FIGURE 4-29: the stagnation absorber plate temperature distribution of conventional BSC and improved BSC with different TES material and without TES is described. As it is seen improved solar cooker absorbed much energy and its maximum temperature is attained as 155°C while maximum temperature attained by conventional solar cooker is about 139°C.

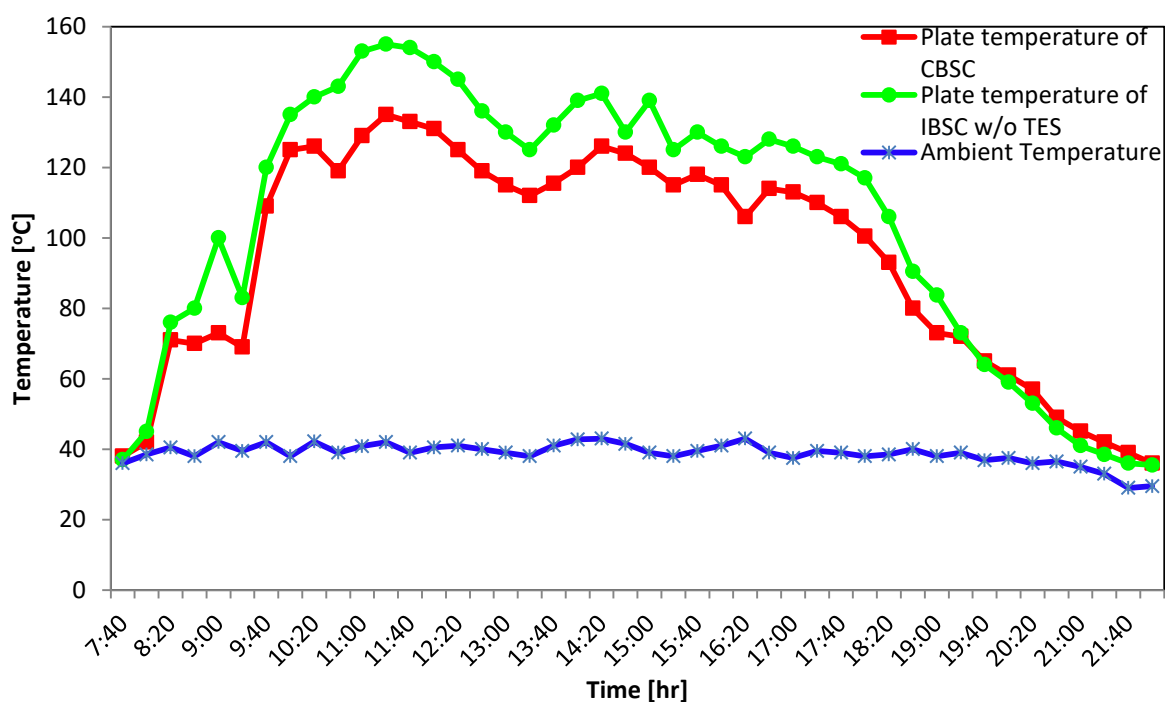


FIGURE 4-29: Plate temperature of improved cooker without TES

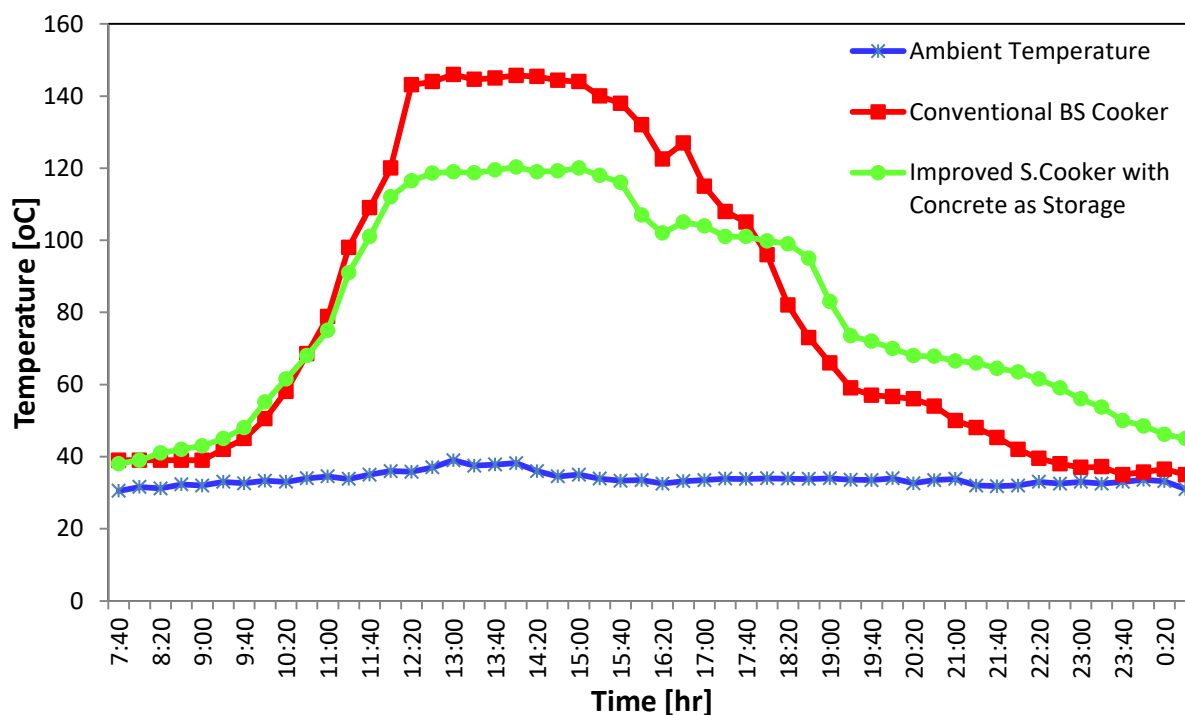


FIGURE 4-30: plate temperature of improved cooker with concrete

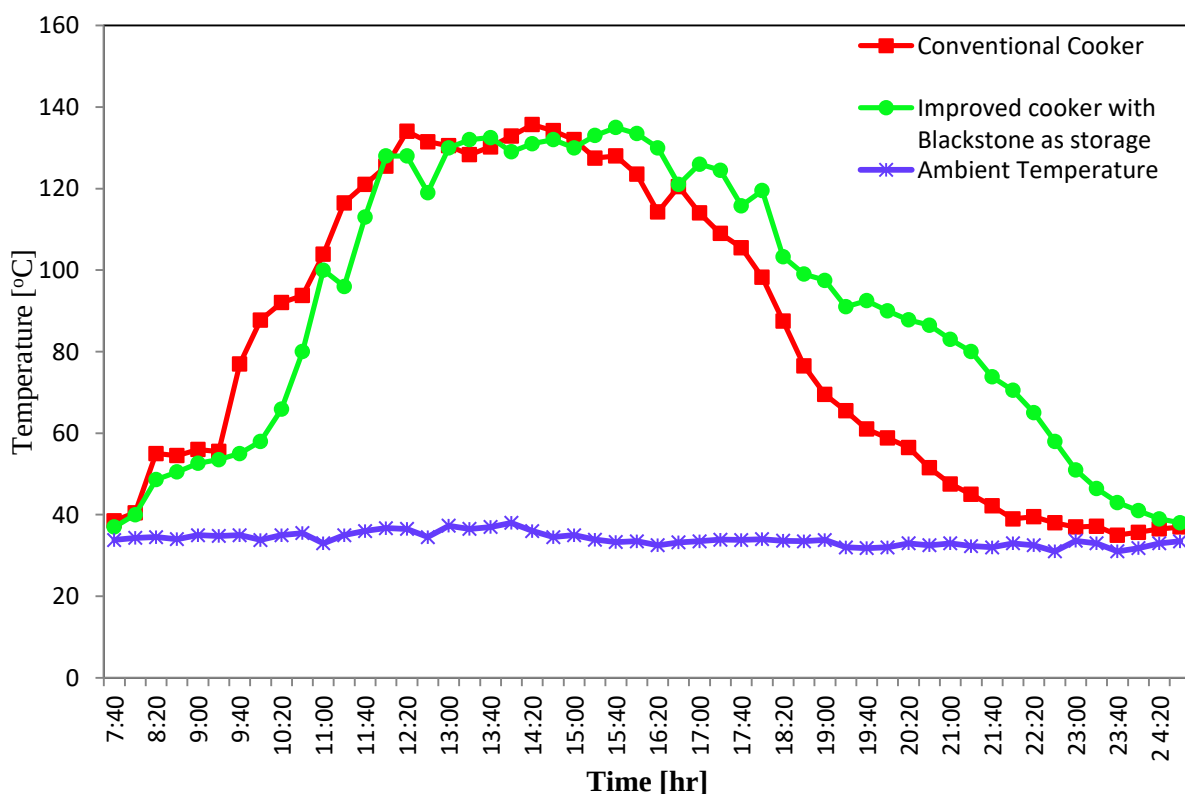


FIGURE 4-31: Blackstone temperature of improved cooker with black stone

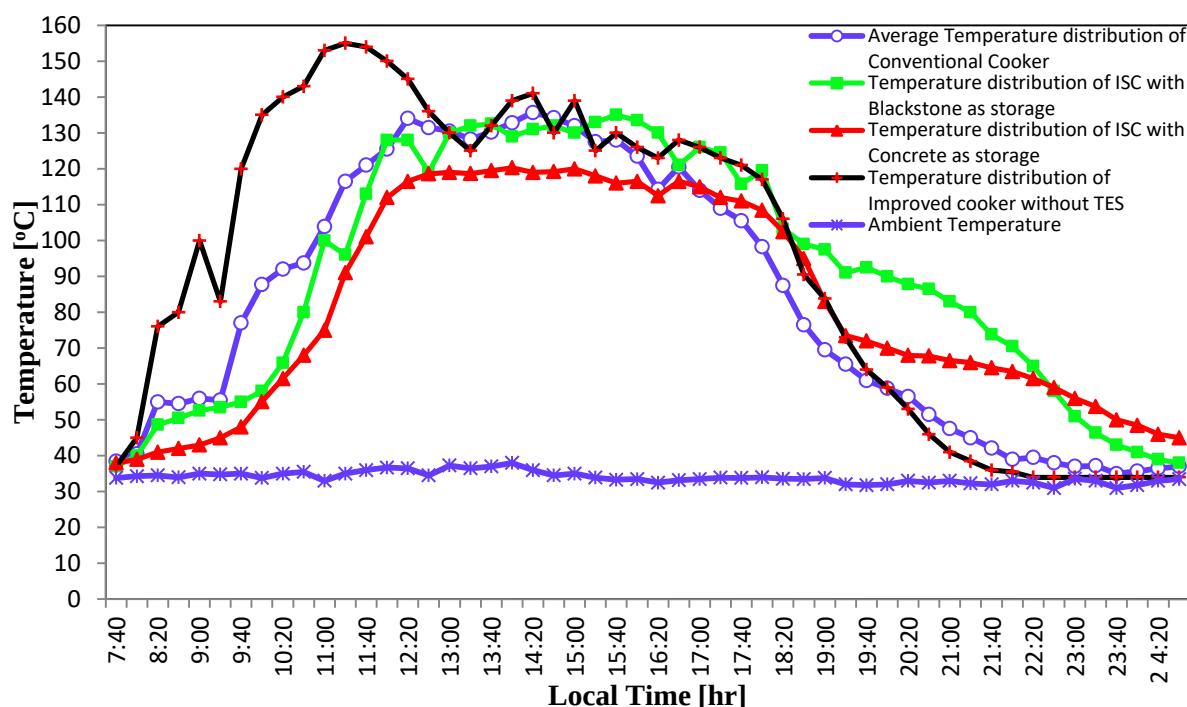


FIGURE 4-32: Comparing of plate temperature of IBSC with Average CBSC

4.2.2.2. Comparing of Water temperature profile

In full load water test equal amount of water added for both cookers and stayed for 4 hours. In FIGURE 4-33 below the plate temperature and water temperature profile has been described. As it is seen in figure below the water testing was started in 10:00 at 38°C for both cookers but after 10 minutes the difference have started wide between both cookers. After one hour, at 11:00, water in the conventional box solar cooker reached 53.5°C and water in improved solar cooker reached 50°C. This much difference is because of in improved solar cooker there was additional 6.25 kg load black stone is put as thermal energy storage. The difference of Plate temperature distributions is also increasing slowly in each of 10 minutes. So averagely water temperature in CBSC and in IBSC increased 3°C and 2.8125°C per each 10 minutes (0.3°C/minute and 0.281°C/minute), respectively. As it is shown in FIGURE 4-36, below, water temperature in the improved box solar cooker without any thermal energy storage is possible to attain above 100°C water temperature in 120 minutes. This can show clearly the difference between improved and conventional solar cooker. As seen in figure both water and absorber plate temperatures are increasing with wide difference in each of 10 minutes. Initially water was at 37°C and after 120 minutes it has become 101.5°C, so averagely it increased 5.375°C per each 10 minutes (0.5375°C/minute).

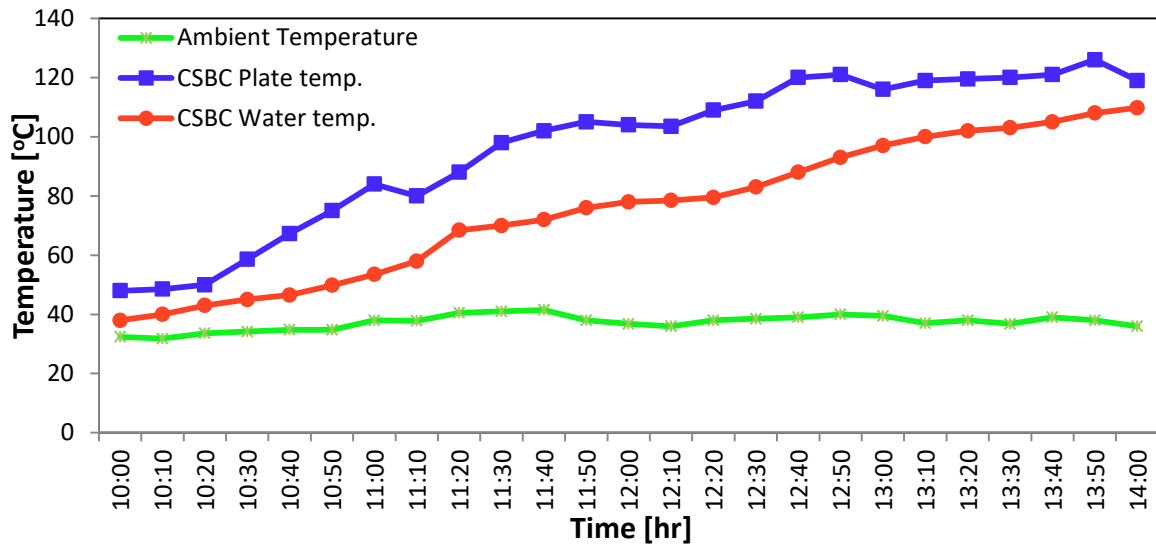


FIGURE 4-33: Load test Temperature profile of CBSC (Averaged)

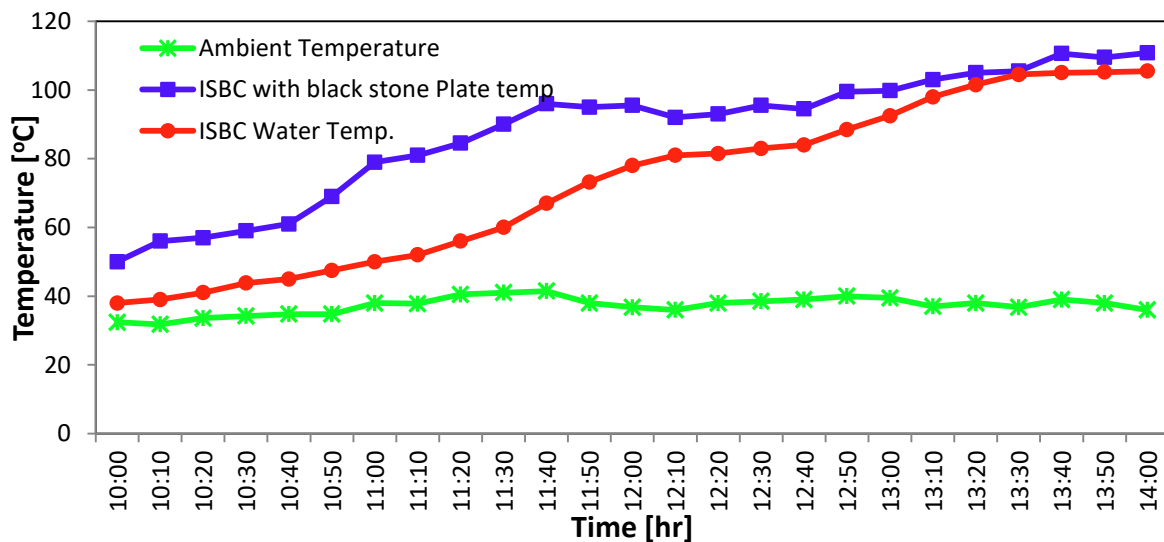


FIGURE 4-34: Load test temperature profile for IBSC with Blackstone as TES

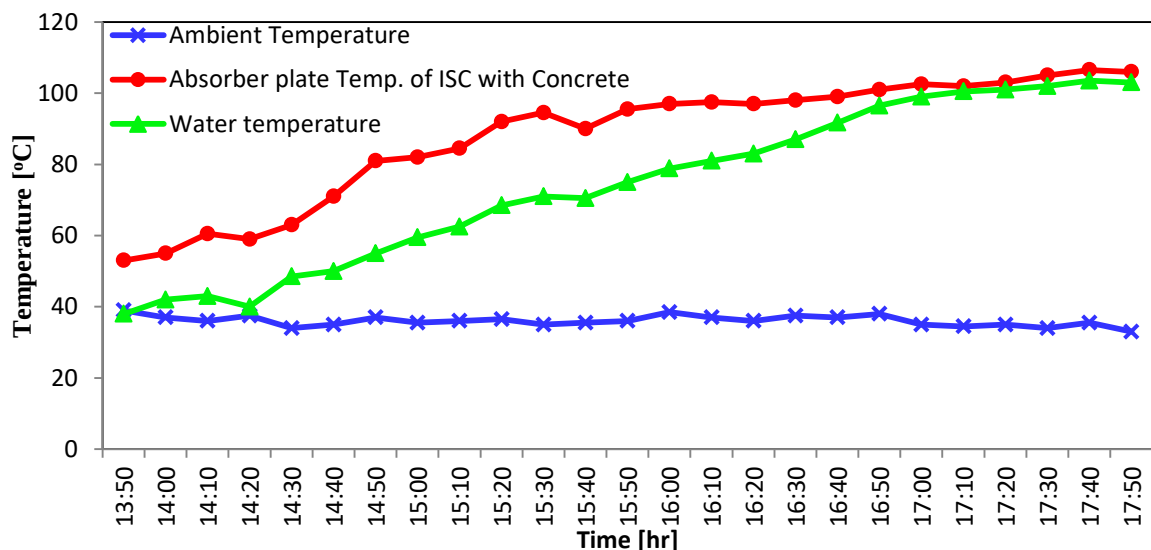


FIGURE 4-35: Load Test Temperature profile for IBSC with Concrete as TES

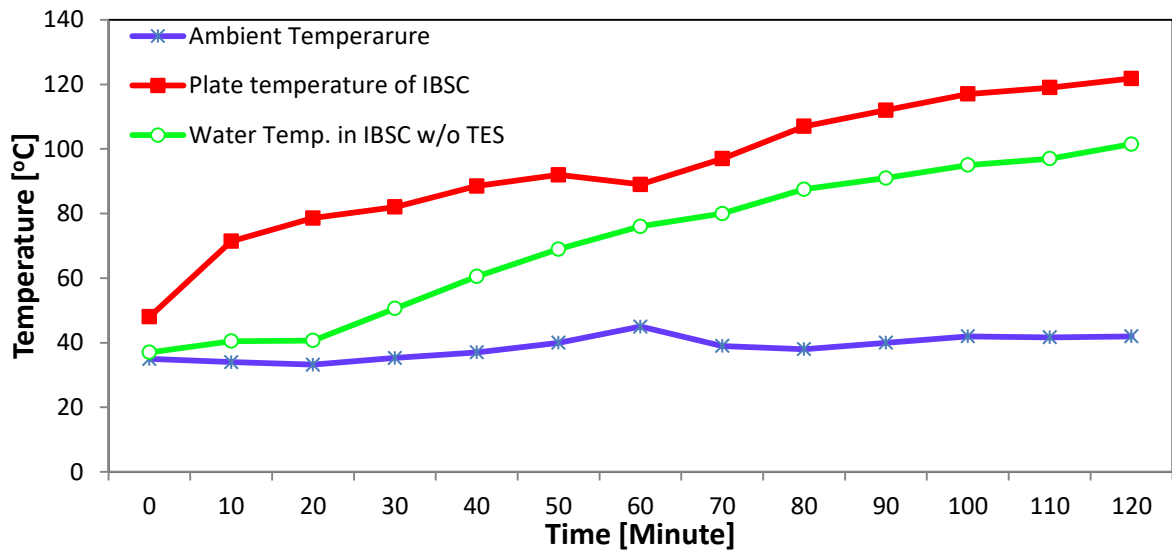


FIGURE 4-36: Water temperature profile for Improved BSC without any TES

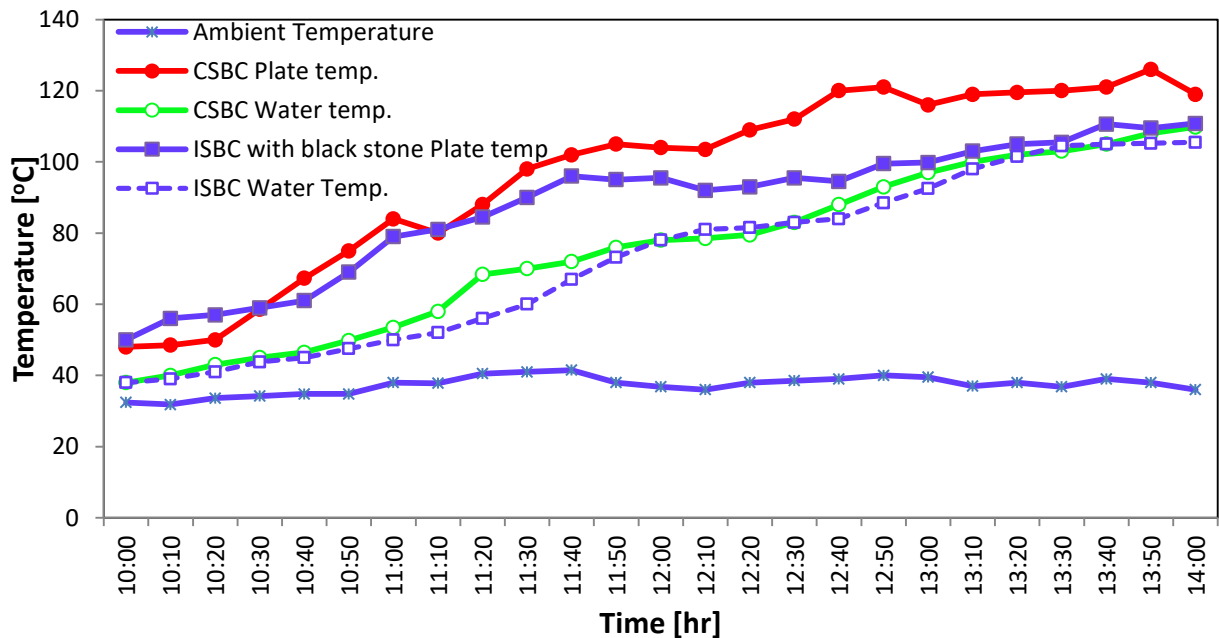


FIGURE 4-37: Comparing of Load test temperature profile

4.2.3. Cooking tests

Cooking test is conducted at 11:00 up to 14:00 in 15th June 2019 G.C (08/10/2011 E.C) 0.5 kg potato with one liter water added in to both cooking pans, and then Shoforo with two liter water have been cooked. The improved cooker without storage cooked the potato in 48th minute, Improved SC with black stone as TES spent 85 minutes to cook and conventional cooker stayed 110 minutes to cook the same amount of potato. Shoforo is put in only by improved cooker and it was cooked enough to drink after 80 minutes. Prediction of sensible heating time required to rise water temperature to 95°C is described below in FIGURE 4-38.

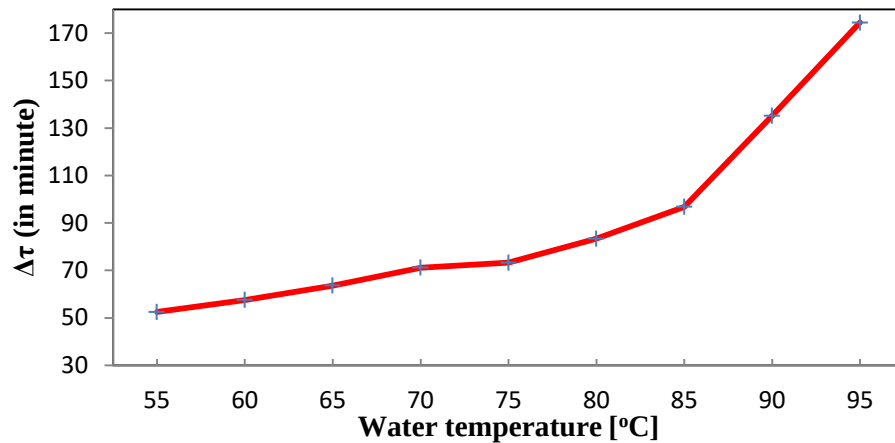


FIGURE 4-38: Prediction of sensible heating time from ambient to 95°C

4.3. Performance measurement of the system

4.3.1. Figures of merits comparison

The theoretical values of first (F1) and second (F2) figures of merits are 0.117 and 0.563 respectively for solar collecting area of 0.25 m² conventional solar cooker. The experimental values of first figure of merits has been described in Appendix E and it's averaged as 0.115, 0.1349, 0.1238 and 0.1453 for conventional BSC, improved BSC with Blackstone, improved BSC with concrete and improved BSC without any thermal storage, respectively. A high value of F1 indicates good optical efficiency and low heat loss factor.

The second figure of merits of solar cookers is also described in TABLE 4-1 below. Its average values are calculated as 0.524, 0.97, 0.865 and 1.0964 for conventional box solar cooker, improved solar cooker with Concrete and with black stone as thermal energy storage and ISC without any TES respectively. A high value of F2 shows cooker has good heat exchange efficiency factor F' , good optical efficiency η_o , and low heat capacity of the cooker interiors and vessels compared to a full load of water. So there is a good relationship between theoretical and experimental analysis of solar cooker performance.

The validation of the study is already accomplished by compering Conventional solar cooker with Improved Solar Cooker and also to validate with review study; Awash (2014) and Shrestha et al. (2007) experimental assessments are selected. The work presented by Shrestha et al (2007) is conventional BSC with and w/o stone pebbles and Awash (2014) designed modified type solar cooker with trapezoidal glazing surface. According to the results described in this thesis work above, improved solar cooker with TES is better than the works of Awash (2014) and shrestha et al (2007). For instance the maximum temperature obtained

without stone pebble is about 130°C; in this thesis also conventional BSC maximum no-load temperature is 145°C. This much difference is revealed due to the difference of volume of cookers. The first and Second figures of merits are 0.19 and 0.55 for shrestha et al work, in this work it is 0.115 and 0.524 respectively.

TABLE 4-1: Result summary of cooker performance (figures of merits)

Solar cookers conditions	1 st Figure of merits		2 nd Figure of merits		Awash(2014)		Shrestha (2007)	
	Exper.	Theor.	Exper.	Theor.	F1	F2	F1	F2
Conventional BSC (0.25m ²)	0.115	0.117	0.524	0.5634	0.125	0.14	0.19	0.55
Conventional BSC (0.0882m ²)	-	0.075	-	0.4218		-	-	-
Improved BSC with concrete	0.135	-	0.865	-	-	-	-	-
IBSC with Blackstone	0.124	-	0.97	-	-	-	0.23	0.27
IBSC w/out TES	0.145	-	1.0964	-	0.125	0.28	-	-

4.3.2. Standardized power vs. Temperature difference comparison

According to ASAE S580 standard (Funk (2013)) the values of standardized cooking power for a temperature difference of 50°C should be computed by using regression equations for the each load tests. Based on this plotted results of the standardized cooking power (Ps) and temperature difference (Td) of Improved BSC without any storage is shown in FIGURE 4-39. The values of standardized cooking power for a temperature difference at 50°C computed by using regression equations are 37.043 W, 39.411W and 87.872 W for conventional BSC, Improved BSC with black stone and Improved BSC without any storage respectively.

This standard is mainly used to compare different cookers or the same cooker in various weather conditions. Therefore as it can be seen from the calculated values improved solar cooker without TES has higher power than other due to this it is able to cook food faster than others. But using this standard alone is not appropriate for hourly averaged solar radiation energy because very low value of R² of linear regression describes that ASAE standard is not as much as good for hourly averaged solar radiation, because it is highly dependent on values

weather condition so it needs direct radiation measurement with each time intervals for temperature measuring.

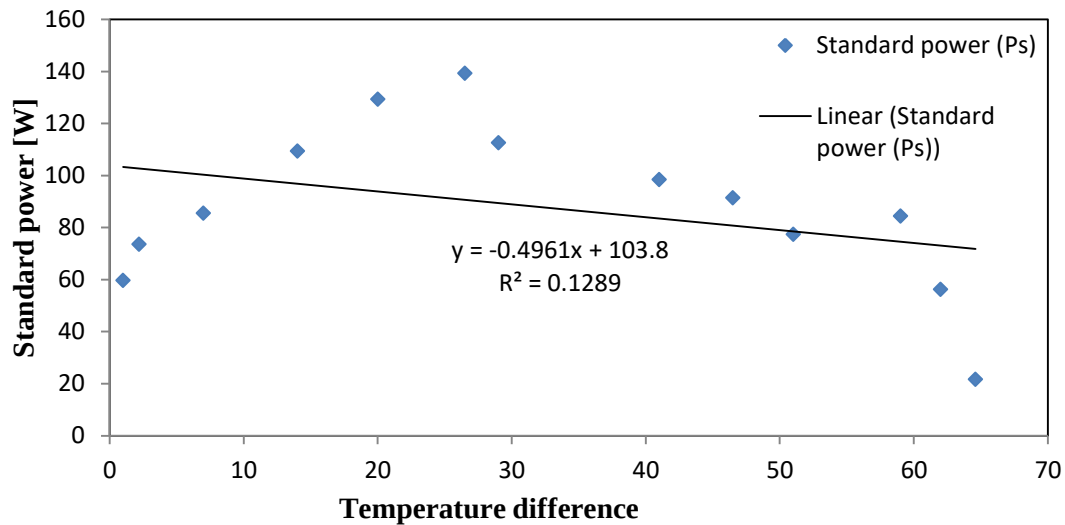


FIGURE 4-39: Standard power (Ps) for ISC w/o TES

4.4. Economic Analysis

Life Cycle Costing (LCC) is the sum of all costs associated with an energy delivery system over a selected period of analysis or over its lifetime. Life Cycle Saving (LCS) is the difference in between the LCC of conventional or alternative fuel system and the LCC of the solar energy system in the present worth (Duffy and Beckman, 1991). These two methods can be used in this economic analysis of the cooker.

The payback period is calculated by considering 10% annual interest, 5% maintenance cost and 5% inflation in fuel prices and maintenance cost. We can assume that charcoal and firewood provides 10% and 90% of rural energy demand respectively. The solar cooker is capable of cooking for about 4 persons, and it will save 50% of cooking fuel per meal. According to Nahar, (2009) the energy for cooking per person is about 900 kJ of fuel equivalent per meal.

4.4.1. Total costs of improved solar cooker

Total cost of improved solar cooker construction has been described in TABLE 4-2 below.

TABLE 4-2: Total cost of the improved solar cooker

No.	Equipment	Amount	Cost per equipment (birr)	Total cost of equipment (birr)
1	4x4 Frame wood	3x3 m (length)	110 per 3 m	330.00
2	Plywood	2m ²	300 per 2 m ²	300.00
3	Reflectors	0.52*0.6 m ²	600 per m ²	150.00
4	Glazing glass	2*0.52*0.6 m ²	250 per m ²	156.00
5	Aluminum foil	0.46*5 m ²	50 per 0.46*5 m ²	50.00
6	Sheet metal as absorber	0.75 m ²	1100 per 2 m ²	412.50
7	Insulation (inset fiber)	3 kg	30 per Kg	90.00
8	Construction and others			660.00
Total cost of the cooker				2048.50

4.4.2. Costs of alternative energy sources

Alternative energy sources in most rural part of Ethiopia are firewood and/or charcoal. So in Omorate, Daassanech, as it is observed 90% and 10% of domestic energy need is met by firewood and charcoal respectively.

Cost of using charcoal and firewood can be calculated as the following:

- Daily energy requirement is 7.2 MJ, (2(twice) x 4 person x 900kJ/person).
- Amount of firewood required to cover 90% of daily energy demand is 4.5 kg.
- Calorific value of charcoal 28 MJ/kg at a cost of 4 birr/kg with an efficiency of 17% for local clay stoves.
- Charcoal requirement per day to meet the energy demand is given by

$$\frac{7.2 \text{ MJ}}{28 \frac{\text{MJ}}{\text{kg}} \times 0.17} = 1.51 \text{ kg}$$

To substitute charcoal to equivalent amount of firewood, by considering 3kg of firewood is required for every 1kg of charcoal, is given by $4.5 / 3 = 1.5$ kg of charcoal.

- Total amount of required equivalent amount charcoal per day is $(0.9*1.5 + 0.1*1.51) = 1.501$ kg.
- Cost of equivalent amount charcoal to meet the daily energy demand is $4 \text{ birr} \times 1.501 = 6.04$ birr.
- Annual equivalent amount of firewood requirement is calculated as $(0.9*4.5 + 0.1*3*1.51) \text{ kg} \times 365 = 1643.6$ kg.

For a lifespan of 10 years about 16.5 tons of wood would be required.

- Annual cost for charcoal or firewood is $6.04 \times 365 = 2204.6$ birr.

The **payback period** was computed using the following relation (Nahar, (2009)):

$$N = \frac{\left[\log \left[\frac{E-M}{a-b} \right] - \log \left[\frac{E-M}{a-b} - C \right] \right]}{\log \left[\frac{1+a}{1+b} \right]} \dots\dots\dots 4.1$$

Where; E = Energy savings per year (Birr),

M = Maintenance cost per year (Birr)

a = Compound annual interest rate per year, (%),

b = Inflation rate in energy and maintenance per year, (%),

N = Payback period (year)

Energy savings per year is calculated by considering 50% of the yearly energy consumption, $E = 0.5 \times 2204.6 \text{ birr} = 1102.3 \text{ birr}$

Maintenance cost per year (M) is 5% of total cost of cooker,

$$M = 0.05 \times 2048.5 = 102.425 \text{ birr}$$

Compound annual interest rate per year (a) is assumed to be 10% of total cooker cost.

Payback period can be calculated as described in equation 4.1

$$N = \frac{\left[\log \left[\frac{1102.3 - 102.425}{0.1 - 0.05} \right] - \log \left[\frac{1102.3 - 102.425}{0.1 - 0.05} - 2048.5 \right] \right]}{\log \left[\frac{1 + 0.1}{1 + 0.05} \right]} = 2.4798$$

TABLE 4-3: Economic analysis of newly improved solar cooker

Year	Cash flow (birr)	Interest (birr)	Maintenance (birr)	Energy savings (birr)	Net savings (birr)
0	-2048.50	-	-	-	-
1	-977.9	204.85	102.425	1102.3	795.025
2	-182.875	97.79	107.55	1157.415	952.075
3	769.2	18.2875	112.84	1215.286	1084.158

Therefore the payback period of improved solar cooker when compared with firewood and charcoal as alternative energy source is 2.5 years.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

A solar cooker with thermal energy storage was designed, constructed and tested for experimental thermal performance at Omorate, Daassanech, Ethiopia. The system designed was modeled by using SOLIDWORKS, and analytically calculated by using Microsoft Excel software.

For thermal energy storage system four frequently used sensible thermal storage materials have been selected and tested. From those four locally available materials to choose the best one its thermal properties have been studied. As described above black stone with its better specific heat capacity and relatively high conductivity was chosen from those materials and inset fiber also found that it can be a good insulator for any thermal systems

From the study and the analysis of the collected data, the conclusions have been summarized as follows;

- The two solar cooking systems were designed and fabricated for experimental testing with solar collector area 0.25m^2 for Daassanech/Omorate weather condition. The designed solar cooker can entrap 201.12W average rate of energy in between 10:00AM up to 14:00 PM in minimum solar intensity month, July.
- The total inner surface areas including absorber plate for conventional solar cooker and for improved one is calculated as 0.8m^2 and 0.645m^2 , respectively. Therefore, improved SC with square glaze or trapezoidal absorber area which has additional 5 cm height to hold thermal storage material became 20% less size than the conventional solar cooker inner area for the same intercept area of the sun.
- The construction of the cooker was carried out at local furniture with local carpenters. The performance testing was carried out in 9th up to 15th June, 2019. The performance evaluation was described by figures of merits; the first figures of merits have become averaged as 0.115, 0.1349, 0.1238 and 0.1453 for conventional BSC, improved BSC (Blackstone), improved BSC (concrete) and improved BSC without any thermal storage, respectively. The second figures of merits average values are also calculated as 0.524, 0.97, 0.865 and 1.0964 for conventional box solar cooker, improved solar cooker

with Concrete and with black stone as thermal energy storage and ISC without any TES respectively. According to BIS standard improved cooker with/without storage are ranked in grade A due to first figure of merits is greater than 0.12 and conventional BSC is categorized in to Grade B.

- The values of standardized cooking power for a temperature difference at 50°C computed by using regression equations are 37.043 W, 39.411W and 87.872 W for conventional BSC, Improved BSC and Improved BSC without any storage respectively. Therefore as it can be seen from the calculated values improved solar cooker without TES has high power than others, due to this it is able to cook food faster than others in the time when good solar intensity is available.
- The system performance and cooking ability of the cookers was compared with each other and then improved solar cooker was able to attain above 100°C temperature of water in morning (8:20 – 10:20) with low solar intensity.
- The black stone with its better specific heat capacity and relatively high conductivity is chosen as a better storage material. About 6.25 kg is used in the cooker bottom which is able to store about 420000 J amount of energy in between 10:00AM to 2:00 PM. And it is made sure that “inset” fiber can be a good insulator for any thermal system.
- The payback period of improved solar cooker when compared with firewood and charcoal as alternative energy source is 2.5 years. The cost of the system was 2048.50 birr (74 US Dollar) and expected annual energy saving 1102.3 Ethiopian birr (39 US Dollar).

5.2. Recommendations

- The solar potential available, the possibility to use it for cooking/ heating and the benefits of an improved solar cooker were presented in the chapters above. Therefore, to use this high potential energy to cooking cum heating in the solar remote areas especially in daassanech, governmental and other NGOs even ASTU should work cooperatively for technology transformation.
- This study could continue further with different thermal storage materials and with different locally available insulations under various weather conditions.
- If glass wiper for cleaning the inner surface of the glass is used in the box under cover glass, it might make a significant difference.

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ANNEX A: Average Solar Radiation Results

TABLE A-1: Average Solar Radiation Results of different source

Months	Sunshine data based GHI weatherbase	Helioclim -3 satellite (France)	NASA data base	National SRD for Omorate	Average of 4 data	NMA for Jinka	Sunshine based averaged SR data
Jan	6.789054	5.730194	6.6216	6.139	6.31997	6.3500571	6.443829
Feb	7.021081	6.147429	6.3814	6.284	6.4585	6.5470284	6.562697
Mar	7.003777	5.723226	6.0490	6.339	6.27876	6.3302545	6.379182
Apr	6.655736	5.1912	5.7507	5.584	5.7954	5.5039623	5.887446
May	6.402462	5.227355	5.7976	5.688	5.77885	5.0319579	5.860035
Jun	6.106914	5.3752	5.4133	5.859	5.6886	3.6965191	5.735646
Jul	5.976383	5.266452	5.3372	5.621	5.5503	3.6586676	5.577911
Aug	6.466117	5.69729	5.7468	6.396	6.07655	4.7657556	6.131786
Sep	6.883461	5.5748	6.1037	6.579	6.2852	4.6036796	6.388194
Oct	6.887971	5.311355	5.5482	6.148	5.9739	5.4368955	6.109012
Nov	6.760407	5.6308	5.7507	6.131	6.06822	5.9481028	6.175466
Dec	6.691206	6.024774	6.1348	6.196	6.2617	6.5290217	6.351157
Annual Average daily solar radiation						6.134 /m2/day	

ANNEX B: SOLIDWORKS and Experimental Pictures of Setups

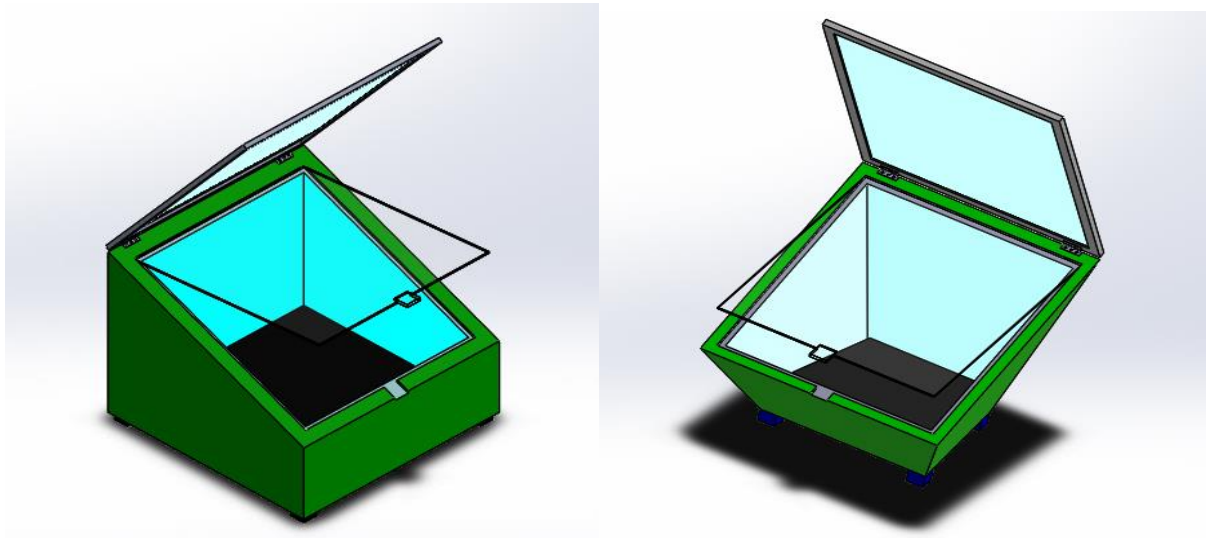


FIGURE B-1: Conventional and Improved Solar cookers with equal aperture area

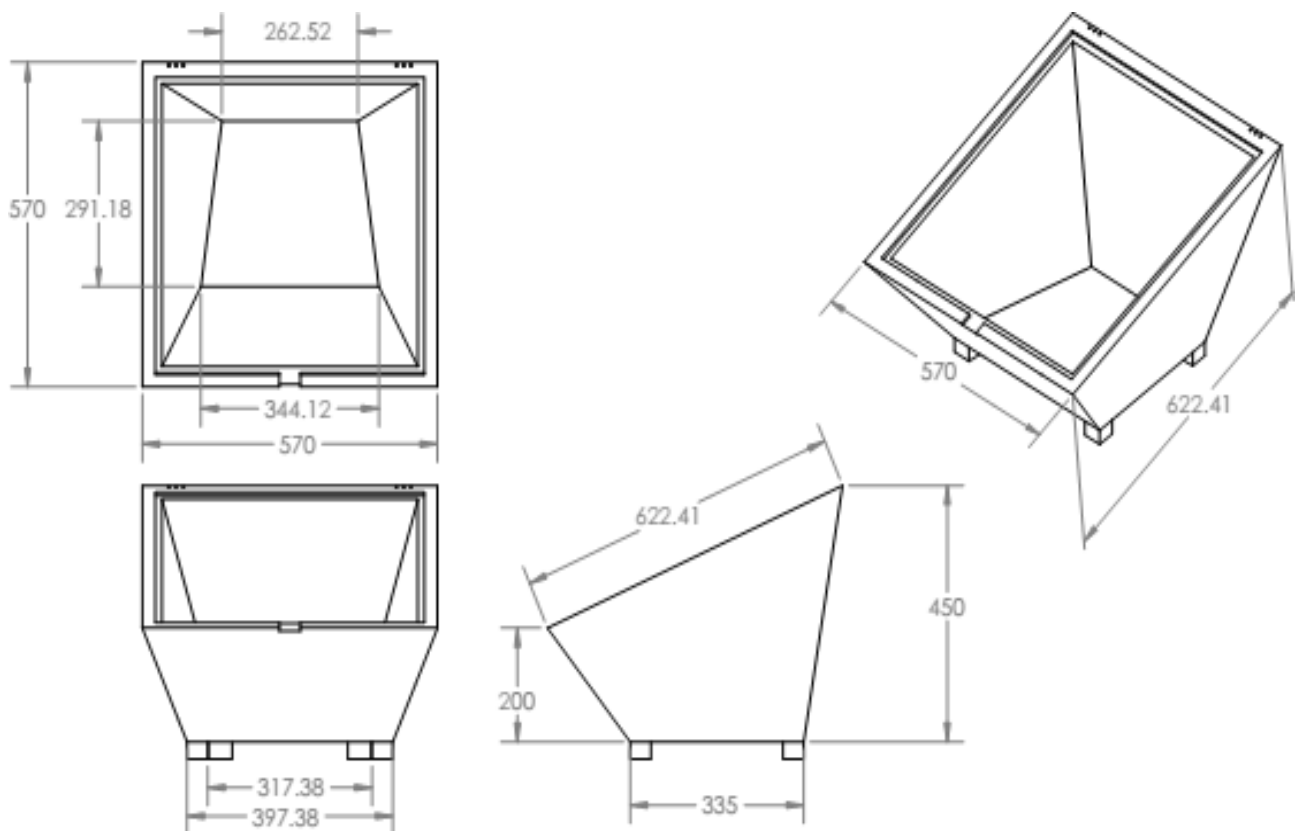


FIGURE B-2: Schematic diagram and dimensions of improved solar cooker



FIGURE B-3: Experimental setups and Cooking tests

ANNEX C: Thermocouple Calibration

C.1. Thermocouple Theory

There are many types of thermometers. Those thermometers measure temperature depending by the characteristics of expansion and contraction of substance, the valuable electrical characteristics (electrical resistance) of materials, or heat radiation energy emitted from surface of material. A thermocouple consists of two dissimilar metal wires, welded or soldered together to join at one end, called the measurement “hot” junction. The other end called the reference “cold” junction, where the wires are not joined, is connected to the signal conditioning circuit, typically made of copper. The voltage produced at the reference junction depends on the temperatures at both the measurement junction and the reference junction. Then it converts to temperature based on the thermocouple reference tables or a data logger. The most popular thermocouple is the type K, consisting of Chromel and Alumel (trademarked nickel alloys containing chromium, and aluminum, manganese, and silicon, respectively), with a measurement range of -200°C to $+1250^{\circ}\text{C}$.

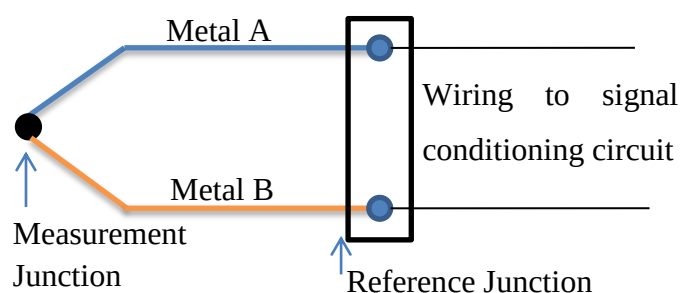


FIGURE C-1: Thermocouple Principle

C.2. Calibration test with standard thermocouples

Calibration of thermometers can be carried out using a reference thermometer in a temperature calibration test by comparing both measurement values of a reference thermometer and other thermometers

Calibration test for four channel digital k-type thermocouple was conducted in thermal laboratory with two standard thermocouples (WL362 and SG742 model) by using 0.2kg water boiling and cooling test for 39 minutes.

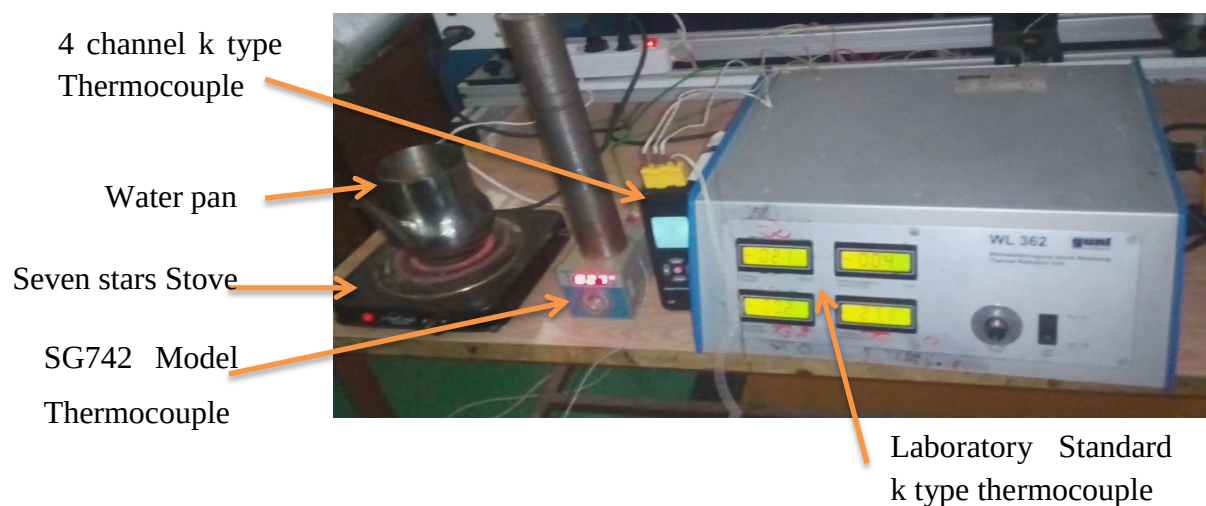


FIGURE C-2: Calibration Setup: Two thermocouples and one calibrator

TABLE C-1: Water temperature measuring test by using k-type thermocouples

Time (minute)	Tw1 (WL362)	Tw2(Digital four channel Thermocouple)	Uncertainty (%) (Tw1-Tw2)*100
1	75.2	74.9	0.398936
3	71.2	71	0.280899
5	68.2	68.4	0.292398
7	64.2	64	0.311526
9	60	59.8	0.333333
11	58.8	58.7	0.170068
13	58	57.8	0.344828
15	56.5	56.575	0.132567
17	55.85	55.45	0.716204
19	54.225	53.7	0.968188
21	52.875	52.5	0.70922
23	51.9	52	0.192308
25	50.975	50.675	0.588524
27	50.475	50.2	0.544824
29	49.125	48.825	0.610687
31	44	44.1	0.226757
33	50.63333	50.33333	0.592495
35	49.83333	49.5	0.668896
37	47	46.9	0.212766
39	44	44.1	0.226757
Average Uncertainty (%)			0.42611

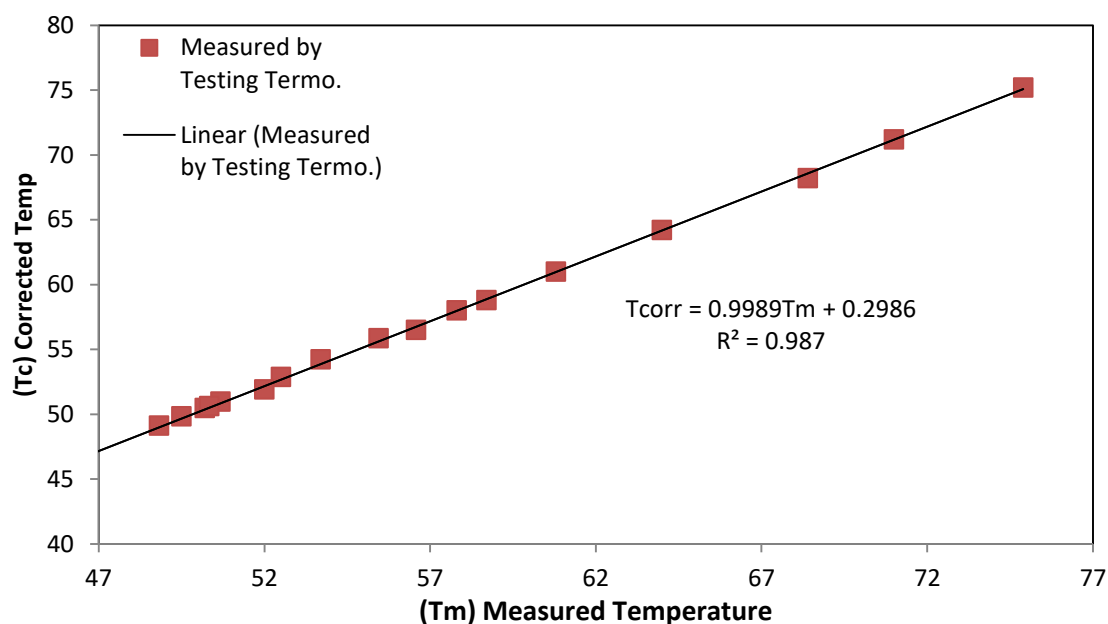


FIGURE C-3: Measured Temperature versus Corrected temperature

So it can be concluded that the four channel k- type thermocouple is good enough with uncertainty of 0.62%. SG742 model thermocouple is not as much as good with 4.34% of average uncertainty.

TABLE C-2: Summary of Sample temperature measurements

Actual Temperature (°C)	Measured Temperature (°C)	Uncertainty (%)
25	24.7286	1.085594
50	49.75613	0.487737
75	74.78366	0.288451
100	99.81119	0.188808
150	149.8663	0.089165

Four channel digital thermometer Specifications

- Serial Number: 2019002867
- Temperature range: -50 to 1350°C or -58 to 2462 oF
- Accuracy: $\pm [0.015\%rdg + 1^{\circ}C (1.8^{\circ}F)]$
- Resolution: 0.1 °C for <1000°C; 1 °C for >1000°C
- Storage temp. and Humidity: -10 to 60°C and 10 to 75% RH
- Power supply: 9V
- Weight: approx. 230g.

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ANNEX D: Theoretical Analysis by Microsoft Excel for Solar Cooker with A_c of 0.25 M^2

TABLE D-1: Theoretical Estimation of No load (stagnation) plate Temperature

Time	A_c	A_e	K	ε_c	ε_p	f	c	T_a	Vw	h _v	U _b	U _l	U _t	T _{p6}	H _i	F ₁
5:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	29	5	17.8	0.9	2	4.625296	35	0	-
6:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	29	5	17.8	0.9	2	5.287114	44.12838	49.27106	0.307044
6:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	29	5	17.8	0.9	2	5.579366	45.13457	49.27106	0.327465
6:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	30	5	17.8	0.9	2	5.60152	46.0944	49.27106	0.32665
7:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.01849	65.41268	197.148	0.164408
7:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.40521	66.13317	197.148	0.168062
7:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.417839	66.14069	197.148	0.168101
8:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.69992	83.01241	356.9843	0.140097
8:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.952569	82.56127	356.9843	0.138833
8:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.945705	82.58114	356.9843	0.138889
9:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	7.167049	97.70463	504.7884	0.128182
9:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	7.364372	96.60124	504.7884	0.125996
9:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	7.349875	96.69628	504.7884	0.126184
10:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.423173	101.5314	520.8713	0.129651
10:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.4856	101.0765	520.8713	0.128777
10:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.479595	101.121	520.8713	0.128863
11:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	35	5	17.8	0.9	2	7.612872	110.5213	608.5863	0.124093
11:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	37	5	17.8	0.9	2	7.725924	111.3297	608.5863	0.122135
11:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	40	5	17.8	0.9	2	7.712738	114.0764	608.5863	0.121719
12:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	43	5	17.8	0.9	2	7.860707	119.5375	639.7059	0.119645
12:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	42	5	17.8	0.9	2	7.944978	117.7982	639.7059	0.118489
12:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	41	5	17.8	0.9	2	7.883575	117.0982	639.7059	0.118958
13:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	41	5	17.8	0.9	2	7.807123	114.2514	608.5863	0.120363
13:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	39	5	17.8	0.9	2	7.763579	112.7403	608.5863	0.121166
13:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	39	5	17.8	0.9	2	7.751959	112.9395	608.5863	0.121494
14:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	38	5	17.8	0.9	2	7.624769	103.5839	520.8713	0.125912
14:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	38	5	17.8	0.9	2	7.506782	104.6448	520.8713	0.127949

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14:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	36	5	17.8	0.9	2	7.506623	102.6423	520.8713	0.127944
15:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	35	5	17.8	0.9	2	7.450102	98.02351	504.7884	0.124851
15:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.383339	97.51243	504.7884	0.12582
15:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.37649	97.55755	504.7884	0.125909
16:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	34	5	17.8	0.9	2	7.165015	82.63545	356.9843	0.13624
16:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.946123	82.57781	356.9843	0.13888
16:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.946014	82.58039	356.9843	0.138887
17:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.689713	65.98401	197.148	0.167306
17:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.414774	66.13924	197.148	0.168093
17:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.417931	66.14075	197.148	0.168101
18:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	6.112512	49.96195	49.27106	0.344258
18:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	5.72492	49.15911	49.27106	0.327964
18:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	5.702252	49.09721	49.27106	0.326707
19:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	5.333864	36.73536	0	-
19:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	4.532517	34.09212	0	-
19:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	4.056687	33.3582	0	-
20:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.736837	33.12599	0	-
20:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.467121	33.04714	0	-
20:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
21:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
21:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	--
21:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
22:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
22:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
22:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
23:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	33	5	17.8	0.9	2	3.202156	33.004	0	-
23:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	30	5	17.8	0.9	2	4.37393	30.91647	0	-
23:40	0.25	0.55	0.045	0.8	0.96	0.759938	520	30	5	17.8	0.9	2	3.935619	30.3106	0	-
0:00	0.25	0.55	0.045	0.8	0.96	0.759938	520	30	5	17.8	0.9	2	3.6372	30.113	0	-
0:20	0.25	0.55	0.045	0.8	0.96	0.759938	520	30	5	17.8	0.9	2	3.429049	30.04362	0	-
														Average values		0.164361

Performance Investigation of Improved Box Type Solar Cooker With Thermal Energy Storage

D.2. Theoretical estimation of Temperature distribution of full load

TABLE D-2: Theoretical Estimation of Full load Temperature

Time	Ac	K	Emm. of cover	Emm. of plate	f	C	Ta	Tp Estimated	Vwind	Hv	Ub	UI	Ut0	mc*Cp	a	b
10:00	0.25	0.05	0.8	0.96	0.7599	520	33	35	5	17.8	0.9	2.2	6.696402854	1800	69.06889	-0.03637
10:10	0.25	0.05	0.8	0.96	0.7599	520	33	38	5	17.8	0.9	2.2	6.604947339	1800	69.06889	0.007921
10:20	0.25	0.05	0.8	0.96	0.7599	520	33	38	5	17.8	0.9	2.2	6.820208848	1800	69.06889	-0.01002
10:30	0.25	0.05	0.8	0.96	0.7599	520	34	39	5	17.8	0.9	2.2	6.795548132	1800	69.06889	-0.00796
10:40	0.25	0.05	0.8	0.96	0.7599	520	34	39	5	17.8	0.9	2.2	6.862127322	1800	69.06889	-0.01351
10:50	0.25	0.05	0.8	0.96	0.7599	520	34	39	5	17.8	0.9	2.2	6.862127322	1800	69.06889	-0.01351
11:00	0.25	0.05	0.8	0.96	0.7599	520	35	40	5	17.8	0.9	2.2	6.837719989	1800	78.16531	-0.01148
11:10	0.25	0.05	0.8	0.96	0.7599	520	35	40	5	17.8	0.9	2.2	6.904372052	1800	78.16531	-0.01703
11:20	0.25	0.05	0.8	0.96	0.7599	520	36	41	5	17.8	0.9	2.2	6.880219079	1800	78.16531	-0.01502
11:30	0.25	0.05	0.8	0.96	0.7599	520	37	42	5	17.8	0.9	2.2	6.923046206	1800	78.16531	-0.01859
11:40	0.25	0.05	0.8	0.96	0.7599	520	38	43	5	17.8	0.9	2.2	6.966202179	1800	78.16531	-0.02218
11:50	0.25	0.05	0.8	0.96	0.7599	520	39	44	5	17.8	0.9	2.2	7.009687807	1800	78.16531	-0.02581
12:00	0.25	0.05	0.8	0.96	0.7599	520	41	46	5	17.8	0.9	2.2	7.025744932	1800	81.36805	-0.02715
12:10	0.25	0.05	0.8	0.96	0.7599	520	42	47	5	17.8	0.9	2.2	7.14213073	1800	81.36805	-0.03684
12:20	0.25	0.05	0.8	0.96	0.7599	520	42	47	5	17.8	0.9	2.2	7.209288777	1800	81.36805	-0.04244
12:30	0.25	0.05	0.8	0.96	0.7599	520	41	46	5	17.8	0.9	2.2	7.227826173	1800	81.36805	-0.04399
12:40	0.25	0.05	0.8	0.96	0.7599	520	41	46	5	17.8	0.9	2.2	7.164737418	1800	81.36805	-0.03873
12:50	0.25	0.05	0.8	0.96	0.7599	520	40	45	5	17.8	0.9	2.2	7.183529851	1800	81.36805	-0.04029
13:00	0.25	0.05	0.8	0.96	0.7599	520	40	45	5	17.8	0.9	2.2	7.120518034	1800	78.16531	-0.03504
13:10	0.25	0.05	0.8	0.96	0.7599	520	39	44	5	17.8	0.9	2.2	7.139564579	1800	78.16531	-0.03663
13:20	0.25	0.05	0.8	0.96	0.7599	520	38	43	5	17.8	0.9	2.2	7.095929529	1800	78.16531	-0.03299
13:30	0.25	0.05	0.8	0.96	0.7599	520	37	42	5	17.8	0.9	2.2	7.052623875	1800	78.16531	-0.02939
13:40	0.25	0.05	0.8	0.96	0.7599	520	36	41	5	17.8	0.9	2.2	7.009646792	1800	78.16531	-0.0258
13:50	0.25	0.05	0.8	0.96	0.7599	520	36	41	5	17.8	0.9	2.2	6.94694385	1800	78.16531	-0.02058
14:00	0.25	0.05	0.8	0.96	0.7599	520	35	40	5	17.8	0.9	2.2	6.966997457	1800	78.16531	-0.02225



Performance Investigation of Improved Box Type Solar Cooker With Thermal Energy Storage

C	Tp1	Ut1	B	C	Tp2	Ut2	B	C	Tp3	Ut3	b	C
1.036367	99.8297	7.344299	-0.090358274	1.090358	94.09775	7.194081	-0.07784	1.07784	95.33828	7.227202	-0.0806	1.0806
0.992079	102.0847	7.441708	-0.061808961	1.061809	97.93822	7.307184	-0.0506	1.050599	98.97743	7.338425	-0.0532	1.053202
1.010017	102.0188	7.471244	-0.064270368	1.06427	97.62879	7.35552	-0.05463	1.054627	98.52154	7.381843	-0.05682	1.05682
1.007962	103.037	7.487236	-0.065603019	1.065603	98.60665	7.366951	-0.05558	1.055579	99.53245	7.391888	-0.05766	1.057657
1.013511	103.0013	7.500538	-0.06671153	1.066712	98.46333	7.378404	-0.05653	1.056534	99.41644	7.404132	-0.05868	1.058678
1.013511	103.0013	7.500055	-0.066671274	1.066671	98.46848	7.376509	-0.05638	1.056376	99.43472	7.402796	-0.05857	1.058566
1.011477	113.1194	7.640173	-0.078347714	1.078348	107.8376	7.507357	-0.06728	1.06728	108.8952	7.534879	-0.06957	1.069573
1.017031	113.0802	7.775111	-0.089592597	1.089593	106.1664	7.61166	-0.07597	1.075972	107.6317	7.645636	-0.0788	1.078803
1.015018	114.1052	7.793149	-0.091095729	1.091096	107.1436	7.606048	-0.0755	1.075504	108.8675	7.649292	-0.07911	1.079108
1.018587	115.091	7.825068	-0.093755657	1.093756	107.9363	7.633895	-0.07782	1.077825	109.7064	7.681474	-0.08179	1.08179
1.022184	116.0766	7.856668	-0.096389035	1.096389	108.7346	7.659475	-0.07996	1.079956	110.5735	7.708845	-0.08407	1.08407
1.025807	117.0621	7.888477	-0.099039723	1.09904	109.5317	7.685278	-0.08211	1.082107	111.4396	7.736767	-0.0864	1.086397
1.027145	122.2866	7.983733	-0.106977755	1.106978	114.2311	7.769383	-0.08912	1.089115	116.2608	7.823845	-0.09365	1.093654
1.036844	123.2207	8.073671	-0.114472622	1.114473	114.1774	7.83823	-0.09485	1.094853	116.5167	7.898725	-0.09989	1.099894
1.042441	123.1558	8.085559	-0.115463291	1.115463	113.99	7.834885	-0.09457	1.094574	116.542	7.902608	-0.10022	1.100217
1.043986	122.1041	8.064323	-0.113693593	1.113694	113.0275	7.814415	-0.09287	1.092868	115.5896	7.884864	-0.09874	1.098739
1.038728	122.1744	8.050964	-0.112580325	1.11258	113.2373	7.804015	-0.092	1.092001	115.7414	7.873859	-0.09782	1.097822
1.040294	121.1263	8.031779	-0.110981571	1.110982	112.2482	7.788802	-0.09073	1.090734	114.723	7.857076	-0.09642	1.096423
1.035043	117.9901	7.975008	-0.106250691	1.106251	109.5456	7.737948	-0.0865	1.086496	111.9161	7.804651	-0.09205	1.092054
1.03663	116.9455	7.912842	-0.101070141	1.10107	109.1818	7.691627	-0.08264	1.082636	111.3357	7.753742	-0.08781	1.087812
1.032994	115.9673	7.880233	-0.098352788	1.098353	108.4008	7.671966	-0.081	1.080997	110.3998	7.728701	-0.08573	1.085725
1.029385	114.989	7.848732	-0.095727643	1.095728	107.6059	7.646536	-0.07888	1.078878	109.5334	7.699933	-0.08333	1.083328
1.025804	114.0105	7.817434	-0.093119518	1.09312	106.8099	7.621061	-0.07676	1.076755	108.6692	7.672325	-0.08103	1.081027
1.020579	114.0624	7.805034	-0.092086191	1.092086	106.9816	7.612588	-0.07605	1.076049	108.7803	7.662147	-0.08018	1.080179
1.02225	113.0318	7.787032	-0.090586011	1.090586	106.0034	7.59791	-0.07483	1.074826	107.7792	7.646074	-0.07884	1.07884

Performance Investigation of Improved Box Type Solar Cooker With Thermal Energy Storage

Tp4	Ut4	b	C	Tp5	Ut5	b	C	Tp6	Tw	Hi	F1	F2
95.07602	7.220843	-0.08007	1.08007	95.12503	7.221948	-0.08016	1.080162	95.1168	49	504.7884	0.123055	1.70311
96.61388	7.302431	-0.08687	1.086869	96.6764	7.303963	-0.087	1.086997	96.59708	60.9453	520.8713	0.122098	1.481878
96.37581	7.320269	-0.08836	1.088356	96.44824	7.322119	-0.08851	1.08851	96.44651	66.30649	520.8713	0.121808	0.837547
97.40856	7.333216	-0.08943	1.089435	97.49033	7.335342	-0.08961	1.089612	97.42617	70.17809	520.8713	0.121769	0.679475
97.24607	7.34521	-0.09043	1.090434	97.33459	7.347555	-0.09063	1.09063	97.32475	72.87967	520.8713	0.121575	0.535252
97.26871	7.343284	-0.09027	1.090274	97.35944	7.345753	-0.09048	1.090479	97.33774	75.20895	520.8713	0.1216	0.51113
106.7578	7.476263	-0.10136	1.101355	106.854	7.478818	-0.10157	1.101568	106.3505	81.98734	520.8713	0.136983	1.412264
105.1322	7.583117	-0.11026	1.11026	105.2533	7.586055	-0.1105	1.110505	105.3414	85.93494	608.5863	0.115582	0.898871
106.4008	7.581881	-0.11016	1.110157	106.5499	7.585559	-0.11046	1.110463	106.4389	89.59614	608.5863	0.115742	0.956175
107.1594	7.613139	-0.11276	1.112762	107.3396	7.61764	-0.11314	1.113137	107.2583	93.19692	608.5863	0.115445	1.105468
108.0181	7.638984	-0.11492	1.114915	108.2178	7.6442	-0.11535	1.11535	108.121	96.78801	608.5863	0.11522	1.332034
108.8684	7.666259	-0.11719	1.117188	109.0772	7.671894	-0.11766	1.117658	108.9764	100.3931	608.5863	0.114982	1.693441
113.7025	7.752851	-0.1244	1.124404	113.9249	7.758835	-0.1249	1.124903	113.5686	106.525	608.5863	0.119241	3.136309
114.7839	7.843862	-0.13199	1.131988	115.0361	7.850488	-0.13254	1.132541	114.9176	111.9486	639.7059	0.112423	4.906506
114.5356	7.855489	-0.13296	1.132957	114.8239	7.863028	-0.13359	1.133586	114.7672	115.6538	639.7059	0.112188	1.694564
113.5368	7.833564	-0.13113	1.13113	113.8564	7.842001	-0.13183	1.131833	113.8349	118.0276	639.7059	0.112294	-3.93888
113.7237	7.822288	-0.13019	1.130191	114.0546	7.831325	-0.13094	1.130944	113.9473	120.5923	639.7059	0.112469	-2.30368
111.657	7.787362	-0.12728	1.12728	111.9845	7.79641	-0.12803	1.128034	112.0259	121.8953	639.7059	0.112592	-0.66957
109.1155	7.723842	-0.12199	1.121987	109.4241	7.732629	-0.12272	1.122719	109.486	121.7208	639.7059	0.108622	0.064578
107.5879	7.65992	-0.11666	1.11666	107.869	7.668002	-0.11733	1.117333	107.8725	121.7884	608.5863	0.114811	-0.02346
105.872	7.608083	-0.11234	1.11234	106.1231	7.615311	-0.11294	1.112943	106.1466	121.9807	608.5863	0.115262	-0.05916
106.2032	7.589259	-0.11077	1.110772	106.4255	7.595699	-0.11131	1.111308	106.3419	123.5831	608.5863	0.115582	-0.47352
105.1517	7.575879	-0.10966	1.109657	105.3574	7.581668	-0.11014	1.110139	105.362	125.122	608.5863	0.115615	-0.39373
105.3444	7.564256	-0.10869	1.108688	105.5407	7.569698	-0.10914	1.109142	105.4761	127.2159	608.5863	0.115803	-0.49258
105.3145	7.566461	-0.10887	1.108872	105.5068	7.57172	-0.10931	1.10931	105.4599	129.6119	608.5863	0.115776	-0.50804
Average values of Figures of merits											0.117141	0.56344

ANNEX E: Results of Experimental Tests

E.1. Stagnation Test

03/10/2011 E.C/ 10/06/2019 G.C Monday

Local Time	Ta	Tp1	Tp2
7:40	30.5	36/Rainy	36/Rainy
8:00	31.6	37/Rainy	36/Rainy
8:20	31.2	37.5/Rainy	36.5/Rainy
8:40	32.3	38/Rainy	37.5/Rainy
9:00	32	37.5/Rainy	38/Rainy
9:20	33	38	38.5
9:40	32.6	45	48
10:00	33.3	50.5	55.1
10:20	33	58.1	61.5
10:40	34	68.5	68
11:00	34.5	78.8	75
11:20	33.8	98	91
11:40	35	109	101
12:00	36	120	112
12:20	35.8	143.1	116.5
12:40	37	144	118.6
13:00	39	146	119
13:20	37.5	144.6	118.7
13:40	37.8	145	119.5
14:00	38.2	145.7	120.3
14:20	36	145.4	119
14:40	34.5	144.4	119.2
15:00	35	144	120
15:20	33.9	140	118
15:40	33.3	138	116

16:00	33.5	132	107
16:20	32.5	122.5	102
16:40	33.2	127	105
17:00	33.5	115	104
17:20	33.9	108	101
17:40	33.8	105	101
18:00	34	96	99.8
18:20	33.9	82	99
18:40	33.8	73	95
19:00	34	66	73
19:20	33.6	59	73.5
19:40	33.5	57	72
20:00	34	56.6	70
20:20	32.6	56	68
20:40	33.5	54	67.8
21:00	33.8	50	66.5
21:20	32	48	66
21:40	31.8	45.3	64.5
22:00	32	42	63.5
22:20	33	39.5	61.5
22:40	32.5	38	59
23:00	33	37	56
23:20	32.5	37.2	53.7
23:40	33	35	50
0:00	33.6	35.7	48.5
0:20	33.2	36.5	46.2
0:40	31	35	45

E.2. Stagnation Temperature with Black stone as thermal Storage

04/10/2011 E.C /11-Jun 2019 G.C

Local Time	Ta	Tp2
7:40	29	37
8:00	30	40
8:20	32.9	48.6
8:40	33.5	50.5
9:00	33	52.6
9:20	33.8	53.5
9:40	34	55
10:00	33.9	58
10:20	34.6	65.9
10:40	35	80
11:00	38	100
11:20	37	96
11:40	40	113
12:00	41	128
12:20	38	128
12:40	36	119
13:00	38	130
13:20	39	132
13:40	41	132.5
14:00	38.5	129
14:20	37	131
14:40	38	132
15:00	37.5	130
15:20	37	133
15:40	38	135

Local Time	Ta	Tp2
16:00	37.5	133.5
16:20	37	130
16:40	36	121
17:00	36.5	126
17:20	36	124.5
17:40	37	115.8
18:00	37	119.5
18:20	36	103.3
18:40	35	99
19:00	35.5	97.5
19:20	34	91
19:40	33.8	92.5
20:00	31.7	90
20:20	33	87.8
20:40	32	86.5
21:00	33	83
21:20	29.5	80
21:40	30.4	73.8
22:00	28	70.5
22:20	26.7	65
22:40	29	58
23:00	27	51
23:20	31.5	46.4
23:40	28	43
0:00	29	41

E.3. Stagnation Temperature with Black stone as Absorber

06/10/2011 E.C /Thursday

Local Time	Ta	Tp2
7:40	29	37
8:00	31	41
8:20	31.8	43.5
8:40	31.8	43.5
9:00	33	55.2
9:20	32	48
9:40	36	65
10:00	38.5	86
10:20	32	59
10:40	33.8	73.2
11:00	30	80
11:20	30	83
11:40	32	90
12:00	31	80
12:20	38	98
12:40	40	120
13:00	39	125
13:20	40.5	119
13:40	41	120.5
14:00	39	120
14:20	38	115
14:40	36.7	108
15:00	38	110
15:20	36.5	99
15:40	37	103

Local Time	Ta	Tp2
16:00	36	81
16:20	36.8	86
16:40	36.5	84
17:00	37	80
17:20	36	78.1
17:40	38.5	79.5
18:00	39	80
18:20	38	79
18:40	38.5	78
19:00	36	75
19:20	34	76
19:40	35	75
20:00	34.5	74
20:20	32	71
20:40	33.5	68
21:00	34	64
21:20	32.5	63
21:40	29	60
22:00	32	56
22:20	33	54.5
22:40	34	51
23:00	34.5	45
23:20	36.5	41
23:40	33	38
0:00	28.5	36.5

E.4. Second Stagnation Test without any thermal storage

07/10/2011 E.C/ 14-Jun Friday

Local Time	Ta	Tp1	Tp3
7:40	36	38	37
8:00	38.5	42	45
8:20	40.5	71	76
8:40	38	70	80
9:00	42	73	100
9:20	39.5	69	83
9:40	45	109	120
10:00	38	125	135
10:20	42.2	126	140
10:40	39	119	143
11:00	40.9	129	153
11:20	42	135	155
11:40	39	133	154
12:00	40.5	131	150
12:20	41	125	145
12:40	40	119	136
13:00	39	115	130
13:20	38	112	125
13:40	41	115.5	132
14:00	42.8	120	139
14:20	43	126	141
14:40	41.5	124	130
15:00	39	120	139
15:20	38	115	125
15:40	39.5	118	130

16:00	41	115	126
16:20	43	106	123
16:40	39	114	128
17:00	37.5	113	126
17:20	39.5	110	123
17:40	39	106	121
18:00	38	100.5	117
18:20	38.5	93	106
18:40	40	80	90.5
19:00	38	73	83.8
19:20	39	72	73
19:40	36.9	65	64
20:00	37.5	61	59
20:20	36	57	53
20:40	36.5	49	46
21:00	35	45.1	41
21:20	33	42	38.5
21:40	29	39	36
22:00	29.5	36	35.5
22:20			
22:40			
23:00			
23:20			
23:40			
0:00			
0:20			
0:40			

E.5. First Load test

TABLE E-1: First Load test

05/10/2011 E.C/ 12-Jun 2019 Wednesday

Local Time	Ta	Tp1	Tw1	Tp2	Tw2
10:00	32.4	48	38	50	38
10:10	31.8	48.5	40	56	39.7
10:20	33.6	50	43	57	41
10:30	34.2	58.6	45	59	43.8
10:40	34.8	67.3	46.5	61	45
10:50	34.8	75	49.8	69	47.5
11:00	38	84	53.5	79	50
11:10	37.8	80	58	81	52
11:20	40.5	88	64.4	84.5	56
11:30	41	98	70	90	60
11:40	41.5	102	72	96	67
11:50	38	105	76	95	73.2
12:00	36.8	104	78	95.5	78
12:10	36	103.5	78.5	92	81
12:20	38	109	79.5	93	81.5
12:30	38.5	112	83	95.5	83
12:40	39	120	88	94.5	84
12:50	40	121	93	99.5	88.5
13:00	39.5	116	97	99.8	92.5
13:10	37	119	100	103	98
13:20	38	119.5	102	105	101.5
13:30	36.8	120	103	105.5	104.5
13:40	39	121	105	110.6	105
13:50	38	126	108	109.5	104.8
14:00	36	119	109.8	110.8	105.5

E.6. Second Load test of Conventional solar cooker

06/10/2011 E.C /Thursday

Local Time	Ta	Tp1	Tw1
10:00	38.5	43.8	31
10:10	33.8	55	40
10:20	32	57	51.2
10:30	32.5	53	50
10:40	33.8	68	52
10:50	32	58	56
11:00	30	56	55
11:10	32	57	55.6
11:20	30	53.8	53
11:30	34	58	55
11:40	32	55	53
11:50	37.8	61.8	54
12:00	33	63	56.3
12:10	38.5	89	68.1
12:20	37	100	72
12:30	41	108	78
12:40	40	105	87.5
12:50	39	108	88
13:00	38	110.5	89
13:10	36	107	93
13:20	37	95	98
13:30	40	89	101.5
13:40	39.5	94	102
13:50	38	108.8	103
14:00	39	111	105

E.7. Cooking Test without storage

TABLE E-2: Cooking test of improved solar cooker without any TES material

08/10/2011 E.C/ Saturday Cooking test without storage

Minutes	Local Time	Ta	Tp2	Tw2	0.5kg food
0	8:20	35	48	37	
10	8:30	34	71.4	40.5	
20	8:40	33.2	78.6	40.7	add
30	8:50	35.3	82	50.6	
40	9:00	37	88.5	60.5	
50	9:10	40	92	69	
60	9:20	45	89	76	
70	9:30	39	97	80	partially cooked
80	9:40	38	107	87.5	cooked enough
90	9:50	40	112	91	
100	10:00	42	117	95	
110	10:10	41.7	119	97	
120	10:20	42	121.8	101.5	

TABLE E-3: Load test of improved solar cooker without any TES material

08/10/2011 E.C/ Saturday Cooking test without storage

Minutes	Ta	Tp2	Tw2
0	38	46	37
10	36.5	72	41.7
20	39.7	76.3	46
30	37.5	78.5	51.5
40	38	85	58
50	38.5	93	65
60	44	96.4	73
70	39.5	103	80
80	40	98.8	86.5
90	41.6	109	92
100	39	114	98
110	40	120	102
120	39	119.5	103.6

E.8. Experimental Results of First Figure of Merit

TABLE E-4: Experimental results of stagnation tests and first figures of merits

Time	Ac	Ae	Ta	Tp1	Tp2(with storage of...)		w/o storage	H(insolation)	F1C	F1N		
					Blackstone	Concrete				Blackstone	Concrete	w/o storage
7:40	0.25	0.55	33.8	38	37	37	37	378.55424	0.011095	0.0084532	0.0084532	0.00845321
8:00	0.25	0.55	34.3	42	42.5	45	45	595.14478	0.012938	0.0137782	0.0179788	0.01797882
8:20	0.25	0.55	34.5	71	62.3	76	76	595.14478	0.06133	0.0467113	0.0697309	0.06973093
8:40	0.25	0.55	34	70	65.25	80	80	595.14478	0.060489	0.0525082	0.0772921	0.07729212
9:00	0.25	0.55	35	73	76.3	100	100	791.66476	0.048	0.0521685	0.0821055	0.08210546
9:20	0.25	0.55	34.8	53.5	68.25	60.75	83	791.66476	0.023621	0.0422527	0.032779	0.06088436
9:40	0.25	0.55	35	77	87.5	84	120	791.66476	0.053053	0.0663159	0.0618949	0.10736868
10:00	0.25	0.55	33.8	87.8	96.5	95.05	135	845.12446	0.332732	0.0741903	0.0724745	0.11974568
10:20	0.25	0.55	35	92.05	102.95	100.75	140	845.12446	0.067505	0.0804024	0.0777992	0.12424206
10:40	0.25	0.55	35.5	93.75	111.5	105.5	143	845.12446	0.068925	0.0899276	0.082828	0.1272002
11:00	0.25	0.55	33	103.9	126.5	114	153	956.33461	0.074137	0.0977691	0.0846984	0.12547909
11:20	0.25	0.55	35	116.5	125.5	123	155	956.33461	0.085221	0.0946321	0.092018	0.12547909
11:40	0.25	0.55	36	121	133.5	127.5	154	956.33461	0.088881	0.1019518	0.0956778	0.12338778
12:00	0.25	0.55	36.7	125.5	138.9	131	150	995.46787	0.089204	0.2534487	0.2454122	0.41518166
12:20	0.25	0.55	36.5	134.05	136.5	130.75	145	995.46787	0.097994	0.1004553	0.0946791	0.10899397

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12:40	0.25	0.55	34.5	131.5	127.5	127.3	136	995.46787	0.097442	0.0934234	0.0932225	0.10196211
13:00	0.25	0.55	37.3	130.5	130	124.5	130	956.33461	0.097455	0.0969326	0.0911815	0.0969326
13:20	0.25	0.55	36.5	128.3	128.5	121.85	125	956.33461	0.095992	0.0962006	0.089247	0.09254083
13:40	0.25	0.55	37	130.25	132.25	125.75	132	956.33461	0.097508	0.099599	0.0928022	0.09933762
14:00	0.25	0.55	38	132.85	134	129.65	139	845.12446	0.112232	0.1135927	0.1084456	0.11950902
14:20	0.25	0.55	36	135.7	136	130	141	845.12446	0.117971	0.1183258	0.1112262	0.12424206
14:40	0.25	0.55	34.5	134.2	131	124.6	130	845.12446	0.117971	0.1141844	0.1066115	0.11300111
15:00	0.25	0.55	35	132	134.5	129.5	139	791.66476	0.122527	0.1256845	0.1193687	0.13136874
15:20	0.25	0.55	33.9	127.5	129	121.5	125	791.66476	0.118232	0.1201266	0.1106529	0.11507396
15:40	0.25	0.55	33.3	128	132.5	123	130	791.66476	0.119621	0.1253056	0.1133055	0.12214766
16:00	0.25	0.55	33.5	123.5	129.75	116.5	126	595.14478	0.151224	0.1617254	0.1394619	0.15542437
16:20	0.25	0.55	32.5	114.25	126.5	112.5	123	595.14478	0.137362	0.1579448	0.1344211	0.15206384
16:40	0.25	0.55	33.2	120.5	124.5	116.5	128	595.14478	0.146687	0.153408	0.1399659	0.15928897
17:00	0.25	0.55	33.5	114	126	115	126	378.55424	0.212651	0.2443507	0.2152928	0.24435072
17:20	0.25	0.55	33.9	109	123.75	112	123	378.55424	0.198386	0.2373504	0.2063113	0.23536918
17:40	0.25	0.55	33.8	105.5	118.4	111	121	378.55424	0.189405	0.2234818	0.2039338	0.23035008
18:00	0.25	0.55	34	98.25	118.25	108.4	117	169.19372	0.379742	0.4979499	0.4397326	0.49056195
18:20	0.25	0.55	33.6	87.5	104.65	102.5	106	169.19372	0.31857	0.4199329	0.4072255	0.42791187
18:40	0.25	0.55	33.5	76.5	94.75	92.75	90.5	169.19372	0.254147	0.3620111	0.3501903	0.33689194
								Average	0.125301	0.1393087	0.1314241	0.15417211

E.9. Experimental Results of Second Figure of Merit

TABLE E-5: Experimental results of Load tests and second figures of merit

Time	Ac	Ae	K	Ta	Tp1	Tw1	Tp2	Tw2	H	F1C	F2C	F1N	F2N
10:00	0.25	0.55	0.05	32.4	48	38	50	38	535.3908	0.0291376	0.1033721	0.03287318	0.6773901
10:10	0.25	0.55	0.05	31.8	48.5	40	56	39.7	535.3908	0.0311922	0.2768299	0.04520062	0.108511
10:20	0.25	0.55	0.05	33.6	50	43	57	41	535.3908	0.0306318	0.4588754	0.04370639	0.2162106
10:30	0.25	0.55	0.05	34.2	58.6	45	59	43.8	535.3908	0.0455742	0.2626188	0.0463213	0.3289371
10:40	0.25	0.55	0.05	34.8	67.3	46.5	61	45	535.3908	0.0607033	0.1775338	0.04893621	0.1486422
10:50	0.25	0.55	0.05	34.8	75	49.8	69	47.5	535.3908	0.0750853	0.3880803	0.06387857	0.2951214
11:00	0.25	0.55	0.05	38	84	53.5	79	50	624.8281	0.0736203	0.3540366	0.06561805	0.2278949
11:10	0.25	0.55	0.05	37.8	80	58	81	52	624.8281	0.0675386	0.5279015	0.06913902	0.193661
11:20	0.25	0.55	0.05	40.5	88	64.4	84.5	56	624.8281	0.0760209	1.3591055	0.07041937	0.3884411
11:30	0.25	0.55	0.05	41	98	70	90	60	624.8281	0.0912251	0.2129133	0.07842157	0.4122506
11:40	0.25	0.55	0.05	41.5	102	72	96	67	624.8281	0.0968266	0.26246	0.08722399	0.7921134
11:50	0.25	0.55	0.05	38	105	76	95	73.2	624.8281	0.1072295	0.581923	0.0912251	0.958992
12:00	0.25	0.55	0.05	36.8	104	78	95.5	78	656.5351	0.1023555	0.3185852	0.08940877	0.9101995
12:10	0.25	0.55	0.05	36	103.5	78.5	92	81	656.5351	0.1028125	0.0855102	0.08529628	0.8639495
12:20	0.25	0.55	0.05	38	109	79.5	93	81.5	656.5351	0.1081435	0.1514149	0.08377313	0.1497448
12:30	0.25	0.55	0.05	38.5	112	83	95.5	83	656.5351	0.1119514	0.535761	0.08681942	0.4132435
12:40	0.25	0.55	0.05	39	120	88	94.5	84	656.5351	0.123375	0.7522967	0.0845347	0.3229914
12:50	0.25	0.55	0.05	40	121	93	99.5	88.5	656.5351	0.123375	0.8513771	0.09062729	1.3053665
13:00	0.25	0.55	0.05	39.5	116	97	99.8	92.5	624.8281	0.1224337	0.982447	0.09650655	1.7709909
13:10	0.25	0.55	0.05	37	119	100	103	98	624.8281	0.1312361	0.8080661	0.10562906	3.291546
13:20	0.25	0.55	0.05	38	119.5	102	105	101.5	624.8281	0.1304359	0.5928272	0.1072295	3.1216846
13:30	0.25	0.55	0.05	36.8	120	103	105.5	104.5	624.8281	0.1331566	0.3196629	0.10995025	6.4017831
13:40	0.25	0.55	0.05	39	121	105	110.6	105	624.8281	0.1312361	0.6492102	0.11459152	0.4116049
13:50	0.25	0.55	0.05	38	126	108	109.5	105.2	624.8281	0.1408387	0.9118363	0.11443148	0.2184977
14:00	0.25	0.55	0.05	36	119	109.8	110.8	105.5	535.3908	0.1550269	1.1634857	0.13971102	0.3230832
Average second figure of merits											0.5201		0.9692

E.10. Conducted experiments in each day

Day 1:- First load test for Improved SBC. (Exp. 1)

Day 2: Without load absorber plate temp distribution test for both cookers (improved with concrete as TES and Conventional cooker). (Stagnation test 8:00-24:40) (Exp. 2)

Day 3:- Stagnation (without load) absorber plate test for improved cooker with black stone as TES (Exp. 3)

Day 4:- Load test with equal amount of water in both solar cookers. (Water boiling test 10:00-14:00) (Exp. 4)

Day 5: Stagnation test for improved solar cooker with black stone as absorber and TES. (Stagnation test 8:00-22:40) (Exp. 5) and 2nd load test for conventional solar cooker (Exp. 6).

Day 6:- Second stagnation absorber plate temperature test for both cookers (improved without any TES and Conventional cooker). (Stagnation test 8:00-24:40). (Exp.7)

Day 7:- Cooking tests (1 liter water with 0.5 kg potato in each (Exp. 8) and again 2 liter water with 0.1kg husk (Shoforo drink (Exp. 9).

All those experiments were accomplished very successfully. But the situations that I was passed were very difficult, especially lack of portable instruments and searching for it, transportation of experimental setup and working alone for long time per day during testing in strange environment hardly passed problems, because of those problems I will never forget that testing time in Daassanech, but the results that I have obtaining in each time were encouraging me.