



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

**“DESIGN AND EXPERIMENTAL INVESTIGATION OF SOLAR
COOKER WITH THERMAL ENERGY STORAGE”**

By; Muluken Biadgelegn

Advisor; Dr. Abdulkadir Aman (Ass. Prof.)

**Addis Ababa, Ethiopia
November 2018**

**“DESIGN AND EXPERIMENTAL INVESTIGATION OF SOLAR
COOKER WITH THERMAL ENERGY STORAGE”**

By; Muluken Biadgegn




**A Thesis Submitted to the School of Graduate Studies of Addis Ababa
University in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering (*Thermal Engineering*)**

**Addis Ababa, Ethiopia
November 2018**

Declaration

I, the under signed, declare that this MSc thesis is my original work, has not be presented for fulfillment of degree for this or other university, and all sources and materials used for the thesis work is acknowledged.


Muluken Biadgelegn

Date 21 / 11 / 2018 signature 

This thesis work has been submitted for examination with my approval as a University advisor

Thesis Advisor

Dr. Abdulkadir Aman (Ass. Prof.)

Date 21 / 11 / 2018 Signature 

Date of submission, November 2018

Thesis Approval Sheet

Student:

Muluken Biadgelegn date 21 / 11 / 2018 signature [Signature]

The following graduate school members certify that this student has successfully presented the necessary written thesis document and oral presentation of this thesis for partial fulfillment of the requirements for the Degree of Master of Science in Thermal Engineering.

Advisor:

Dr. Abdulkadir Aman (Ass. Prof.) Date 21 / 11 / 2018 signature [Signature]

Internal Examiner:

Dr. Kamil Dino Date 22 / 11 / 18 signature [Signature]

External examiner:

Dr. Tesfaye Dama Date 22 / 11 / 18 signature [Signature]

Thermal and Energy Conversion Chair:

Dr. Abdulkadir Aman (Ass. Prof.) Date 21 / 11 / 2018 signature [Signature]

School Dean:

Dr. Yilma Tadesse (Ass. Prof.) date 23 / 11 / 2018 signature [Signature]



ACKNOWLEDGEMENT

Above all, I thank my God for giving me all the strength and health during this period of challenges. Next, I am very pleased to thank all the people who in one way or another helped me to successfully accomplish this MSc program. Especially; I would like to express my profound and sincere gratitude to my advisor, Dr. Abdulkadir Aman, for his advice and inspiration from the early stage of the research work to the final level. His valuable guidance and interest in the research topic was a prime mover for my daily activities.

It is an honor for me to express my sincere gratefulness to my late father, my mother and all of my siblings for their support and love. However, this year is very dark year for me because my father and my uncle (Alemneh Wollele) pass away consecutively. It is my prayer, may God put their soul in the heaven. Father, your encouragement and support have a big effect for this success. Therefore, your ambition is already succeeded, thank you very much.

I am especially grateful to my wonderful and caring mother Abeba Dejen for her efforts and encouragement all the way in my life. This is a great reward for her to see the result of her inspiration. Mamaye, your inspiration and dedication were my springboards in every step of my careers; I love you and God bless you.

I take this opportunity to acknowledge and thank my friend Asfaw Minalu for his continuous support and encouragement from starting to finish of this work. Asfaw I haven't word to thank your support, thank you very much and God bless you.

My deepest acknowledgement is going to the school of Mechanical and Industrial Engineering (AAiT- AAU) for giving the chance to do this MSc program and supporting different instruments during test.

For the last but not least, my acknowledgement is going to my friends (Kehali A., Seyfu T., Alene A., Mamaru W. and all my friends) who are always beside of me during this work.

ABSTRACT

Cooking is the major necessity for people all over the world. It accounts for a major share of energy consumption in developing countries. Therefore, there is a critical need for the development of alternative and affordable methods of cooking. Solar cooking is a novel and eco-friendly method of harnessing sun's energy. Solar cookers can be of a great use in saving fuel and enabling in eco-friendly cooking of food.

Solar energy is available during daytime only and also intermittent. So, thermal storage is important for indoor solar cooking requirements and will ensure continuity of service, reduce the use of conventional energy, and give a reasonable cooking time compared with conventional cooking. The solar cooker designed for this study is 1.5m^2 aperture area of compound parabolic dish concentrator integrated with thermal storage media (1.5 liter of oil and 0.74 kg of rock) as an absorber (area of 0.4m^2) to increase the duration of the effective energy storage period without tracking and utilize thermal energy for night cooking.

The overall system is designed with an assumption to cook 1 kg of rice in 45 minutes requiring power of 522 W which is obtained from the stored energy from the sun. Therefore, the numerical simulation, experimental test, and validation of the two results are done. An absorber with thermal storage is simulated by COMSOL software to show temperature distribution. As it is shown in the simulation section, the temperature of TES could reach 365 K after 6 hours. Where as in the experimental result, due to so many losses the energy reduced in some extent and it reaches 354 K. Even if it has low energy, it can cook the required food by placing TES in the insulated tank during discharging. Therefore, there were deviations between experiment and simulation because the model did not account the basic losses and frustration of solar radiation in case of numerical simulation. The model of the TES system was validated with experimental results and a brief reason was found between experiment and simulation for the charging cycle.

The discharging of TES is started after it is lifted from solar collector and it is placed on the insulated tank and loaded by pot with water. This is maximum temperature of water reached after 40 minutes is 355 K (82°C).

TABLE OF CONTENTS

ABSTRACT	i
LIST OF FIGURES	iv
LIST OF TABLES	v
CHAPTER ONE	1
1. INTRODUCTION	1
1.1. Background of the study	1
1.2. Problem Statement	4
1.3.1. Main objective	5
1.3.2. Specific objectives are to;.....	5
1.4. Significance of the Study	5
1.5. Delimitation of the study	6
1.6. Structure of the Thesis	6
CHAPTER TWO	7
2. REVIEW OF RELATED LITERATURE	7
2.1. Cooking.....	7
2.2. Solar Cookers.....	7
2.2.1 Direct Solar Cookers	8
2.2.1.1. Box type solar cooker	8
2.2.1.2. Panel type solar cooker	9
2.2.1.3. Concentrating type solar cooker	10
2.2.2. Indirect solar cookers	11
2.3. Thermal energy storage (TES).....	13
2.3.1. Sensible heat storage	14
2.3.2. Latent Heat Thermal Storage (LHTS).....	15
2.3.3. Heat Storage using chemical reactions.....	17
2.4. Solar Cooker with Thermal Energy Storage	17
2.5. Thermal Insulating Materials	21
2.5.1. Insulation between Different Medias	23

CHAPTER THREE	26
3. MATERIALS AND METHODS.....	26
3.1. Methods of the Research and System Description.....	26
3.1.1. Theoretical design of parabolic solar collector	28
3.1.1.1. Estimation of available solar radiation potential.....	28
3.1.1.2. Sizing and Thermal Analysis of Parabolic Solar Collector.....	30
3.2. Selection of Sensible Heat Thermal Energy Storage (SHTES)	39
3.2.1. Solid Storage Media	41
3.2.2. Liquid storage media.....	41
3.2.3. Heat Transfer Analysis between an Absorber and Thermal Energy Storages..	44
3.2.3. Heat energy stored in the thermal energy storage	46
3.3. COMSOL Multiphysics Simulation.....	48
3.3.1. Numerical Simulation of thermal energy storage.....	48
3.4. Construction of parabolic Solar Collector and Solar Cooker with TES.....	50
3.4.1. Selection of Materials for the Construction of Solar collector.....	50
3.4.2. Construction of solar collector and solar cooker with TES.....	50
CHAPTER FOUR.....	54
4. RESULTS AND DISCUSSIONS	54
4.1. Numerical Results and Discussions.....	54
4.2. Experimental Results and Discussions.....	56
4.2.1. Charging Temperature of TES	56
4.2.2. Discharging Temperature of TES.....	58
4.3. Validation of Numerical simulation.....	58
CHAPTER FIVE	60
5. CONCLUSIONS AND RECOMMENDATIONS.....	60
5.1. Conclusions	60
5.2. Recommendations	61
REFERENCES.....	62
Appendix.....	68

Annex 71

LIST OF FIGURES

Figure 2.1 ; Box Type Solar Cooker..... 9

Figure 2.2 ; Panel Solar Cooker..... 10

Figure 2.3 ; The Principle of Concentrating Solar Cooker 11

Figure 2.4 ; Indirect Solar Cooker with Thermal Storage 13

Figure 2.5 ; Simple schematic representation of TES integration and operation 13

Figure 2.6 ; Heat storage and release processes of the PCM 16

Figure 3. 1: flow chart of thesis work 27

Figure 3. 2; 3D overall system..... 27

Figure 3.3 ; Basic dimensions of parabolic solar collector..... 31

Figure 3. 4 ; 3D Drawing of Solar Absorber with TES (left), Top view (right)..... 44

Figure 3. 5: thermal resistance diagram..... 45

Figure 3.6 ; Absorber Inside Insulated Tank 47

Figure 3.7 ; Chart of COMSOL Multiphysics analysis 48

Figure 3. 8; part drawings of Absorber 51

Figure 3. 9 ; Photograph of Solar Absorber..... 51

Figure 3. 10; parabolic solar collector 52

Figure 3.11 ; Photograph of Experimental Setup..... 52

Figure 3.12 ; Photograph of Temperature Measurements 53

Figure 4.1 ; Mesh of Geometry..... 54

Figure 4.2 ; Temperature Distribution on the Absorber 54

Figure 4.3; Temperature Versus Time in Absorber 55

Figure 4.4; Temperature variation on solar cooker with TES 56

Figure 4. 5; Discharging temperature of TES 58

Figure 4.6; Validation of numerical result..... 59

LIST OF TABLES

Table 3-1 ; Solar radiation of Addis Ababa	28
Table 3-2 ; Thermal properties of rock	41
Table 3-3 ; Thermal properties of thermia Oil B	43
Table 3- 4: variation of thermal properties with temperature of thermal oils.....	43
Table 3-5 ; Basic input parameters for simulation.....	49

Nomenclatures

A_{ap}	area of aperture (m^2)
A_{abs}	area of absorber (m^2)
C	concentration ratio
D_{ap}	diameter of aperture (m)
f	focal length (m)
H	height (m)
I_b	beam solar radiation (W/m^2)
L	length (m)
m_{rock}	mass of rock (kg)
n	number of days
T	temperature
Q_{abs}	absorbed energy (W)
$Q_{rad,loss}$	radiation heat loss (W)
$Q_{conv,loss}$	convective heat loss (W)
V_f	volume of food (m^3)
SWH	solar water heater
CPC	compound parabolic collector
C_p	specific heat storage (kJ/kg.K)
TES	thermal energy storage
HTF	heat transfer fluid

SHS	sensible heat storage
STES	sensible thermal energy storage
LHTES	latent heat thermal energy storage
PCM	phase change material
ST	standard time
δ	Declination
ω	Hour angle
θ_z	Zenith angle
η	Efficiency
SHT	solar heat storage
ψ	Rim angle

CHAPTER ONE

1. INTRODUCTION

1.1. Background of the study

The world is experiencing major industrial development and population growths have caused a significant increase in energy demand. Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognized universally and historical data verify that there is a strong relationship between the availability of energy and economic activity [1]. This growth in demand was mainly covered by the source of fossil fuels. Other factors such as gas emissions greenhouse and environmental problems have pushed the scientific research and technological development to find new energy solutions based on the use and diversification of energy resources efficiently. Among the new resources renewable energy found that are now considered as the engine of development of new generation on the horizon for the coming decades [2].

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. These technologies use the sun's energy and its direct and indirect effects on the earth (solar radiation, wind, falling water and various plants, i.e. biomass), gravitational forces (tides), and the heat of the earth's core (geothermal) as the resources from which energy is produced. These resources have massive energy potential; however, they are generally diffused and not fully accessible, most of them are intermittent, and have distinct regional variability. These characteristics give rise to difficult, but solvable, technical and economic challenges. Nowadays, significant progress is made by improving the collection and conversion efficiencies, lowering the initial and maintenance costs, and increasing the reliability and applicability.

The sun is the source of life on the earth, but at the same time it is a “free” source of energy forms any systems using this resource to power a process [3]. Solar energy is

available in abundance in most parts of the world. The amount of solar energy incident on the earth's surface is approximately 1.5×10^{18} kWh/year, which is about 10,000 times the current annual energy consumption of the entire world. The density of power radiated from the sun (referred to as solar energy constant) is 1.373 kW/m^2 . Thus, solar energy is the major part of renewable energy which is radiant light and heat from the sun harnessed using a range of ever-evolving technologies such as solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis [4].

Solar Energy can be utilized through Solar Photovoltaic and Solar Thermal Systems. Solar thermal systems can be flat plate type (for low temperature ranges) or concentrator type (for medium and high temperature ranges), which show considerable potential as best options to overcome the crisis / problems. The use of solar concentrator technology in various industries, including the process industry, which holds considerable potential in medium temperature applications, is in the process of gaining due attention from scientists, engineers and developers [5].

Solar energy is one of the best ways of reducing the use of nonrenewable resources. With solar energy, the sun's rays are used to generate electricity, heat water or other fluids, charge battery, heat homes through glass windows and cook food [6]. Solar thermal energy is a renewable energy source widely used worldwide. Applications range from domestic solar water heaters (SWHs) to sophisticated solar farms for power generation [7]. The solar energy is converted to thermal energy by solar collectors, which is a term used to describe a multitude of different by converting it into useful heat. Thus, solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium.

Solar parabolic dish system has the best concentration ratio and the radiation flux has maximum. The dish structure must track fully the sun to reflect the beam into the thermal receiver. The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. Parabolic-dish systems can achieve temperatures in excess of 1500°C . Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called distributed-receiver systems [8]. Furthermore, compound parabolic concentrator is of the non-imaging type

concentrating solar collector. CPC consist of two parabolic reflectors at the two ends (left and right) of the absorber plate and hence it is known as compound parabolic concentrator. Here the incident rays after reflection from the reflector are not focused at a point but are simply collected on absorber surface [8], [9]. The objective was to increase the duration of the effective temperature period by capturing the maximum solar energy in the morning and afternoon without tracking. To obtain the required temperature for longer period of time, the solar energy needs to be captured efficiently in the morning and afternoon.

A solar cooker is a device which uses the energy of direct sun rays (which is the heat from the sun) to heat, cook or pasteurize food or drink. The solar cooking which saves a significant amount of conventional fuels is the simplest, safest, clean, environment friendly, and most convenient way to cook food without consuming fuels or heating up the kitchen [10].

However, solar energy is available during daytime only and also intermittent. This is the main drawback of solar energy for solar energy applications. Since, food is required during noon as well as night hours. It is straightforward to cook food during noon due to an availability of solar energy, but night time it is impossible. Therefore, the solar energy storage is the significant factor for the efficient design of solar cooking. The thermal energy is stored as a sensible or latent heat.

Sensible heat storage systems utilize the heat capacity and the change in temperature of the material during the process of charging or discharging - temperature of the storage material rises when energy is absorbed and drops when energy is withdrawn. One of the most attractive features of sensible heat storage systems is that charging and discharging operations can be expected to be completely reversible for an unlimited number of cycles [11].

Thermal oils have the advantage that they act both as the heat transfer and the heat storage medium. These applications include steam generation, cooking of food etc. For small scale domestic applications which require non-sophisticated heat exchangers, thermal oils can be utilized. Therefore, this thesis research studies compound parabolic dish solar cooker with oil and rock as a thermal storage for cooking purpose.

1.2. Problem Statement

Energy is a central part of every human being's daily life either it is in the form of chemical energy (food), thermal energy (heat), or electricity.

Cooking is one of the very important and necessary household chores in every society of the world. Energy consumption for cooking in developing countries is a major component of the total energy consumption, including commercial and non-commercial energy sources. In the rural areas of most developing countries cooking is usually done in open fires fueled by firewood. In the cities, stoves are more common and fueled by wood, charcoal, kerosene and sometimes flue gas. In many regions, especially East Africa (including Ethiopia), oil-derived fuels are expensive, and wood-based fuels are becoming increasingly scarce.

However, the consumption of wood for cooking purpose is also the main cause of deforestation, soil erosion and health problems of women.

Moreover, combustion of fuel and wood release carbon dioxide (CO₂) and other greenhouse gases, as well as pollutants that have contributed to environmental problem such as global warming, air and water pollution and other damage to earth eco-system.

Thus, with increasing population, economic growth, and environmental concerns, the use of solar energy in domestic cooking is becoming a good alternative for sustainable development [13]. The solar cooking saves a significant amount of conventional fuels. The solar cooking is the simplest, safest, clean, environment friendly, and most convenient way to cook food without consuming fuels or heating up the kitchen [15].

While most solar cookers in use today do not have heat storage, this feature will alleviate the mismatch between solar heat energy supply and energy demand for cooking. Even if there is heat storage, heat is circulated with heat transfer fluid through pipe for indoor cooking or it is used for direct (outdoor) cooking. Thus, it has loss of heat in the pipe and it requires extra equipment's which main cause for unnecessary cost is. The use of heat storage for outdoor cooking has also health problems because of light rays. Heat storage is important for indoor solar cooking requirements and will ensure continuity of service, reduce the use of conventional energy, and give a

reasonable cooking time compared with conventional cooking. Thus, this study deals with the design and experimental investigation of solar cooker with heat energy storage for indoor cooking.

1.3. Objective of the Study

1.3.1. Main objective

The main objective of this study is to design, construct and do experimental investigation of solar cooker with thermal storage.

1.3.2. Specific objectives are to;

- Asses solar radiation potential of the selected site (Addis Ababa, Ethiopia).
- Design compound parabolic dish solar collector based on available solar radiation and energy required for cooking.
- Design an absorber with thermal storage based on the radiation that comes from the parabolic dish solar collector and useful energy delivered.
- Modeling and simulation of an absorber by COMSOL with storage media to predict temperature distributions.
- Construct a prototype of solar cooker and investigate experimentally the performance of the solar cooker with thermal energy storage.

1.4. Significance of the Study

The study of solar cookers is needed due to;

- ✓ High cost or Unavailability of commercial fuels – Kerosene, Coal, cooking gas and Electricity.
- ✓ Deforestation caused by increasing firewood consumption.
- ✓ Use of dung and agricultural waste as fuels instead for soil enrichment.
- ✓ Health risk due to smoke and carbon dioxide released from fuels during burning.

The main benefits of this project are;

- No smoke evolution, thus clean.
- No pollution, thus environment friendly.
- No soot accumulation on pots.

- Available every day, thus renewable.
- Solar Energy does not contribute to global warming, acid rain or smog.

Need for TES is due to;

- A mismatch exists between the energy supply and energy demand.
- Intermittent energy sources are utilized for meeting the energy demand.
- An energy supply for catering the critical and part load demand is limited.

1.5. Delimitation of the study

This research mainly involves the thermal analysis of solar compound parabolic dish collector, design of absorber, COMSOL software simulation of an absorber with, construction of prototype and experimental investigation by assessing the solar radiation of Addis Ababa. However, the detail optimization of an absorber and economic analysis of overalls system were not included in this study.

1.6. Structure of the Thesis

Chapter one; in this chapter the title is introduced briefly, why this study is needed and how it can solve the problem is described and the scope of the study was also written.

Chapter two; in this chapter the basic literatures which are related with this study are studied in detail and the basic gaps of authors (papers) are defined.

Chapter three; in this chapter, how this study is accomplished, all the components of parabolic solar collector are theoretically designed and thermodynamic analysis of solar collector is studied to. In this chapter the thermal energy storage is studied in detail and oil and rock is selected as thermal energy storage based on their basic selection criteria. The heat transfer analysis of TES is also defined. COMSOL software is introduced briefly and its boundary conditions are discussed. Furthermore, the construction of solar collector with TES is discussed.

Chapter four; experimental results, Numerical result and Validation of the two are clearly discussed

Chapter five; the basic conclusion is drawn. Furthermore, the recommendation and future works are briefly listed.

CHAPTER TWO

2. REVIEW OF RELATED LITERATURE

2.1. Cooking

The cooking is based on heating of a given food to the boiling temperature of water and in the second part the food is kept at the boiling temperature for a certain period of time depending on the nature of the food. Cooking is considered as one of the most important things for the living of human being. Without cooking, it is difficult to live on earth [15].

Lof GOG [16] has described the principles of cooking. As per his principle, the energy requirement is at maximum during the sensible heating period. Heat required for physical and chemical changes involved in cooking is less. The energy required for a specific cooking operation is not always well defined and can vary widely with the cooking methods used. During cooking, 20% of heat is spent in bringing food to boiling temperature, 35% of heat is spent in vaporization of water and 45% of heat is spent in convection losses from cooking utensils. Insulating the sides of the vessel and keeping the vessel covered with a lid can considerably reduce the heat losses.

2.2. Solar Cookers

A solar cooker is a device which uses the energy of direct sun rays (which is the heat from the sun) to heat, cook or pasteurize food or drink. The vast majority of solar cookers presently in use are relatively cheap, low-tech devices. Because they use no fuel and cost nothing to operate, many nonprofit organizations are promoting their use worldwide in order to help reduce fuel costs (for low-income people) and air pollution, and to slow down the deforestation and desertification caused by gathering firewood for cooking. Solar cookers are classified into direct and indirect solar cookers depending upon the heat transfer mechanism to the cooking pot. Direct type solar cookers use solar radiation directly in the cooking process while the indirect cookers use a heat transfer fluid to transfer the heat from the collector to the cooking unit [17, 18].

Cooking with the energy of Sun is not a new or novel idea. Solar cookers have attracted the attention of many researchers so far. Different types of solar cookers have been developed and tested all over the world. Today, there is challenge to manufacturing and evaluation of efficient and cheap solar cookers. There has been a considerable interest recently in the design, development and testing of various types of solar cookers [19].

2.2.1. Direct Solar Cookers

Direct solar cookers may be considered the most common type available due to their ease of construction and low-cost material.

Direct solar cookers can however, only be used during periods of direct sun shine. Therefore, they have limited usefulness when the sun shine is intermittent due to weather conditions and cannot be used in off-sun conditions [20].

Commercially successful direct type cookers are box type, concentrating type and panel type cookers.

2.2.1.1. Box type solar cooker

Box type solar cooker is most commonly used solar cooker for personal/domestic purpose. This type of cooker has transparent glass or plastic top. It has simple construction such as square box, rectangular and cylindrical. Inside wall of cooker is painted by black color only. All side is insulated except window side which is double glazed. Sunlight falls on reflective wall and bounce toward pot and dark bottom which is in contact with pot inside must be reflective radioactive heat loss. Box type solar cooker is an ideal solar cooker for domestic cooking purpose, during most of the year except the monsoon season and cloudy days. This type solar cooker takes nearly 1.5 to 2 hours to cook for items such as rice, vegetable. Thus, cooking is similar that of microwave cooking. It has temperature range up to 150°C and it is presented in [21]. Absorber tray is one of most significant components of a solar box cooker. Solar radiation passes through the glazing part and absorbed by a surface painted black called absorber tray. An absorber tray first of all should have a remarkably high absorptivity in order to transfer maximum radiant energy to food in the cooking pot [22]. The advantage and the disadvantage of box-type solar cooker are discussed in [17]. Thus, the main advantages of box-type solar cookers are: they make use of both direct and

diffuse solar radiation, several vessels can be heated at once, they can double as an oven (not for crispy baked goods) and they are light and portable and the disadvantages of solar box cookers include: slow cooking process due to low temperatures, cooking must be limited to the daylight hours, the glass cover causes considerable heat losses and such cookers cannot be used for frying or grilling.

Solar box cookers are ideally suited to preparing dishes, which require a long, slow cooking time. The cooker can be used to cook pulses, rice, hotchpotch etc. It can also be used to prepare simple cakes, roast cashew nuts, dry grapes, finger chips etc. The cooking takes place slowly at relatively low temperature, thus cooking is very similar to that of microwave cooking. The cooked items in box solar cooker are very tastier, healthier and with all-natural minerals, vitamins and proteins. It however cannot be used for frying or Chapatti making [23].

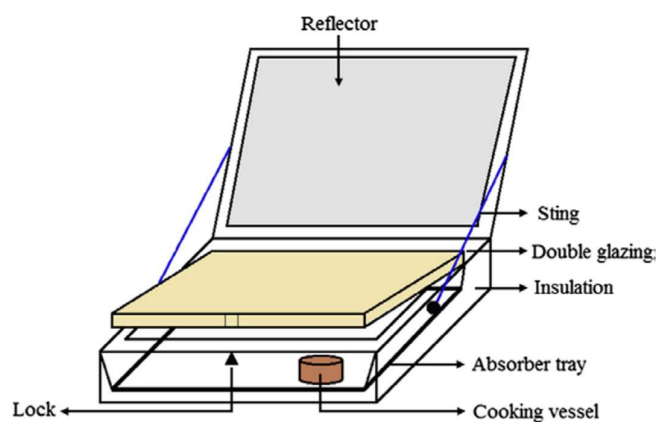


Figure 2.1 ; Box Type Solar Cooker [23]

2.2.1.2. Panel type solar cooker

Solar panel cookers may be considered the most common type available due to their ease of construction and low-cost material. In solar panel cookers, sunlight is concentrated from above. This method of solar cooking is not very desirable since it provides a limited cooking power. On the other hand, this type of solar cookers is highly appreciated by people living or travelling alone. Solar panel cookers utilize reflective equipment in order to direct sunlight to a cooking vessel which is enclosed in a clear plastic bag [22]. In this solar cooker multiple reflective panel are used for collecting sunlight on the cooking vessel.

Panels are unstable in high winds and do not retain as much heat when the sun is hidden behind the cloud. This cooker requires just four reflective panels and it is easier one. It has temperature range up to 200-250°C [17].



Figure 2.2: Panel Solar Cooker [17]

2.2.1.3. Concentrating type solar cooker

Concentrating solar collectors are optical devices that concentrate low density solar radiation falling on their reflective surface onto a small area (absorber), thus turning the low energy density into high energy density. At the absorber surface, solar radiation is converted into thermal power and, due to high flux of solar radiation falling on it, high temperatures are produced and this effect can be used for different purposes including cooking.

The most elementary kind of reflector cooker is one that consists of (more or less) parabolic reflectors and a holder for the cooking pot situated at the cooker's focal spot [24]. A solar parabolic cooker simply consists of a parabolic reflector with a cooking pot which is located on the focus point of the cooker and a stand to support the cooking system. Concentrating type solar cooker is working on one or two axes tracking with a concentration ratio up to 50 and temperature up to 300 °C, which is suitable for cooking. Cookers that concentrate light from below and cookers that concentrate light from above are the two major types of concentrating solar cookers [17].

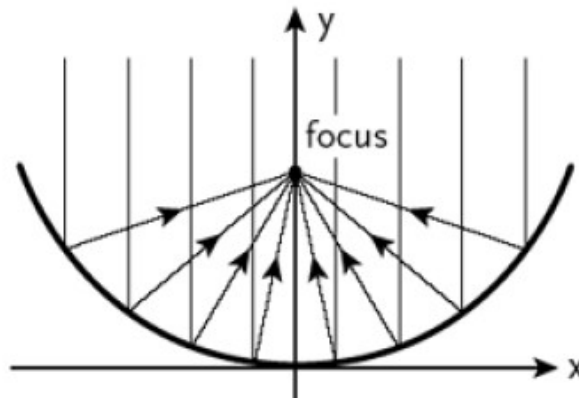


Figure 2. 3 ; the Principle of Concentrating Solar Cooker [24]

A concentrating solar cooker uses large inexpensive reflective surfaces like anodized aluminium sheet or glass mirrors, which are usually less expensive. The smaller absorbing (receiving) surface is insulated from all sides except the side exposed to concentrated solar energy. The cost and size of reflector is determined by heating capacity desired. The concentrating solar cooker involves direct sunlight to function and thus concentrator must be frequently orientated towards the sun. Advantages include high cooking temperatures, virtually any type of food can be cooked and short heat-up times are possible. Most direct-focusing cookers are also unstable at wind speeds exceeding 10 km/h. Further, size, cost, the risk of fires and sun burns and the inconvenience to adjust the cooker are additional disadvantages [25].

MOHAMMED [26] studied the design and development of a parabolic dish solar water heater for domestic hot water application (up to 100°C). For effective performance the design requires that the solar water heater track the sun continuously, and an automatic electronic control circuit was designed and developed for this purpose. His Experimental test runs carried out showed that the overall performance of the solar water heater was satisfactory.

2.2.2. Indirect solar cookers

A.Veremachi et.al [27] proposed in indirect solar cooker with heat storage. Direct solar cookers can only be used during periods of direct sun shine. Therefore, they have limited usefulness when the sun shine is intermittent due to weather conditions and cannot be used in off-sun conditions. To overcome the limitations of direct solar cookers, a thermal storage is essential in the solar system. Solar heat can then be

collected while the sun is available and stored for later use. So, a solar stove with heat storage, which has a potential to enable indirect and off-sun cooking.

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 pot. Solar cooker with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category. The two basic system components are the solar collectors with reflectors and a cooking unit. Peanut or sunflower oil is used as heat transfer medium and the cooker is designed with two non-removing pots. Disadvantages of this cooker are non-removable pots, which makes cleaning and dishing food difficult [17].

A. Veremachi et.al [27] experimentally investigated the indirect solar cooker by using parabolic dish concentrating collector such that the parabolic dish solar cooker is coupled with Siliconized Carbide (SiC) honeycomb as absorbing material and air as heat transfer fluid (HTF). The collected heat is stored as sensible heat in rock bed heat storage. The rock-bed is a two-phase system comprising a solid material and HTF. During charging mode, the HTF enters the storage at high temperature and as it goes through the voids gives up heat to the rocks and emerges at the exit at low temperature. The absorber was tested for two different mass flow rates in order to evaluate its potential as absorber material for solar cooker prototype with HS. The results indicate that the increase in flow rate leads to decrease in the temperature of HTF. Besides, the two flow rates gave a considerable good collector thermal efficiency of around 70%. The results of this study, concerning both high temperatures and efficiency show that an air based solar cooker is possible.

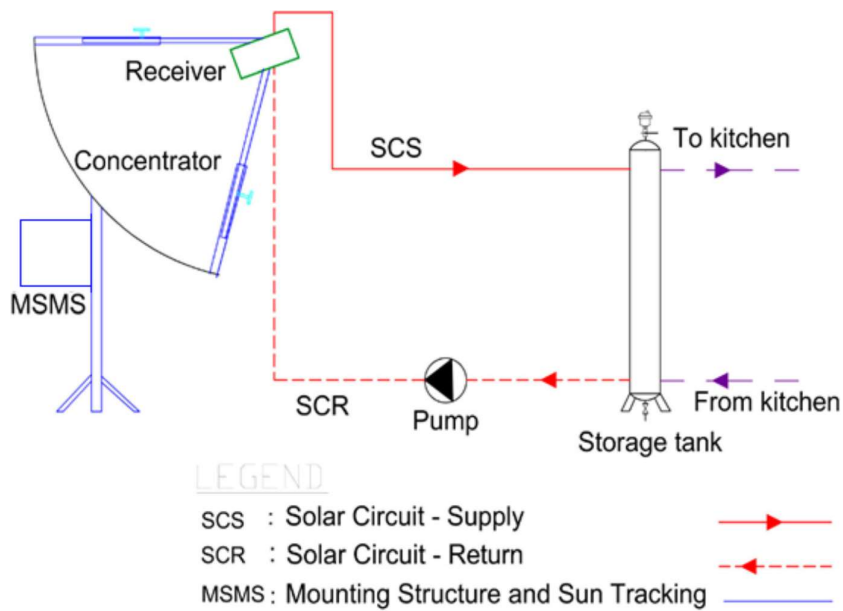


Figure 2.4; Indirect Solar Cooker with Thermal Storage [27]

2.3. Thermal energy storage (TES)

Thermal energy storage systems have an enormous potential to make the function of thermal energy equipment more effective and to facilitate large-scale energy substitutions. Thermal energy storage is defined as the temporary holding of thermal energy in the form of hot or cold substances for later utilization. They are highly valuable from an economic perspective. It is an advanced energy technology that has recently attracted increasing interest for thermal applications such as space and water heating, cooling, cooking and air-conditioning. It appears to be the most appropriate method for reducing the mismatch between the supply and demand of energy. Therefore, it is an attractive technology for meeting society’s needs and more efficient way of energy uses [28].

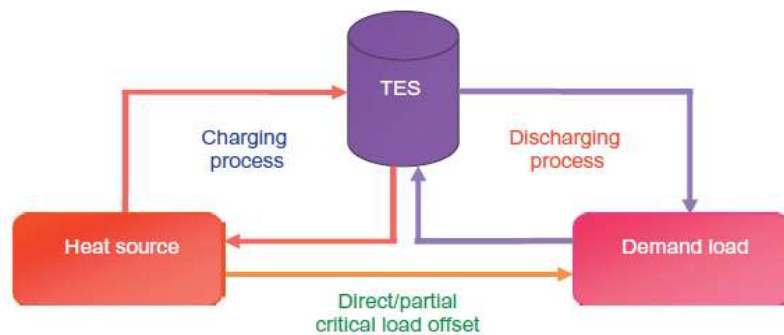


Figure 2.5 ; Simple schematic representation of TES integration and operation [28]

Typically, during the charging process (usually at part load conditions), the quantity of the heat energy that is required to offset the critical load demand (during on-peak periods) is stored in the TES. During discharging process, the stored thermal energy is retrieved from the TES and supplied to the end-use utility for the desired purpose. By integrating TES with the conventional thermal interface systems, the energy redistribution in the form of load shifting from on-peak to off-peak conditions can be effectively achieved. This in turn enables the cooling/heating plant or utility to operate at its base capacity or nominal capacity and thereby helps accomplish enhanced energy efficiency and operational performance of the thermal system [29].

TES deals with the storing of energy by cooling, heating, melting, solidifying, or vaporizing a material; the energy becomes available as heat when the process is reversed. Storage by causing a material to raise or lower in temperature is called sensible heat storage; its effectiveness depends on the specific heat of the material and, if volume is important, on the density of the storage material. Heat storage materials absorb heat through standard heat transfer mechanisms, e.g., radiation, conduction, and convection [30].

A major classification of TES systems is based on the type of storage material used. Heat can be stored in the form of sensible, latent and thermo-chemical energy.

2.3.1. Sensible heat storage

Sensible heat storage is achieved by raising the temperature of a material - liquids such as water, oil-based liquids, molten salts etc. or solids such as rocks, metals, and others. The amount of heat stored is a function of the medium's heat capacity and is linearly dependent on the temperature increase. The larger the difference between the high temperature and low temperature system, the higher is the heat stored by the material. All of the currently installed thermal energy storage systems in solar thermal electric plants store energy use sensible heat. The current systems use two-tanks with either oil or molten salt. Both oil and molten salt systems were found to be technically feasible [31]. The amount of energy input to TES by a sensible heat device is proportional to the difference between the final and initial temperatures of the storage medium, its mass and its specific heat [32].

The main theme of a Sensible Heat Storage (SHS) system is the storage of thermal energy that arises by increasing the temperature of a material in solid or liquid phase. Such a system uses the heat capacity and temperature change of the material occurring during the charging and discharging process. The temperature change, specific heat of the medium and the amount of storage material greatly affects the amount of heat stored [33].

In sensible TES (STES), the temperature of the storage material is increased by virtue of the energy being stored in that material. That is, the internal energy of the storage material is influenced by the energy being stored, which would raise the temperature of the material. In an STES, the heat capacity or the heat energy stored in the material can be directly related to the mass (m), specific heat capacity (c_p), and temperature difference (ΔT) of the material. This physical dependence can be expressed in the form of equation given by [29].

$$Q = mc_p \Delta T$$
$$= mc_p (T_h - T_l)$$

Where T_h and T_l are the maximum and initial temperature of the material, ($T_h - T_l$) is referred to the temperature swing.

2.3.2. Latent Heat Thermal Storage (LHTS)

The material of LTES undergoes a phase change process for storing or discharging heat energy. The phase change process, solid to liquid or vice versa, normally occurs at/near isothermal conditions. The heat stores in a material when the material undergoes phase transition from solid to liquid state by absorbing the heat energy supplied to it. Similarly, the energy discharges from the material when it solidifies. Materials with this property are called phase change materials (PCMs).

Storage systems based on PCMs can be smaller, more efficient and provide a lower cost alternative to sensible thermal storage systems. There have been many studies on solar TES systems using PCMs. Of the different forms of phase change processes, the solid-liquid transition is efficient in terms of low volumetric expansion compared to the liquid- gas transition and high latent heat compared to the solid- solid transition. During

phase change, heat is stored in the medium without an increase in the temperature. Due to this reason, PCMs can store larger amounts of heat compared to sensible storage media, for the same operating temperatures.

Several types of PCMs are available based on the type of application. For example, for melting ranges between 0⁰C and 200⁰C, PCMs such as paraffin's, fatty acids, polymers, salt hydrates and sugar alcohols may be used. For higher melting temperatures, salts, salt eutectics, high performance polymers, metal alloys and carbonates are available [30].

It is important for the TES system to have good heat transfer between the HTF and storage media, and also to have fast charging and discharging capability. Though PCMs can store large amounts of heat, most of them have low thermal conductivity which leads to slow charging and discharging rates. This problem can be overcome by improving the effective thermal conductivity of the PCMs which can be achieved by:

1. Adding materials with high thermal conductivity to pure PCM;
2. Forming small macro capsules of PCM and enhancing convective heat transfer by submerging the PCM capsules in a liquid.

PCMs have the capacity of storing sensible heat as a change of their temperature, below and above phase transition temperature, and latent heat enthalpy during their phase transition.

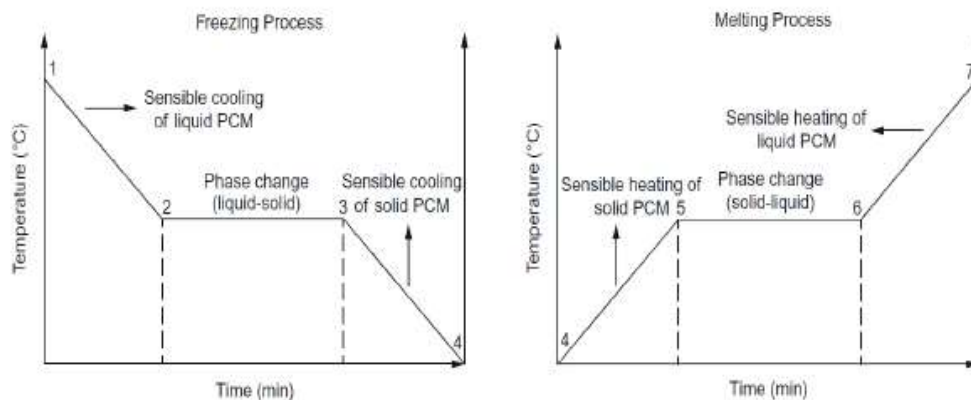


Figure 2.6 ; Heat storage and release processes of the PCM [30]

The overall storage capacity of LTES system with a PCM is given by:

$$Q = \int_{T_i}^{T_m} mc_p dT + ma_m \Delta H_m + \int_{T_m}^{T_f} mc_p dT$$

Where a_m —fraction melted, ΔH_m - heat of melting per unit mass (J/kg), T_i - initial temperature,

T_m -melting temperature, T_f - final temperature, m - mass of PCM and C_p - PCM heat capacity

2.3.3. Heat Storage using chemical reactions

Storage by means of chemical reactions has also been considered by many researchers for a wide range of temperatures using reversible endothermic/exothermic reactions. Drawbacks may include complexity, cyclability, uncertainties in the thermodynamic properties of the reaction components and of the reaction kinetics under a wide range of operating conditions, high cost, toxicity, and flammability [30].

2.4. Solar Cooker with Thermal Energy Storage

Since solar radiation is an inherently time-dependent energy resource, storage of energy is essential if solar is to meet energy needs at night or during daytime periods of cloud cover and make a significant contribution to total energy needs. Since radiant energy can be converted into a variety of forms and feasible to be stored such as; thermal energy, chemical energy, kinetic energy, or potential energy. Generally, the choice of the storage media is related to the end use of the energy and the process employed to meet this application. The optimum capacity of the storage device for a given solar process depends on the time dependence of the solar availability, the nature of the load, the cost of auxiliary energy, and the price of the process components. These factors must all be weighed carefully for a particular application to arrive at the system design (including storage size), which minimizes the final cost of delivering energy [34]. Storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings. Energy storage of all types plays an important role in energy conservation.

Mawire A et.al [35] used the system to carry out discharging simulations for the thermal energy storage system (TES). It was observed from the results that the TES system at a constant flow rate allows for a higher rate of heat utilization. However, this is not beneficial to the cooking process since the maximum cooking temperature is not maintained for the duration of the discharging period. On the other hand, the controlled load power discharging method (variable flow rate) has a slower initial rate of heat utilization but the maximum cooking temperature is maintained during the whole discharging process, and this is desirable for the cooking process. They also further introduced the energy balance equations to model a solar energy capture (SEC) system and thermal energy storage (TES) system for an indirect parabolic solar cooker. An oil-pebble bed is used as the TES material. A Simulink block was used to solve the equations and to perform energy and exergy analyses. The results indicate a greater degree of thermal stratification and energy stored when using constant temperature charging than when using constant-flow rate charging. There are greater initial energy and exergy rates for the constant-flow rate method when the solar radiation is low. Energy efficiencies using both methods are comparable whilst the constant-temperature method results in greater exergy efficiency at higher levels of solar radiation.

Schwarzer and Silva [36] had carried out performance analysis of flat plate type solar cooker with vegetable oil as sensible energy storage material. He made design of flat plate collector in such a way that, the heated oil naturally conducted upwards. Hence the requirement of the pump is neglected. They have carried out experiments during sunny days. After several experiments, they found that the vegetable oil is a good material as sensible heat storage material.

Mussard M. [37] developed a low cost small-scale parabolic trough coupled with a thermal storage unit for higher temperature cooking. The system is built with a self-circulation loop and uses thermal oil. The thermal behavior of the system was simulated using the finite-volume method. He compared different sensible and latent heat storage materials and concluded on the relevance of latent heat-based systems. He also showed that a glass cover with an air gap around the absorber would not improve the efficiency at low temperatures, but when reaching high temperatures (around 220 °C), thermal insulation would be necessary. A storage mainly based on thermal oil is much more efficient than on aluminum crossed by thermal oil channels.

Comparison between the current heat storage and the direct cooker for boiling water even with a standard pot shows that heat storage increases cooking time from 27 to 38 min. He also showed that the selective coating does not drastically improve the efficiency of the system, but the use of an evacuated tube around the absorber reduces by a factor of 2 the charging time of the heat storage.

A. Mawireet al. [38] presented Charging experiments to evaluate the thermal performance of three thermal energy storage oils for solar cookers. They evaluated the three thermal oils such as; Sunflower Oil, Shell Thermia C and Shell Thermia B. Energy and exergy based thermal performance parameters are evaluated. The exergy factor can be a useful parameter to evaluate thermal performance of small oil stratified storage tanks since it considers both the initial temperature of the storage tank and the ambient temperature conditions. The performance of the thermal oils was found to be comparable under low power charging at a high flow-rate. They found the thermal oil with the highest density and specific heat capacity (Sunflower Oil) was to be more effective under high power charging at a low flow-rate.

R. SENTHIL et al. [39] proposed that the sensible heat transfer (SHS) materials were found effective in the storage of heat as well as aiding conduction heat transfer during the cooking process. The SHS provides uniform heat supply to the inner cooking vessel and around 300 kJ and 900 kJ with solid and liquid SHS materials respectively to the cooked foods to keep warm for the later periods also is investigated experimentally. The near spherical shaped solid materials can provide better conduction heat transfer. They showed experimentally the maximum temperature attained by sunflower oil, coconut oil and olive oil were 115°C, 96°C, and 104°C, respectively. It is shown that stone pebbles having higher efficiency because of its higher specific heat among the other solid SHS materials and is around 8%, whereas sunflower oil having the better performance due to its high density and high specific heat compared to other oils. During the afternoon session, the SHS materials in the cooking vessel were found useful in providing heat for a shorter duration after the lean solar time and evening.

Mawire A. et al. [40] presented characterization of edible sunflower as Sunflower Oil is widely used in the cooking industries in South Africa for preparing fast foods like chips and fried foods. They experimentally showed that High temperature charging was

found to be the most viable option which resulted in higher energies, higher exergies, higher thermal gradients and higher exergy factors. For the discharging cycles, the higher flow-rate resulted in a fast heat transfer rate which destroyed thermal stratification earlier but heated up water faster. The lower discharging flow-rate ensured that the discharging cycle could be carried out for a longer period. This was beneficial in utilizing the stored energy and exergy for a longer period so that it could be used for cooking foods that take longer times to cook. There is a need to investigate on an optimal flow-rate for better heat transfer and for using the stored energy more effectively. Exergy factor profiles during charging and discharging cycles showed characteristic dips, which corresponded to the time when the thermal gradients started to decrease.

Buddhi et al. [41] used Stearic acid as TES in a box type solar cooker and tested the system with cooking load and without cooking load. The results were compared with the results of performance studies on conventional solar box cookers reported in the literature. The results with the PCM storage documented the feasibility of solar cooking even in absence of solar radiation.

S. D. Sharma et al. [42] designed, developed, and tested a solar cooker based on an evacuated tube solar collector integrated with a PCM (commercial grade erythritol). Water was used as HTF and a pump circulated the water from the collector to the storage. The authors performed boiling tests after charging the storage until temperatures of 130°C. However, the ratio of the storage energy to the solar radiation was somewhat low and the system was considered costly for the low-income communities.

K. Schwarzer et al. [43] developed several versions of a solar cooker, with and without TES. The system uses thermal oil as HTF with natural circulation in copper pipes. The pipes can be extended behind a wall to allow for in-door cooking. The thermal efficiency was experimentally determined using a water boiling test and was found to be about 40%.

A. Saxena et al. [44] investigated different PCMs to find out their suitability as TES for cooking purposes using a box type solar cooker. Stearic acid was selected as an appropriate PCM and used in solar box cooker experiments, with and without the heat

storage. Stearic is, due to its availability and low cost (in India), commonly used as a heat storage material. Performance studies of the two solar cookers were conducted using stagnation temperature tests and water boiling tests at load conditions. The cooker with the heat storage showed good performance.

M. Mussard et al. [45] performed a comparative experimental study on direct cooking with the SK14 concentrator and an indirect cooker with a parabolic trough system with naturally circulating oil from the absorber to “Solar Salt” heat storage. The thermal performance comparison was made with a water boiling test and a meat frying test. A challenge with cooking on top of heat storage is that imperfections on the surface limit the thermal contact between a cooking pot and the storage surface. The top plate of the storage can be used directly as a frying surface. A cooking pot in the SK14 is illuminated directly, including the sides of the pot, whereas a flat frying pan is more difficult to use in the SK14.

Asfafaw H. et al. [46] done the thermal storage loaded with two kilos of solar salt and it was experimented and simulated in COMSOL. The PCM was completely melted after it was charged by an average power of 650W for 4.5 hours; the storage showed a slow increment up on charging near the saturated temperature of the steam. A useful heat was stored for more than one day in this experiment. The experimental and COMSOL simulation results for charging of the storage gave a similar result. Therefore, simulation of an absorber by COMSOL software is the preferable way.

2.5. Thermal Insulating Materials

Thermal insulators are those materials that prevent or reduce various forms of heat transfer (conduction, convection and radiation). Insulator resists the heat transfer from out to in or in opposite direction whether the environment temperature is high or low. There are many advantages of thermal insulation that isolates the building from the heat and reduces the energy consumption as well as the costs of air-conditioning operation. Also, it makes the indoor temperature of the building stable and non-volatile.

To make the thermal insulator an economical process, the following factors should be chosen carefully:

- The amount of insulation material and thickness
- The cost of insulation material and labor costs for installation.

- The amount of energy saving and the reduction in greenhouse emissions.

It is used to choose a quality of insulation material that satisfies the balance between the economic saving and the energy saving. The amount of the total cost is equal to the total cost of insulating material plus the cost of energy saved in the building for a certain period.

The primary reasons for insulation are many and varied, the main ones being:

- To conserve energy
- To reduce heat loss or gain
- To maintain a temperature condition
- To maintain the effective operation of equipment
- To assist in maintaining a product at a constant temperature
- To prevent condensation
- To create a comfortable environmental condition

The type and thickness of insulation depend on the foregoing primary reasons together with the parameters of the specific conditions. Economic thickness is the thickness of insulation, which will result in minimum total cost of energy losses plus the cost of the erected insulation.

There are different types of insulation materials among those; fiber glass, cellular glass, foamed plastic and calcium silicate, ash and etc. are the most commonly used materials.

i. Rigid polyurethane foam (PUR/PIR)

Rigid polyurethane foam (PUR/PIR) is a closed-cell plastic. It is used as factory made thermal insulation material in the form of insulation boards or block foam, and in combination with various rigid facings as a constructional material or sandwich panel. Polyurethane in-situ foams are manufactured directly on the building site. In modest material thicknesses, rigid polyurethane foam (PUR/PIR) offers optimal thermal insulation coupled with an exceptional space-utility advantage [47].

ii. Fiberglass insulation

Fiberglass insulation is fibrous glass, made either plain or with a heat resistant binder in order for the fiberglass to hold its shape. Fiberglass is the most popular insulation, and it comes in many forms. In the form most commonly used for pipe lines, it is molded and shaped into semicircular sections and into different shapes. The binder is the critical factor for the ultimate temperature for which it can be used. Fiberglass is

recommended for temperatures up to 422°C. A high temperature, flexible blanket can be used with temperatures up to 530°C [48 and 49].

iii. Ash insulation

Ash is a waste product from the combustion of fire wood especially in the preparation foods with the largest share in baking Injera. In some cases, ash from fire wood is used as nutrient for plants because it improves the fertility of soil. Particularly the wood ash is used for insulation system because: ash is completely burned material, so it has very low thermal conductivity; again, it is a waste material, so there is no cost for it and available everywhere locally and there is no fire hazard and is not toxic, so there is no problem of safety.

In the countryside's where finding matches is difficult, to start firing early in the morning what mothers used to do is that they cover the fired charcoal with wood ash estimated about 3 to 5 cm thickness in the evening. Thus, they can get the charcoal with its fire early in the morning. This shows us that the ash conserves the energy in the charcoal, by protecting entering cold air from outside in to the fired charcoal and by protecting energy loss from the charcoal the outside environment. So, the idea of using ash as insulation material is from this experience.

Ash is the inorganic incombustible part of fuel left after complete combustion and contains the bulk of the mineral fraction of the original biomass. Currently the biomass ash is used in addition to thermal insulator, in several manufacturing processes such as cement clinker production, production of bricks, binding material for soil stabilization and also as a raw material for the production of synthetic aggregates, fertilizers or liming agents. Wood ash is generated as a by-product of combustion in wood fired power plants, paper mills, and wood burning factories [50].

In this study wood ash is used as thermal insulator to reduce the loss of heat to the environment during cooking. Because of its ease of availability, minimum cost and heat storage capacity.

2.5.1. Insulation between Different Medias

i) Insulation from Conduction

Conduction occurs when materials, especially solids, are in direct contact with each other. High kinetic energy atoms and molecules bump into their neighbors, increasing

the neighbor's energy. This increase in energy can flow through materials and from one material to another [51].

Solid to Solid; to slow down the transfer of heat by conduction from one solid to another, materials that are poor conductors are placed in between the solids. Examples include: Fiberglass is not a good conductor nor is air. That is why bundles of loosely packed fiberglass strands are often used as insulation between the outer and inner walls of a house.

Conductive heat cannot travel through a vacuum. That is why a thermos bottle has an evacuated lining. This type of heat cannot be transferred from one layer to the other through the thermos bottle vacuum.

Gas to Solid; to slow down the heat transfer between air and a solid, a poor conductor of heat is placed in between. A good example of this is placing a layer of clothing between us and the cold outside air in the winter. If the cold air was in contact with our skin, it would lower the skin temperature. The clothing slows down that heat loss. Also, the clothing prevents body heat from leaving and being lost to the cold air.

Liquid to Solid; likewise, when you swim in water, cold water can lower your body temperature through conduction. That is why some swimmers wear rubber wet suits to insulate them from the cold water.

ii) Insulation from Convection

Convection is transfer of heat when a fluid is in motion. Since air and water do not readily conduct heat, they often transfer heat (or cold) through their motion. A fan-driven furnace is an example of this. Insulation from heat transfer by convection is usually done by either preventing the motion of the fluid or protecting from the convection. Wearing protective clothing on a cold, windy day will inhibit the loss of heat due to convection [51], [52] [53].

iii) Insulation from Radiation

Hot and even warm objects radiate infra-red electromagnetic waves, which can heat up objects at a distance, as well as lose energy themselves. Insulation against heat transfer by radiation is usually done by using reflective materials. A thermos bottle not only has

an evacuated lining to prevent heat transfer by conduction, but it also is made of shiny material to prevent radiation heat transfer. Radiation from warm food inside the thermos bottle is reflected back to itself. Radiation from warm outside material is reflected to prevent heating cold liquids inside the bottle [53] [54].

So far, different authors have studied different solar cookers with different thermal energy storage. Now this paper is going to study the compound parabolic solar collector for cooking purpose with oil and rock as thermal energy storage. Thus, the cooking is indoor cooking and the main difference of this cooking from the above literature is that an absorber with thermal energy storages is placed on the focal point of the two dishes until an absorber store enough thermal energy for cooking. Then after an absorber is lifted from the solar collector and placed within the insulated material inside the kitchen for cooking. Therefore, this is used to remove the extra material need like pump, motor and circulating insulated pipe which reduces the cost of the overall system and losses of heat energy in the pipe and pump.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Methods of the Research and System Description

The detail reading of related literatures (papers) and finding out the gap is the major method of this study. There are many papers which are done previously; hence most of them have low efficient and sun dependent. Thus, this study can maximize the time of solar radiation capturing due to its compound parabolic dish solar collector and improve the efficiency collector. Moreover, this research paper is done by collecting and analyzing data related to solar radiation of Addis Ababa (Ethiopia). The overall system is designed, constructed and tested. The absorber with thermal energy storage (oil and rock) is simulated to show temperature distribution of solar absorber by using the COMSOL software. Finally, software result and the experimental result were validated and the MATLAB software is used to sketch all the graphs.

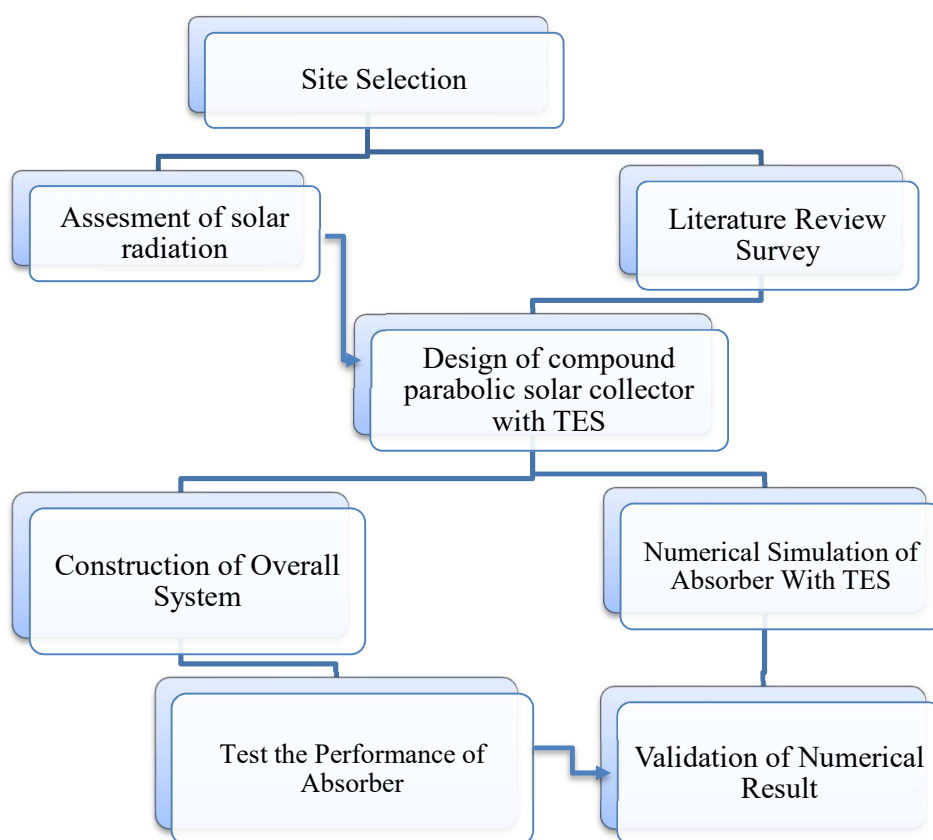


Figure 3. 1: flow chart of thesis work

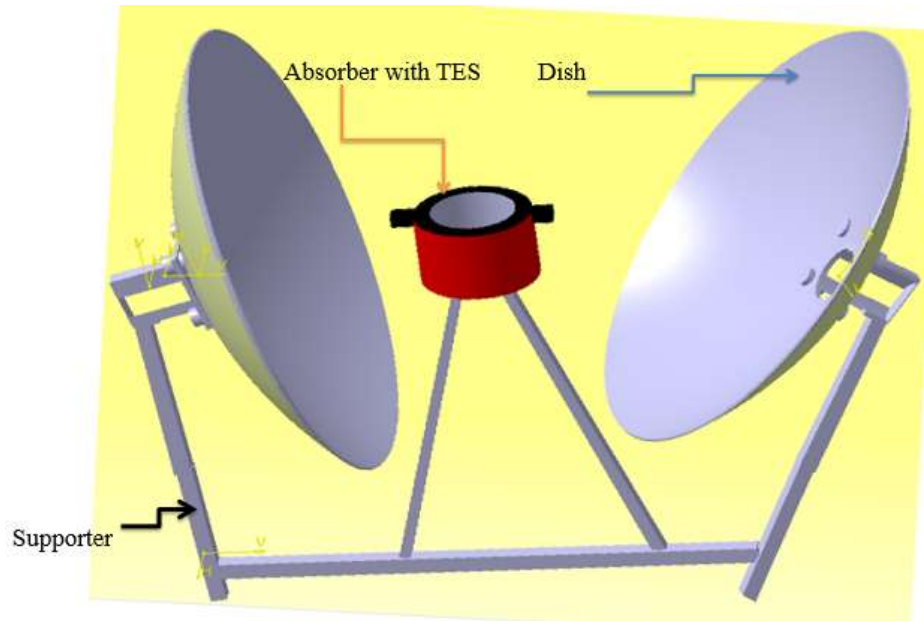


Figure 3.2; 3D overall system

Description of the proposed system: The mode of cooking is indoor cooking; an absorber with thermal energy storages is placed on the focal point of the two dishes until an absorber store enough thermal energy for cooking. The parabolic dish type collector is tracked manually for every 30 minutes. When the discharging is started, the solar cooker is transferred from the parabolic solar collector to insulator box and loaded with cooking load.

During evening cooking, inner material (rock) transfers its stored heat to the cooking pot while the outer material (oil) helps in compensating the loss to maintain its performance even during the transfer of cooker from the dish to insulator box.

This is used for to remove the extra material need like pump, motor and insulated circulating pipe which reduces the cost of the overall system and losses of heat energy on the pipe and pump.

3.1.1. Theoretical design of parabolic solar collector

3.1.1.1. Estimation of available solar radiation potential

This is the monthly average global radiation data which is taken from the Ethiopian meteorology agency and used as precondition to design solar collector.

Table 3-1; solar radiation of Addis Ababa

Monthly average Global radiation [W/m ²]												
	Month of the year											
Year	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec.
2014	604	620	616	524	529	513	432	441	547	608	595	598
2015	613	631	628	597	556	524	465	470	611	615	632	638
2016	556	632	623	438	522	438	396	414	-	-	-	585
Aver.	591	627.7	622.3	519.7	535.7	491.7	431	441.7	579	611.5	613.5	607

Source: Ethiopian National Meteorology agency

- Latitude angle, $\phi = 9.033$
- Month under consideration for design solar collector is **JULY** at which global radiation is minimum

- Declination

The *declination* is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation:

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right], n = 198 \text{ (July 17th; recommended average day)}$$

$$\delta = 21.2^\circ$$

- Where, n is the day of year (i.e. $n = 1$ for January 1, $n = 32$ for February 1, etc.). Declination varies between -23.45° on December 21 and $+23.45^\circ$ on June 21.

- *Sunset Hour Angle*

The sunset hour angle ω_s is the solar hour angle corresponding to the time when the sun sets. It is given by the following equation:

$$\omega_s = \cos^{-1}(-\tan \phi \tan \delta)$$

$$\omega_s = 93.53^\circ$$

- *Hour angle (ω)* is the hour angle of a point on the earth's surface is defined as the angle through which the earth would turn to bring the meridian of the point directly under the sun. Hour angle and solar time in hour are related as follows and for this case one can calculate hour angle at 1: 30 PM:

$$\omega = (ST - 12) \times 15^\circ$$

$$\omega = 22.5^\circ$$

- *Zenith angle* is the angle between the sun's ray and the perpendicular line to a horizontal plane.

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

$$\theta_z = 24.84^\circ$$

Extraterrestrial Radiation (H_o)

Solar radiation outside the earth's atmosphere is called extraterrestrial radiation. Daily extraterrestrial radiation on a horizontal surface and H_o , can be computed for the day of year n from the following equation:

$$H_o = I_{SC} \left[1.0 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \cos(\theta_z) \text{----- (3.1)}$$

$$I_{SC} = \text{hour constant in energy units } \left(1367 \frac{\text{W}}{\text{m}^2} \right)$$

$$H_o = 1201.04 \text{ W/m}^2$$

Monthly average solar daily radiation on horizontal surface

Monthly average solar daily radiation is calculated from the monthly average global radiation. Now it is calculated by multiplying the monthly average solar radiation values by the number of hours in the day to get solar radiation.

$$\bar{H} = 431 \text{ W/m}^2$$

- \bar{K}_T is clearness index and its values depend on the location and the time of year considered; It is usually between $0.3 \leq \bar{K}_T \leq 0.8$.

$$\bar{K}_T = \frac{\bar{H}}{H_o} = 0.36$$

- Monthly average daily diffuse radiation is calculated from global radiation through the following formula:
 - For values of the sunset hour angle ω_s less than 81.4° :

$$\frac{H_d}{\bar{H}} = 1.391 - 3.560\bar{K}_T + 4.189\bar{K}_T^2 - 2.137\bar{K}_T^3$$

- For values of the sunset hour angle ω_s greater than 81.4° :

$$\frac{H_d}{\bar{H}} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.82\bar{K}_T^3$$

$$H_d = \bar{H} [1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T^2 - 1.82\bar{K}_T^3] \text{----- (3.2)}$$

$$= 431 [1.311 - 3.022(0.36) + 3.427(0.36)^2 - 1.82(0.36)^3]$$

$$H_d = 195.97 \text{ W/m}^2$$

- The monthly average daily beam radiation I_b is simply computed from:

$$I_b = I_g - H_d \text{----- (3.3)}$$

$$= 359.2 \text{ W/m}^2$$

3.1.1.2. Sizing and Thermal Analysis of Parabolic Solar Collector

Solar dish concentrators are generally concentrators that concentrate solar energy in a small area known as focal point. Dimensions of reflecting surfaces in solar dish concentrator are determined by desired power at maximum levels of isolation and efficiency of collector conversion [55].

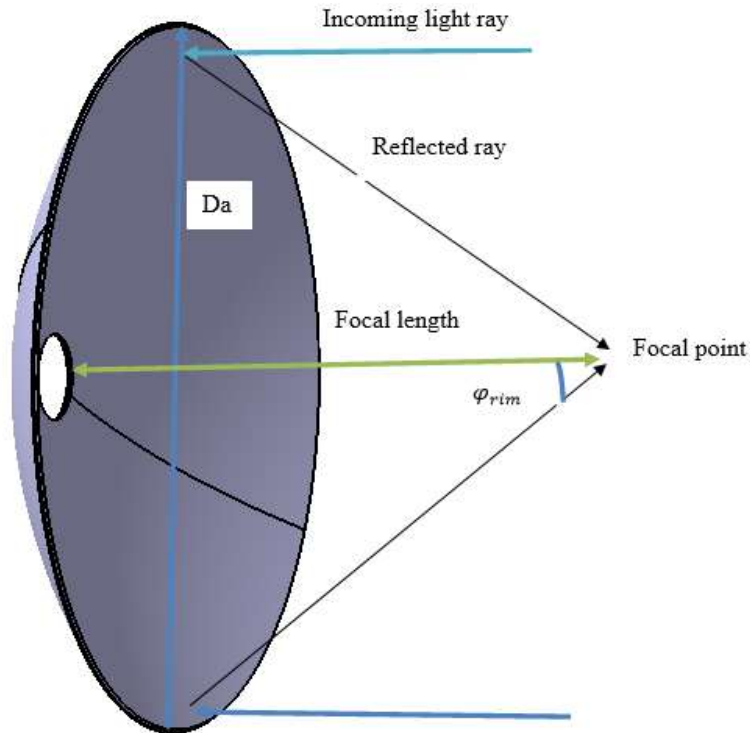


Figure 3.3; Basic dimensions of parabolic solar collector

Basically, there are two main components of parabolic solar concentrator:

1. **Reflector:** Reflectors for solar concentrators should have the highest reflectance as possible. Its function is to focus beam-solar radiation onto the receiver, which is located at the focus of the system.
2. **Receiver:** The receiver should have the highest absorptance for solar radiation as possible and must be constructed with high-conductivity metals in order to conduct efficiently the absorbed heat into the heat transfer fluid.

The heat demand load of the cooker is such that it will cook about **1kg of rice** at a time for the optimum number of family.

The volume of rice, V_{r1} , to be cooked is given as:

$$V_{r1} = m_{r1}/\rho_{r1}$$

Where m_{r1} is mass of rice to be cooked and ρ_{r1} is density of rice to be cooked (777 to 847 kg/m³) [47]. The average density of rice is 812kg/m³.

$$V_{r1} = 1\text{kg}/812\text{kg/m}^3 = 0.00123\text{m}^3$$

For cooking process, the optimum rice to water ratio by volume is 1:2 [57], [58]. Therefore, the volume of water (V_{w1}) required to cook the volume of rice (V_{r1}) is given by:

$$V_{w1} = 2V_{r1} = 2 \times 0.00123 = 0.00246\text{m}^3$$

The total volume of food (V_{f1}) to be cooked is:

$$V_{f1} = V_{r1} + V_{w1} = 0.00123 + 0.00246\text{m}^3 = 0.00369\text{m}^3$$

The mass of water (m_{w1}) required for cooking is:

$$\begin{aligned} m_{w1} &= \rho_{w1} \times V_{w1}, \text{ the density of water at room temperature is } 998\text{kg/m}^3 \\ &= 998 \times 0.00246 = 2.458\text{kg} \end{aligned}$$

The total mass of food to be cooked (m_{f1}) is:

$$\begin{aligned} m_{f1} &= m_{r1} + m_{w1} = 1 + 2.458\text{kg} \\ &= 3.458\text{kg} \end{aligned}$$

After the cooking process, the volume of cooked rice V_{f2} (including water) expands to about 3.2 to 3.5 times the volume of dry (uncooked) rice [59], [60]. An average factor of 3.35 is taken for this study.

$$\text{Therefore, } V_{f2} = 3.35V_{r1} = 3.35 \times 0.00123 = 0.004187\text{m}^3$$

If the amount of water lost is taken as directly proportional to the amount of water required, then the amount of water lost during cooking using solar cookers is 10%. Hence, the mass of water, m_{w2} , remaining in the cooked food is:

$$m_{w2} = 0.9m_{w1} = 0.9(2.458) = 2.2122\text{kg}$$

Mass of water lost;

$$m_{w1} = m_{w1} - m_{w2} = 2.458 - 2.2122 = 0.2458\text{kg}$$

An absorber of the cooker will be cylinder with external diameter ($D_{o,abs}$), external height ($H_{o,abs}$), internal diameter ($D_{i,abs}$), and internal height ($H_{i,abs}$) and the thickness (t_{abs}).

By considering the heat transfer and space requirement for oil and rock and the weight of an absorber, the optimum thicknesses of solar absorber that are taken for design;

- ✓ The thickness of absorber (t_{abs}) = 3mm
- ✓ The thickness of oil filled (t_{oil}) = 50mm
- ✓ The thickness of rock filled (t_{rock}) = 30mm
- ✓ Thickness of the pot (t_{pot}) = 3mm
- ✓ Thickness of oil-rock separator = 1mm

The internal volume of the cooking pot = the volume of the food after cooking = $0.0041875m^3$.

Therefore, internal Area of the pot (A_{pot}) \times the internal height of the pot ($H_{i,pot}$), but for optimum design the internal diameter of pot and internal height of pot is equal.

$$\frac{\pi D_{in,pot}^2}{4} \times H_{i,pot} = V_{f2} \text{-----} (3.4)$$

$$\frac{\pi D_{in,pot}^3}{4} = V_{f2} = 0.004187m^3$$

$$D_{in,pot} = \{(4 \times 0.004187)/\pi\}^{-3} = 0.1747m = H_{i,pot}$$

Therefore, the outer diameter of the cooking pot is given by:

$$D_{o,pot} = D_{in,pot} + 2t_{pot} = 0.1807m$$

The outer diameter of absorber is given by:

$$D_{o,abs} = D_{o,pot} + 2t_{oil} + 2t_{rock} + 0.002 = 0.1807 + 2(0.05) + 2(0.03) + 0.002 = 0.3427m$$

The outer height of an absorber is:

$$H_{o,abs} = H_{in} + t_{tot} = 0.1747 + 0.088 = 0.2627m \approx 0.26m$$

Then, the effective surface area of an absorber is:

$$A_{abs} = \frac{\pi D_{o,abs}^2}{4} + \pi D_{o,abs} H_{o,abs} \text{-----} (3.5)$$

$$= \pi \left(\frac{(0.3427)^2}{4} \right) + \pi (0.3427 \times 0.2627) = 0.375 \approx 0.4m^2$$

The area filled with thermal energy storage (oil + rock) can be given as:

$$A_T = A_{oil} + A_{rock} + A_{ring} = \left(\frac{\pi \times 0.05^2}{4} \right) + \left(\frac{\pi \times 0.03^2}{4} \right) + \left(\frac{\pi \times 0.001^2}{4} \right) = 0.00267m^2$$

The volume of thermal energy storage is calculated as:

$$V_{oil} = A_{oil} \times L_{eff},$$

The effective oil filled length of absorber is;

$$L_{eff} = 2(0.2427 - 0.003) + (0.3027 - 0.003) = 0.7791m$$

Therefore, $V_{oil} = \left(\frac{\pi \times 0.05^2}{4} \right) \times 0.7791 = 0.00152976m^3 = 1.529$ litter of oil and,

$$V_{rock} = A_{rock} \times L_{eff,rock} = \left(\frac{\pi \times 0.03^2}{4} \right) \times (2(0.2427 - 0.126) + (0.3027 - 0.126))$$

$$V_{rock} = 0.00028988m^3 \approx 0.0003m^3$$

The density of black rock (ρ) = 2490kg/m³

The mass of the rock is calculated as;

$$m_{rock} = \rho \times V_{rock} = 0.747kg$$

Receiver is placed in focal area where reflected radiation from solar concentrator is collected. In the process of designing, parabolic solar concentrators one always seeks for the minimum size of the receiver. With small receiver size, one can reduce heat losses as well as cost of whole system. Also, small receiver size provides increase of absorbed flux on the surface of receiver. This is the way of obtaining greater efficiency in conversion of solar radiation to heat.

The useful energy (Q_u) for one cycle of cooking is calculated as:

$$Q_u = Q_{u1} + Q_{u2} \text{ ----- (3.6)}$$

Where Q_{u1} is heat required to raise the sensible temperature food to 93°C and Q_{u2} is the heat energy required to convert 0.25 kg of water at 93°C to steam.

$$Q_{u1} = (m_{w1}C_{pw} + m_{r1}C_{pr})(T_{f1} - T_{fo}) \text{ -----(3.7)}$$

Where, the specific heat capacity of water and rice is 4186 J/kg k and 1552.816 J/kg k respectively. The temperature of food raises from ($T_{fo} = 22^\circ\text{C}$ to $T_{f1} = 93^\circ\text{C}$, the boiling point of water at Addis Ababa is 93°C).

$$\begin{aligned} \text{Therefore, } Q_{u1} &= [(1 \times 4186) + (2.5 \times 1552.816)](93 - 22) \\ &= 572.83\text{kJ and} \end{aligned}$$

$$Q_{u2} = m_{w1} \times L_w$$

Where, $L_w = 2.26 \times 10^6$ J/kg is the latent heat of vaporization of water at 93°C.

$$Q_{u2} = 0.25\text{kg} \times 2.26 \times 10^6 \text{ J/kg} = 565\text{kJ}$$

The useful energy can be obtained by:

$$Q_u = (572.83 + 565) \text{ kJ} = 1137.83\text{kJ}$$

The total cooking time of one cycle of 1kg rice can be estimated as 45minuts = 2700 seconds

Therefore, the useful power (Qu) is 1137.83kJ/2700seconds = 421Watts

Since the collector is compound parabolic dish (have two dishes) assuming with equal sizes and equal performances, so half of the useful power (i.e. 210.5Watt) is used to design individual collectors.

The *thermal efficiency* is defined as the ratio of the useful energy delivered, to the energy incident at the concentrator aperture.

It given as:

$$\eta_{th} = \frac{\dot{Q}_u}{A_{ap}I_b} \text{-----} (3.8)$$

The incident solar radiation consists of beam and diffuse radiation. However, the majority of concentrating collectors can utilize only beam radiation. The thermal efficiency range of most solar concentrators is 40%-60% [61]. Thus, for this study the average thermal efficiency 50% is used by considering the optical performance and manufacturing accuracy of solar collector.

Therefore, area of an aperture can be calculated as:

$$A_{ap} = \frac{\dot{Q}_u}{\eta_{th}I_b} = \frac{210.5}{0.5 \times 359.2} = 1.17m^2 \approx 1.2m^2$$

Therefore, the diameter of an aperture is given as:

$$D_{ap} = \left(\frac{4A_{ap}}{\pi}\right)^{\frac{1}{2}} = 1.24m \approx 1.25m$$

The "concentration ratio" is used to describe the amount of light energy concentration achieved by a given collector. Two different definitions of concentration ratio are in general use [62]. The concentration ratio C is the ratio of the effective area of the concentrator aperture to the area of the receiver and is given as:

$$C = \frac{A_{ap}}{A_{abs}} = 3,$$

The focal length of the dish is obtained from:

$$f = \frac{D_{ap}^2}{16h}$$

Where, h = the depth of dish and it is assumed to be 0.15m

$$f = \frac{1.25^2}{16 \times 0.15} = 0.65m$$

The relationship between the focal length and the diameter of parabolic dish is known as the relative aperture and it defines shape of the paraboloid and position of focal point. The shape of paraboloid can be also defined by rim angle ψ_{rim} . Usually paraboloids that are used in solar collectors have rim angles from 10 degrees up to 90 degrees. The relationship between the relative aperture and the rim angle is given by [55], [61].

$$\frac{1}{4 \tan(\psi_{rim}/2)} = \frac{f}{D_{ap}} = 0.5857$$

$$\psi_{rim} = 2 \tan^{-1}(0.5857) = 60.71^\circ$$

The solar cooker has two equal parabolic solar collectors and the solar radiations received at the aperture area of the parabolic dish reflector are calculated by the formula:

$$I_{ap} = 2A_{ap}I_b = 862.08W$$

The radiations after falling on solar dish are reflected at the receiver plate of dish. Highly reflective Aluminium sheets with reflectivity of 80% are used. The solar radiation reflected by the dish is given as:

$$I_{RD} = I_{ap}\rho_{ap} = 689.664W$$

An absorber is made up of aluminium material absorptivity of 85%. A radiation absorbed by the absorber is:

$$Q_{absorbed} = I_{RD}\alpha_{abs} \text{-----} (3.9)$$
$$= 586.21W$$

Again, not all the energy absorbed at the absorber surface is converted into useful energy. The high energy density at the absorber surface gives a high temperature. Therefore, temperature gradients between absorber and ambient arise and become a driving force for heat losses; the absorber becomes hotter than the surrounding components and ambient. As such, heat losses may occur in different modes (mainly convection and radiation). Since solar absorber is exposed to the moving air so it has convection and radiation heat losses. The ability of the absorber to minimize heat losses

is related to thermal efficiency of the absorber. Thermal efficiency of the absorber is given by the following expression:

$$\eta_{absorber} = \frac{Q_u}{Q_{absorbed}} = 51.5\%$$

From the energy balance equation formulated for the absorber;

$$Q_{absorbed} = Q_u + Q_{loss} \text{-----} (3.10)$$

Heat losses found from the system are the convective and radiation heat losses. The heat loss by convection depends upon convective heat transfer coefficient of air. The coefficient of convection is the function of velocity of air. Hence the heat loss by the convection is more as compared to radiation, as of high temperature difference in surface of Aluminium absorber and ambient air.

The heat loss (convection and radiation) from the absorber to environment is determined as:

$$\begin{aligned} Q_{loss} &= Q_{conv,loss} + Q_{rad,loss} = Q_{absorbed} - Q_u \\ &= 586.21 - 421 = 165.21\text{W} \end{aligned}$$

This indicates that only 28.2% of energy is lost to the surrounding by convection and radiation mood of heat transfer from absorber.

The absorbed heat energy on the solar absorber is also given as;

$$Q_{abs} = m_{abs}c_{p,abs}(T_{av} - T_{amb}) \text{-----} (3.11)$$

Where T_{av} and T_{amb} are average temperature of absorber and ambient temperature respectively and an absorber is made up of Aluminium with density = 2700kg/m³, specific heat capacity = 0.88kJ/kg K and thermal conductivity 204W/m°C. Assume that the properties of Aluminium does not varying with the variation of temperature of an absorber.

$$m_{abs} = \rho_{Al} \times V_{abs} = 2700\text{kg/m}^3 \times A_{abs} \times H_{abs}$$

$$= 2700 \times 0.0336 \times 0.2627 = 23.8 \text{ kg}$$

The solar receiver (absorber) is placed on the focus of dish collector and the system is exposed to solar radiations from 9:00am to 3:00pm. After 3:00pm the absorber is lifted from the parabolic solar collector and placed in the insulator box and loaded for evening cooking. Thus, Energy absorbed by absorber for the charging time of 6 hours and assuming constant solar radiation is reaching an absorber is given by:

$$Q_{\text{abs}} = 732.768 \text{ W} \times 6 \text{ hr} = 3517.26 \text{ Whr}$$

Then the average temperature of absorber surface is calculated as;

$$T_s = \left(\frac{Q_{\text{abs}}}{m_{\text{abs}} c_{p,\text{abs}}} \right) + T_{\text{amb}} = 899.57 \text{ K}$$

This is a surface temperature of an absorber which reaches in 6 hours. However, from this energy 28.2% is lost to the surrounding since; an absorber is exposed to air. Therefore, the remaining temperature to be stored on the thermal energy storage and needed for evening cooking is; $T = T_s - T_{\text{loss}} = 617.1 \text{ K}$ and hence,

$$T_{\text{left}} = 617.1 \text{ K} = 344.1 \text{ }^\circ\text{C}$$

Now it is a time to calculate the overall heat loss coefficient (U_l) and it is determined from the equation:

$$U_l = \frac{Q_{\text{loss}}}{A_{\text{abs}}(T_{\text{av}} - T_{\text{amb}})} = \frac{1084.32 \text{ W}}{1.5 \text{ m}^2(617.1 - 295) \text{ K}} = 2.24 \text{ W/m}^2\text{ }^\circ\text{C}$$

3.2. Selection of Sensible Heat Thermal Energy Storage (SHTES)

SHTES is cheaper than LHTES for small storage volumes but its energy storage density is lower. Low thermal conductivities, degradation of phase change materials (PCMs) after numerous charging and discharging cycles and the expense in manufacturing of PCMs are added disadvantages of PCMs as compared to SHTES materials for small scale domestic usage. Sensible heat storage materials include thermal oils, rocks, water, metals and salts [63].

The selection of a TES system for a particular application depends on many factors, including storage duration, economics, supply and utilization temperature

requirements, storage capacity, heat losses and available space. Sensible TES are simpler in design than latent heat or thermo-chemical storage systems but suffer from the disadvantage of being bigger in size and cannot store or deliver energy at a constant temperature [64].

The specific application for which a thermal storage system is to be used determines the method to be adopted. Some of the considerations, which determine the selection of the method of storage and its design, are as follows [65];

- The temperature range, over which the storage has to operate.
- The capacity of the storage has a significant effect on the operation of the rest of the system. A smaller storage unit operates at a higher mean temperature. This results in a reduced heat transfer equipment output as compared to a system having a larger storage unit. The general observation which can be made regarding optimum capacity is that “short-term” storage units, which can meet fluctuations over a period of two or three days, have been generally found to be the most economical for building applications.
- Heat losses from the storage have to be kept to a minimum. Heat losses are particularly important for long-term storage.
- The rate of charging and discharging.
- Cost of the storage unit: This includes the initial cost of the storage medium, the containers and insulation, and the operating cost.

Other considerations include the suitability of materials used for the container, the means adopted for transferring the heat to and from the storage, and the power requirements for these purposes.

STES materials are commonly classified as solid and liquid storage materials. Solid storage materials include rocks, stones, brick, iron, soil, concrete etc. and liquid storage materials include mainly water and oils. Solid STES are common for space heating and high temperature (solar) heating applications. It usually operated in temperature ranges

of 40 to 75°C for rock beds/concrete and over 150 °C for metals in these applications respectively [66].

3.2.1. Solid Storage Media

Solid particulate matter requires a heat transfer fluid to store thermal energy at medium to high temperatures. Energy can be stored in rocks or pebbles packed in insulated vessels. This type of storage is used very often for temperatures up to 100°C in conjunction with solar air heaters. It is simple in design and relatively inexpensive. Typically, the characteristic size of the pieces of rock used varies from 1 to 5 cm. An approximate rule of thumb for sizing is to use 300 to 500 kg of rock per square meter of collector area for space heating applications. Rock or pebble-bed storages can also be used for much higher temperatures up to 1000°C [65].

The reason behind developing solid storage includes:

- Reduced risks of leakage at elevated temperatures
- Feasible to store very high temperatures (solar power plants)

The difficulties and limitations relative to liquids can be avoided by using solid materials for storing thermal energy as sensible heat. But larger amounts of solids are needed than using water, due to the fact that solids, in general, exhibit a lower storing capacity than water. The cost of the storage media per unit energy stored is, however, still acceptable for rocks.

Table 3-2; Thermal properties of rock

Thermal conductivity (W/m/K)	1.2 to 5.9
Specific heat capacity (kJ/kg K)	0.854

3.2.2. Liquid storage media

Water is SETES used as a heat transfer fluid should be pressurized to store energy at temperatures above its boiling point. Thermal oils have the advantage that they act both as the heat transfer and the heat storage medium for medium to high temperature domestic applications. These applications include steam generation and cooking of food. There are different types of thermal oils; sunflower oil, engine oil, thermia oil B and thermia oil C. Thus, the oil which is used for this study (theoretical study) as

thermal energy storage is thermia oil B; because of its efficiency, cost, heat transfer ability, low viscosity and etc.

Shell Thermia Oil B is a paraffinic mineral oil heat transfer fluid for indirect closed fluid heat transfer systems operating at bulk temperatures up to 320°C.

Applications

- Heat transfer fluid for indirect closed fluid heat transfer systems operating at bulk temperatures up to 320°C

Performances Features

Good low temperature properties

Shell Thermia Oil B is fluid down to -18°C. Therefore, no special precautions are necessary when closing down plant in cold weather. Should the temperature fall below -18°C no expansion takes place.

Low vapour pressure

Below temperatures of 320°C, the vapour pressure of Thermia B is less than atmospheric pressure. High pressure pipe work and heat exchangers, used with vapour phase heat transfer fluids, are therefore unnecessary.

Good heat transfer characteristics

Shell Thermia Oil B has a relatively low viscosity with good temperature/viscosity characteristics which ensure high heat transfer coefficients and consistent properties cover a wide temperature range.

Performance Benefits

- Low cost
- High thermal stability
- Operating temperature range from -18°C to + 320°C.
- Good oxidation stability
- Low viscosity to promote high heat transfer coefficients

- Good viscosity/temperature characteristics
- Low vapour pressure
- Non-corrosive

Table 3-3; Thermal properties of thermia Oil B

Temperature (°C)	0	20	40	100	150	200	250	300	340
Density (Kg/l)	0.876	0.863	0.850	0.811	0.778	0.746	0.713	0.681	0.655
Specific heat capacity (kJ/kg °K)	1.809	1.882	1.954	2.173	2.355	2.538	2.72	2.902	3.048
Thermal conductivity (W/m/K)	0.136	0.134	0.133	0.128	0.125	0.121	0.118	0.114	0.111
Prandtl number	3375	919	375	69	32	20	14	11	9

The thermal properties of the oils are temperature dependent and their temperature dependent are shown table below [63].

Table 3- 4: variation of thermal properties with temperature of thermal oils

Thermal Oil	Density (kg/m ³)	specific heat capacity (J/kg K)	Thermal conductivity (W/mK)
Sunflower Oil	$\rho = 930.62 - 0.65T$	$C_{ps} = 2115.00 + 3.13T$	$K_s = 0.161 + 0.018\exp(-\frac{T}{26.142})$
Shell Thermia C	$\rho = 893.00 - 0.67T$	$C_{pC} = 1798.00 + 3.58T$	$K_C = 0.121 + 0.132\exp(-\frac{T}{18.659})$
Shell Thermia B	$\rho = 876.00 - 0.65T$	$C_{pB} = 1809.00 + 3.5T$	$K_B = 0.118 + 0.018\exp(-\frac{T}{168.66})$

Table 3.4 shows the thermal properties of the different oils as a function of the temperature. Sunflower Oil has the highest temperature dependent density and specific heat capacity. The thermal conductivities are seen to be within the same range.

The ambient temperature variation for Shell Thermia C and Sunflower Oil is higher than that of Shell Thermia B. The greatest rises from the initial storage tank temperatures are seen with Shell Thermia B (the lowest density oil). This is attributed to its lower thermal mass and viscosity during the charging period. All thermal profiles

show a characteristic rise of the upper level temperatures at the later part of charging and written by Fareed. M. et.al [63].

One of the important characteristics of a storage system is the length of time during which energy can be kept stored with acceptable losses. If solar energy is converted into a fuel such as hydrogen, there will be no such a time limit. Storage in the form of thermal energy may last for very short times because of losses by radiation, convection and conduction. Another important characteristic of a storage system is its volumetric energy capacity, or the amount of energy stored per unit volume. The smaller the volume, the better is the storage system. Therefore, a good system should have a long storage time and a small volume per unit of stored energy [46].

3.2.3. Heat Transfer Analysis between an Absorber and Thermal Energy Storages

The mode of heat transfers from the outer surface of absorber to the thermal storage and to the cooking pot is conduction heat transfer because it is due to the contact of different bodies.

The basic microscopic mechanism of conduction is the motion of molecules and electrons. It can occur in solids, liquids and gases. In metallic solids it has both lattice vibrations and random motions of free electrons. In liquids it has partly random molecular motions and some sort of vibration of the liquid lattice structure.

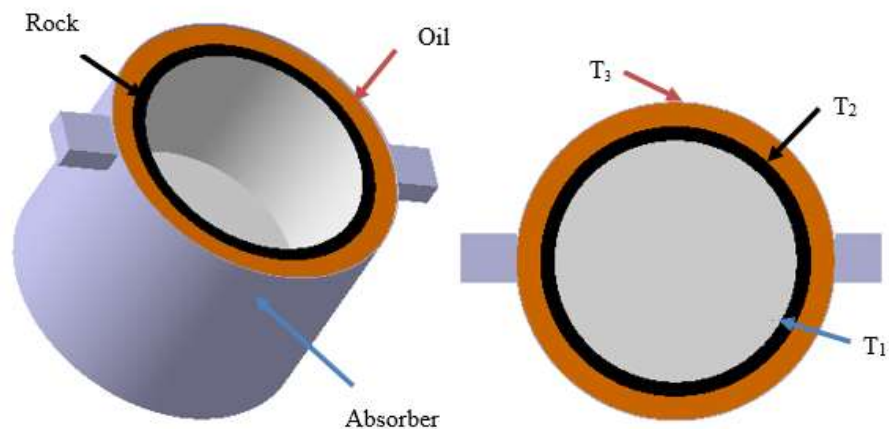


Figure 3. 4; 3D Drawing of Solar Absorber with TES (left), Top view (right)

Thermal resistance circuit

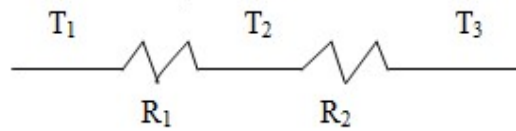


Figure 3.5: thermal resistance diagram

$$R_T = R_1 + R_2 = \frac{\ln(r_3/r_2)}{2\pi L_{oil}K_{oil}} + \frac{\ln(r_2/r_1)}{2\pi L_{rock}K_{rock}} = 1.8 \text{ K/W}$$

Temperature T_1 is lower than temperature T_2 and T_2 is lower than T_3 . Heat flows from the high temperature to the low temperature. If A is the area normal to the direction of heat flow, Fourier's Law states that the amount of heat flow is proportional to the area A , the temperature difference and inversely proportional to the thickness of the wall.

Consider now the composite system of above Figure 3.4 and 3.5; recalling how we treated the composite plane wall and neglecting the interfacial contact resistances, the heat transfer rate may be expressed as [60];

$$Q = -KA \frac{dT}{dr} = -K(2\pi rL) \frac{dT}{dr} \text{----- (3.12)}$$

Basic Assumptions;

- The heat transfer flow is one dimensional
- Thermal properties of rock and Aluminium cannot vary with temperature
- No heat generation and heat transfer rate are constant.

The average thermal conductivity of oil and rock is 0.123 and 3.5 W/m K respectively, and $L_{oil} = 0.2627m$, $L_{rock} = 0.2117m$, $r_1 = 0.09335m$, r_2 and r_3 are 0.12435 and 0.17735m, respectively.

To calculate the temperature at the intermediate of oil and rock one uses the following equation.

$$Q = \frac{2\pi K_{oil}L_{oil}(T_3-T_2)}{\ln(r_3/r_2)} = \frac{2\pi K_{rock}L_{rock}(T_2-T_1)}{\ln(r_2/r_1)} \text{----- (3.13)}$$

$$T_3 = T_{left} = 617.1K \text{ and } T_1 = 366K, \text{ therefore, } T_3 > T_2 > T_1$$

$$\frac{2\pi K_{oil}L_{oil}(T_3 - T_2)}{\ln(r_3/r_2)} = \frac{2\pi K_{rock}L_{rock}(T_2 - T_1)}{\ln(r_2/r_1)}$$

By rearranging $T_2 = 374.54K = 101.54^\circ C$

3.2.3. Heat energy stored in the thermal energy storage

The amount of stored thermal energy depends on the specific heat of the medium, the temperature change and the amount of storage material.

The maximum possible theoretical energy that can be stored in the oil depends on the temperature difference between oil before charging and after charging. It also depends on the mass of the storage material.

The rate of heat stored in the oil is initially more but it decreases with time because the rate of heat stored in the oil depends upon the temperature difference i.e. change in temperature of oil. Initially the heat stored in the oil is at a faster rate due to large temperature difference of the oil and bottom surface of Aluminium absorber but it decreases with increase in temperature of oil.

The maximum theoretical energy stored in the oil during charging can be expressed as;

$$Q_{oil,stored} = m_{oil}C_{p,aver}\Delta T = \rho_{ave}VC_{p,ave}(T_{aver} - T_a) \text{ ----- (3.14)}$$

Where, $\rho_{ave} = 762.1kg/m^3$ is average density and $C_{p,ave} = 2.4465kJ/kg K$ is average specific heat capacity of oil and average oil temperature $(T_{aver}) = \frac{344.1^\circ C + 101.54^\circ C}{2} = 222.95^\circ C$, and $T_a = 22^\circ C$

$$Q_{oil,stored} = 573.16kJ$$

The heat energy stored in the rock during charging is also calculated as;

$$Q_{rock,stored} = m_{rock}C_{p,rock}\Delta T = m_{rock}C_{p,rock}(T_{aver} - T_a) \text{ ----- (3.15)}$$

Where, $m_{rock} = 0.747kg$, $C_{p,rock} = 0.854kJ/kgK$, average rock temperature $(T_{aver}) = \frac{101.54 + 93}{2} = 97.27^\circ C$ and $T_a = 22^\circ C$

$$\therefore Q_{rock,stored} = 47.56kJ$$

The total energy stored from solar energy in the thermal energy storage;

$$Q_{stored} = Q_{oil,stored} + Q_{rock,stored} \text{ ----- (3.16)}$$

$$= 620.667kJ$$

Since an absorber is exposed in the radiation for 6hours and the time taken to cook food is 45minuts. Therefore, the total energy stored in the TES is within 6hours is given as;

$$Q_{stored} = \frac{620.667 \times (6 \times 60)}{45} = 4965.33kJ$$

Hence, the energy needed to cook the food for once a time is 1137.83kJ. When we compared the required energy for cooking and the stored, the stored energy is too higher than the required. Therefore, the stored energy in the thermal energy storage can cook the food of 1kg of rice 4.7 times. Therefore, this is the main advantages of thermal energy storage. However, this result is without considering heat losses, i.e. the losses during the cooking on the insulated tank, manufacturing quality in parabolic solar collector and the effect of heat transfer between heat storage due to material thickness and thermal conductivity of material affects the efficiency of storage. Even if it has such a loss, an absorber is placed in the ash insulation and stored energy can cook the food more once.

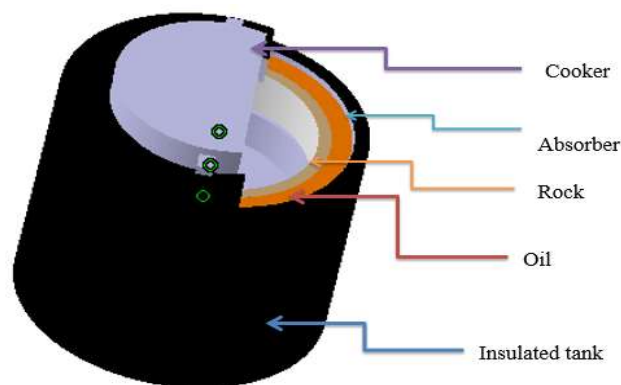


Figure 3.6; Absorber Inside Insulated Thank

3.3. COMSOL Multiphysics Simulation

COMSOL Multiphysics provides two kinds of operation modes, graphical user interface style, and command style by creating scripts. Both modes provide convenience for users mostly. Script mode is mainly for optimum design and second development for COMSOL Multiphysics. COMSOL Multiphysics includes three sections: Pre-process, solution, and post- process. Creating finite element model and setting load parameters belong to pre-processing. Mesh division and solving equations are all belong to solution section. Results visualization and analysis are belonging to post- processing.

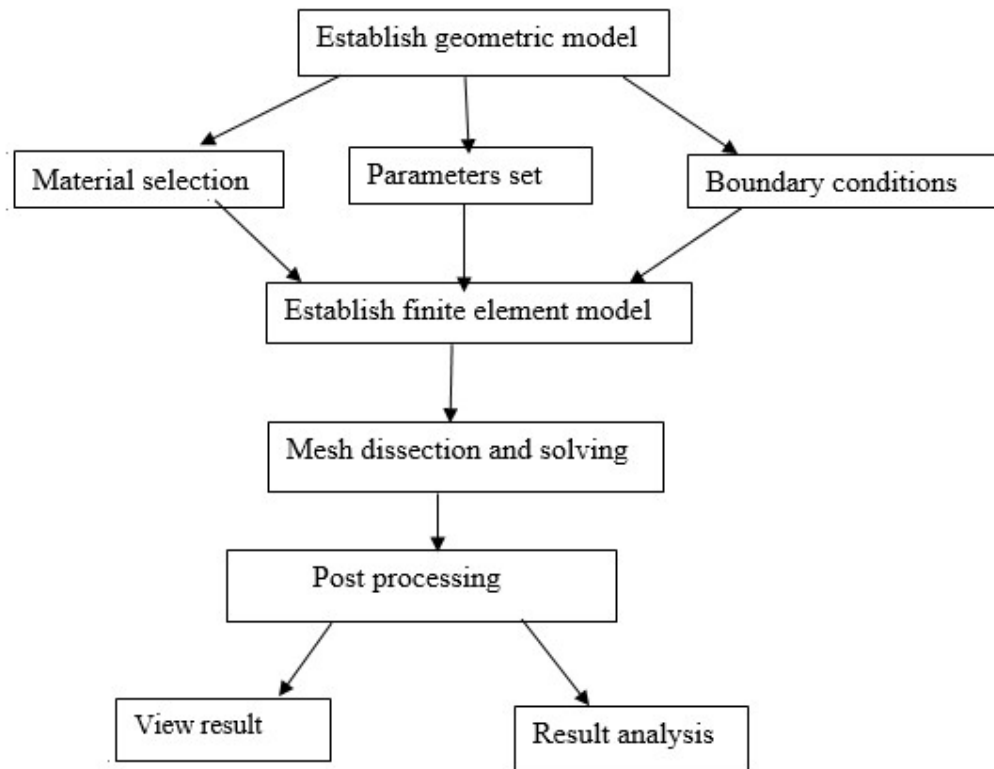


Figure 3.7; Chart of COMSOL Multiphysics analysis

3.3.1. Numerical Simulation of thermal energy storage

Input parameters are outside surface temperature of an absorber, material properties of absorber and thermal energy storage, heat flux of the outer surface of absorber and surrounding conditions.

Basic Boundary conditions;

- ✓ In the outside surface of absorber temperature is constant, the uniform temperature was selected (T_s) = 344.1°C (617.1K).
- ✓ The static pressure in the outer surface of the absorber was set to be environmental.
- ✓ The heat convection between the outer surface and the environment ($h = 11.8$ W/m² °C).
- ✓ In the inner surface (pot) the cooking uniform temperature is also selected.
- ✓ The simulation is time dependent (transient) and two-dimensional temperature distribution across the absorber.

The governing equation for the heat transfer process within the TES is the energy equation for conduction and convection. However, the effect of convection heat transfer within this study can be neglected. Therefore, there is no convective term in this case and the energy equation for the analysis of thermal energy storage unit can be simplified and expressed in equation below.

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) = \nabla(k \nabla T)$$

Where, ρ , C_p and k are the density, specific heat capacity, and thermal conductivity respectively of the sensible heat storage.

Table 3-5 ; Basic input parameters for simulation

Material	Parameters	Values
Absorber (carbon steel)	Specific heat capacity	0.486kJ/kg.°C
	Thermal conductivity	54W/m °C
	Density	7833kg/m ³
	Thickness	3mm
Engine Oil	Specific heat capacity	2367.5J/kg K
	Thermal conductivity	0.1W/m K
	Density	762.1kg/m ³
	Thickness	50mm
Rock (granite rock)	Specific heat capacity	0.854kJ/kg K

	Thermal conductivity	3.5W/m K
	Density	2490kg/m ³
	Thickness	30mm

3.4. Construction of parabolic Solar Collector and Solar Cooker with TES

3.4.1. Selection of Materials for the Construction of Solar collector

Aluminium with 0.5mm thickness was selected over steel for the dish construction, because of its lightness, lower cost, ease of fabrication and energy effectiveness in use of material. Its light weight reduces the overall weight of the system. Moreover, it has high quality and good specular reflectance with its reflectivity of 85%. In this test the two dishes are constructed with the diameter of 1m with 12cm depth.

Material for the Absorber; carbon steel was selected over copper and Aluminium because of its ease of fabrication (welding) and energy effectiveness (thermal conductivity) in use of material. For this experimental test, 1.5mm thickness carbon steel is used for an absorber, oil storage and rock storage.

Material for Thermal energy storage; 1.5 liter of used engine oil and 0.74kg of rock is used for experimental test.

Cooking material; water is used for this test instead of rice and pot is made up of Aluminium.

3.4.2. Construction of solar collector and solar cooker with TES

This experiment is performed to investigate the thermal performance of solar cooker with the rock and used engine oil in inner and outer space respectively. The reason why oil is used on the outer space is that, it is used as heat transfer fluid and also used as insulator during discharging period (due to its low thermal conductivity).

Solar cooker is made up of two hollow concentric cylindrical and a pot is placed at their center. This solar cooker is constructed by bending and then welding the bended steel. The test section of solar cooker is based on compound parabolic dish collector. This

system consists of parabolic dish collector and solar cooker with thermal storage. Used engine oil and rock is used as thermal storage and filled hollow space of outer and inner wall of solar cooker, respectively. Therefore, the solar cooker is exposed to solar radiation for 8:30hour (for test) to charge the thermal energy. At 5:30pm the solar cooker is lifted and placed in hallow space cylinder which is insulated by ash and loaded by pot to cook food for evening.

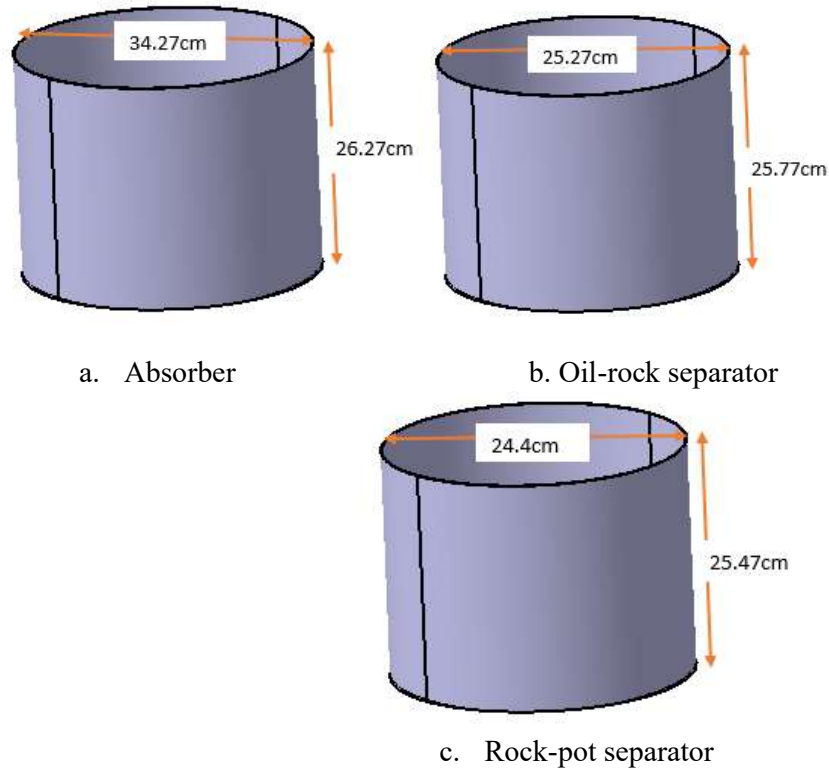


Figure 3.8; part drawings of Absorber

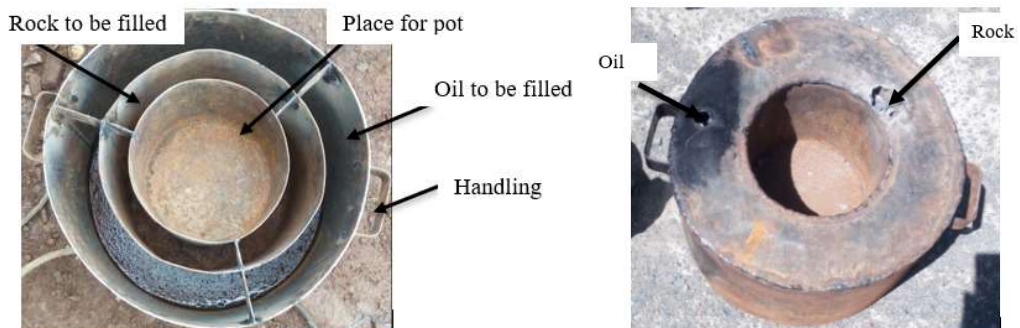


Figure 3.9; Photograph of Solar Absorber

The solar dish is a point focusing collector which includes concentrator, absorber with thermal storage for placing the cooker and frame as shown below with figure 3.9.

Hence, the parabolic solar collector is made from Aluminium sheet and constructed by bending and connecting the two tips. At the focal length of both parabolic dish collector, an absorber with TES is provided upon which cooker is to be placed. The tracking of parabolic dish collector is done manually and for that tracking screw is provided at the bottom of parabolic dish. The parabolic dish collector is adjusted in such a way that the shadow of tracking screw does not affect. After setting this position, the parabolic dish collector is locked in that position by the holding screw provided at the bottom of dish. Tracking screw is provided at the bottom of parabolic dish so that the dish can be tracked with the movement of sun with 30 minutes.

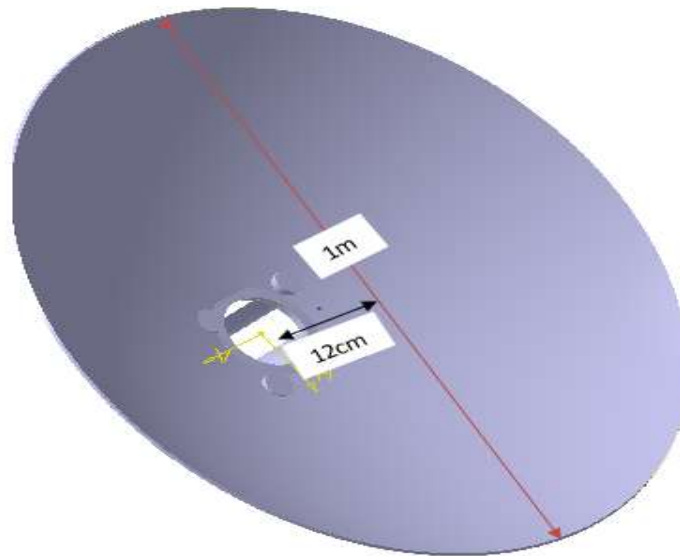


Figure 3.10; parabolic solar collector



a. Over all system

b. Manual tracking of parabolic solar collector

Figure 3.11 ; Photograph of Experimental Setup

The temperatures of Sensible heat storage materials; absorber surface and cooking medium are measured with thermocouple which is connected with a digital temperature indicator that shows the temperature in degree Celsius. The charging temperature of absorber surface, used engine oil and rock is recorded as shown in the below photograph. Thus, the temperature is measured within 30minutes gap.



a. Measuring temperature of absorber surface b. measuring temperature of used engine Oil



c. Measuring temperature of rock

Figure 3.12 ; Photograph of Temperature Measurements

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1. Numerical Results and Discussions

This COMSOL simulation is needed to show the temperature distribution on the absorber and to know how much energy is reached to the pot. Therefore, this is used to decide whether the model is preferable for further experimental test or not.

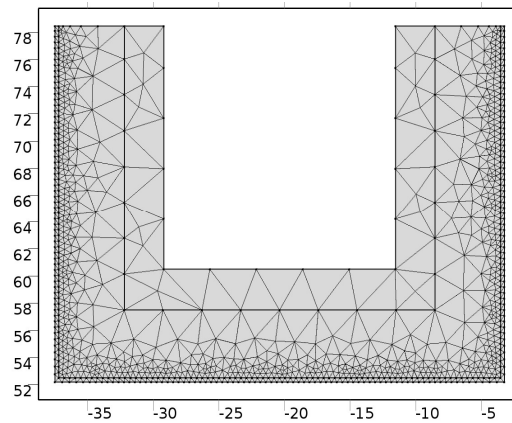
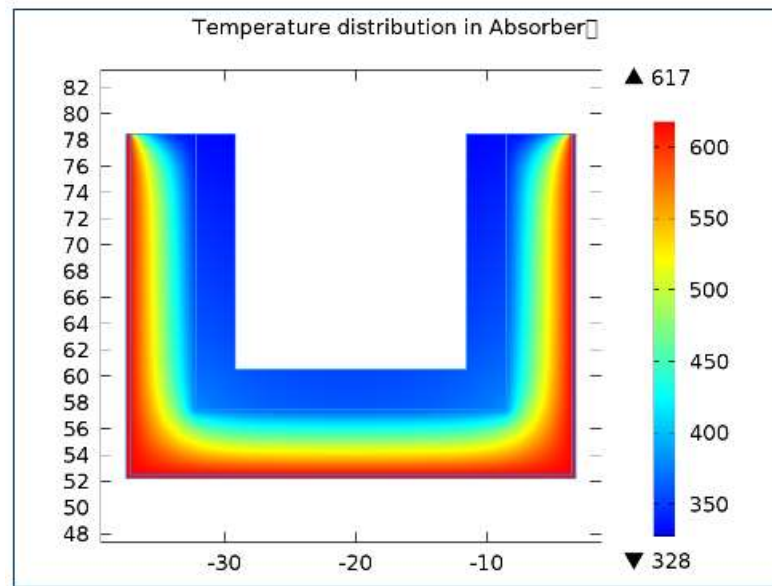


Figure 4.1 ; Mesh of Geometry



Temperature distribution in Absorber

Figure 4.2; Temperature Distribution on the Absorber

As shown in the above figure 4.2, nearly all heat energy is passed from the outer surface to inner surface of carbon steel. This is due to its low thickness and high thermal conductivity of carbon steel absorber. However, in the Oil (TES), the temperature is distributed by reducing its value from outer to inner side. This is because large thickness and low thermal conductivity, but it has high heat capacity. That is why it is used for as thermal storage, so it collects all the coming heat from absorber and stores 2 to 3 hours. Moreover, in the rock, temperature is distributed by reducing its value in a limited number that is why it has small thickness and high thermal conductivity as compared to Oil. Therefore, all the stored heat energy in the Oil and Rock is used for evening cooking. When one compares the theoretical design and computer simulation of an absorber, in case of theoretical the working temperature which is needed to cook the rice is 93°C (boiling temperature), whereas in COMOSOL simulation the minimum temperature which reaches the cooking material (pot) is nearly 350K (77°C) after 6hours. However, this temperature is continuously delivered to the pot and the temperature of cooking unit increases and reaches to the boiling point.

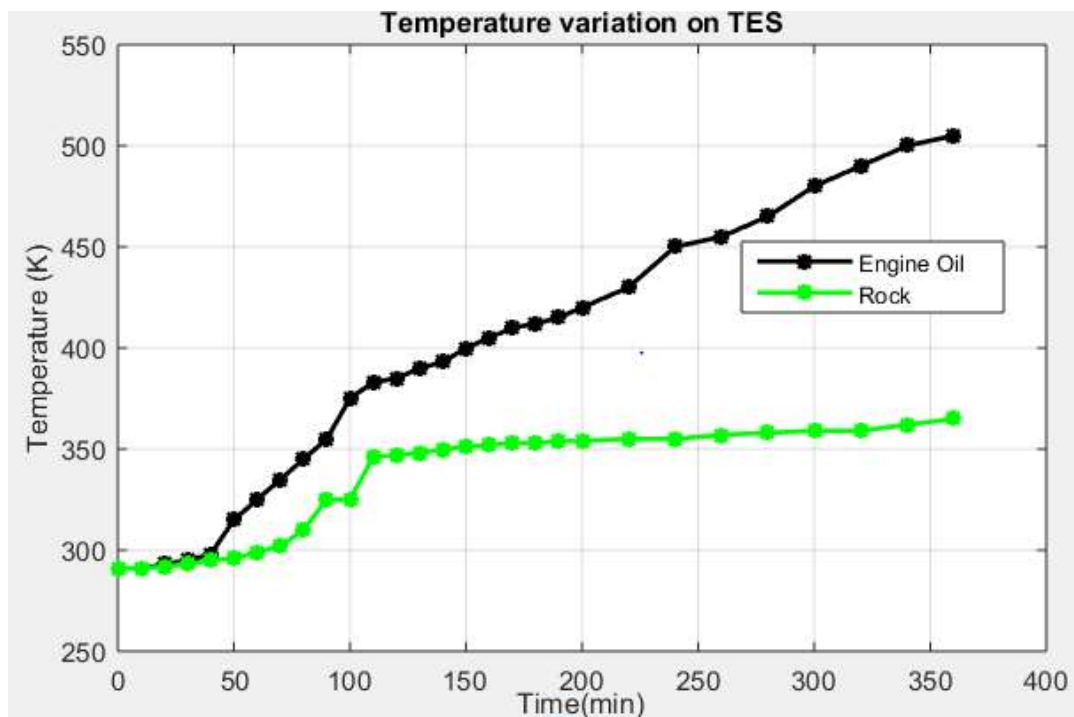


Figure 4.3; Temperature versus Time in Absorber

The temperature in the absorber surface is taken as constant throughout the day that is what has been taken as an assumption in theoretical design. Therefore, its temperature

is taken as constant and taken as initial condition i.e. 617.1k. In both rock and oil, the temperature is nearly the similar to ambient for first 40minutes. Thus, in the rock, the temperature increases radically from 50 to 110minutes. However, after 110minutes the temperature increases in small difference. Furthermore, the temperature of oil is increasing linearly with the time after 40 minutes. Therefore, the maximum temperature reached after 6hours in oil and rock are 505K and 365K respectively. The result obtained by theoretical calculation in rock is 366K, is the boiling point of water. Moreover, one compares the values which are obtained by theoretical calculation with COMSOL results, so the values are difference of only 1K. The temperature obtained from software is less than value from theoretical calculation for oil and the value of temperature obtained by theoretical calculation in rock is nearly equal with software result. Thus, 365K can reach the surface of pot which is nearly enough to cook the food by neglecting conduction losses in the cooking material.

4.2. Experimental Results and Discussions

4.2.1. Charging Temperature of TES

The test is carried out in Addis Ababa institute of Technology campus (5kilo). Thus, the experimental test is involved on September month in 5 consecutive days and recorded with 30 minutes gap from 9:00am to 5:30pm. Hence, the only average charging temperature of five day of absorber surface, oil and rock is reported.

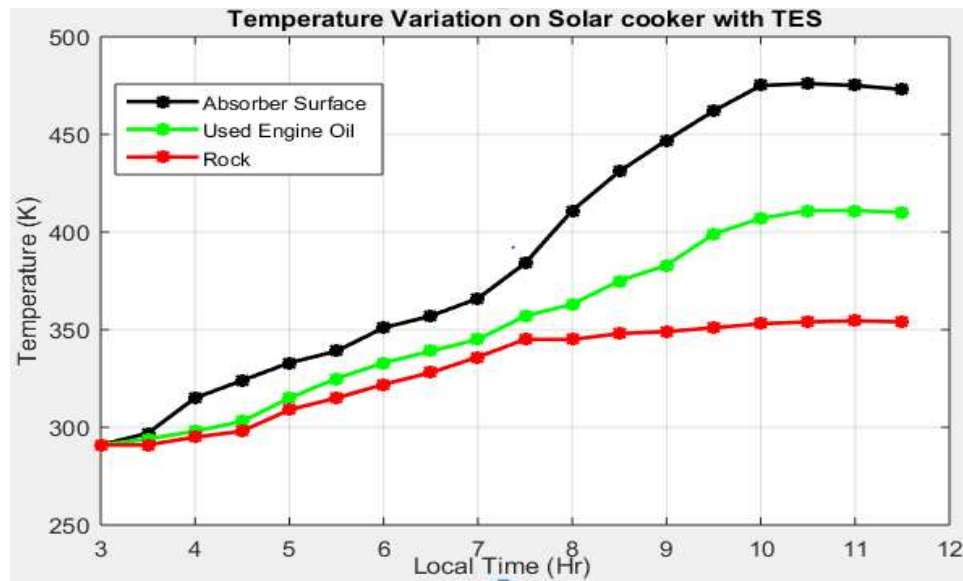


Figure 4.4; Temperature variation on solar cooker with TES

The charging temperature of an absorber surface increases nearly linearly with time from 3hr to 7hr local time (9am to 1pm) and reaches to 366K (93°C). Moreover, it increases rapidly from 7hr to 10hr local time (1pm to 4pm) and reaches 476K (203°C), that is why the sun is on the head and solar radiation on Addis Ababa is high on this time compared with other hours. Hence, the day is going to evening and the sun is going to set, therefore, the temperature of an absorber surface is reducing slowly from 10hr to 11:30hr local time (4pm to 5:30pm) and reaches to 473K (200°C) at 11:30hr local time (5:30pm), in which discharging is started. However, this all heat energy cannot transfer from absorber surface to the oil; this is due to the convection loss, radiation loss and conduction losses. The temperature on the used engine oil increases linearly till 7:00hr local time (1pm) like absorber surface and reaches 345K (72°C). After 7:00hr local time (1pm) the temperature increases gradually until 10:00 hour local time (4pm) and reaches 411K (138°C). Thus, the oil stores all this heat energy and it acts as heat transfer medium which transfers this heat energy to rock. Hence, this all heat energy cannot transfer to rock; this is due to low thermal conductivity of oil and losses like radiation and conduction. The temperature of the oil is nearly constant and reducing in a small number from 10:00 to 11:30hr local time (4pm to 5:30pm) and reaches to 410K (137°C). Therefore, the reason why engine oil is used is that it cannot losses the temperature easily with short time and it is available freely. The thermal conductivity and storage capacity are low compared to thermia oil B. Even though, the TES can store energy which is nearly enough to boil the water. Therefore, it can be concluded that, the system can be more effective if it uses Thermia oil B used for practical test like theoretical study. Because it is used as heat storage medium and insulated material (low thermal conductivity). The temperature of rock increases linearly from 3:00 to 7:30hr local time (9am to 1:30pm) and reaches 345K (72°C) but it increases slowly for the last hours and reaches 354.5K (81.5°C) at 11:00hr local time (5pm). Thus, this energy directly reaches continuously to pot until the water is boiling. After 10:30 hr local times (4:30pm), an absorber is lifted and placed in the insulated tank and loaded by pot with water.

4.2.2. Discharging Temperature of TES

The discharging of TES is started after solar cooker is lifted from the focal point of the compound parabolic solar collector. Hence, it is placed on the insulated tank (insulated with ash) and loaded by pot with water.

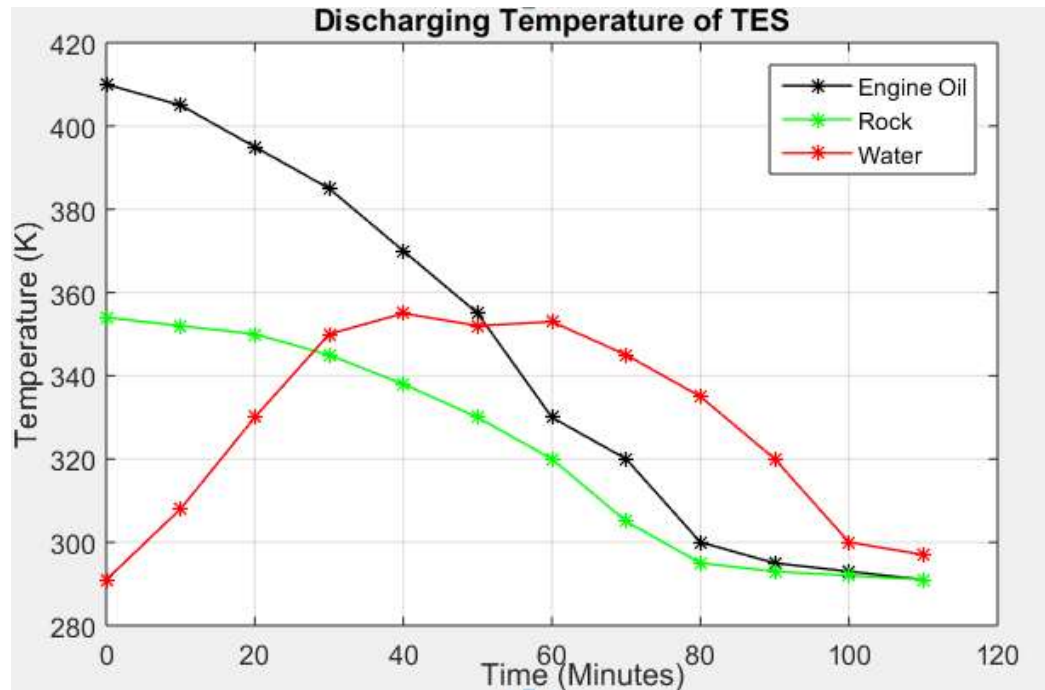


Figure 4.5; discharging temperature of TES

The temperature of TES is reducing gradually by discharging its heat energy to pot and surrounding. Thus, the temperature of water is increasing radically till 40minutes from its ambient condition and it reaches 355K (82°C). Since, an absorber is not covered effectively by insulation; this leads further decrement of temperature from TES. However, water itself is used as TES, this why the temperature of water is nearly constant from 40minute to 60 minutes and it gradually decreases after 60minutes.

4.3. Validation of Numerical simulation

To validate the accuracy of the model, the numerical result (fig. 4.3) is compared with the experimental result (fig. 4.4) of the charging of thermal energy storage as shown below figure.

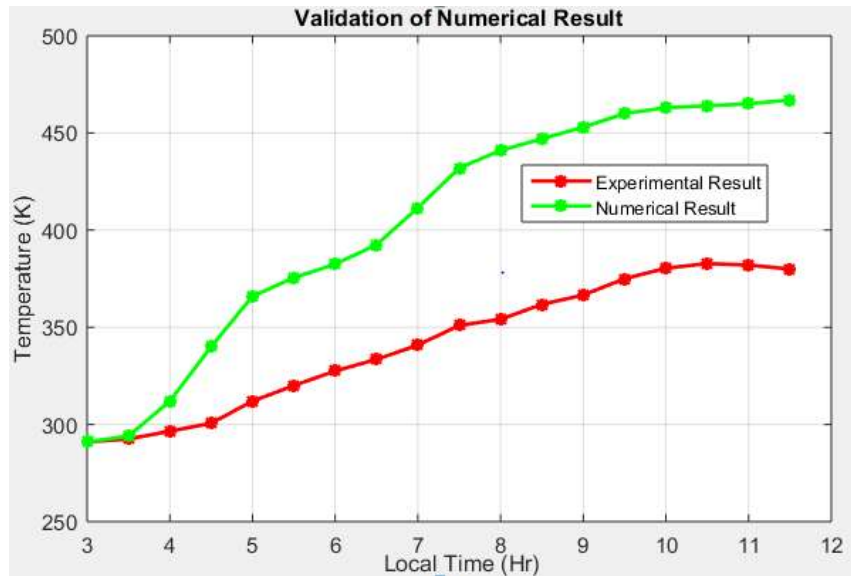


Figure 4.6; Validation of numerical result

The figure shows that although there are some deviations between simulation and experiment, but the variation of the temperature distribution is nearly similar in nature. Both in experimental and numerical graph are nearly the same with ambient temperature for first 30 minutes. Thus, the graph of numerical simulation is rapidly increasing with time after 30 minutes as shown in the above graph. This is because, an absorber is exposed in constant solar radiation throughout the day and it does not consider any manufacturing inaccuracy in case of numerical simulation. However, in the experimental test, the temperature of TES increases slowly till 10:30hr local time (4:30pm), this is due to the solar radiation frustration with time and there are a lot of losses like thermal conductivity of material, manufacturing accuracy, efficiency of solar reflectors (dishes) and thermal losses (conduction, convection, and radiation). Therefore, the maximum average charging TES (oil and rock) temperature in numerical simulation is 467K and where as in experimental test is 380K.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The main limitation of solar energy is available only in day time. Therefore, this study had been studied by adding the oil and rock as thermal energy storage on the absorber for evening cooking, in which sun light was not exist. One of the important characteristics of a storage system is the length of time during which energy can be kept stored with acceptable losses. In this study, overall system is designed, numerical simulation and experimental test is carried out.

The absorber area of $0.4m^2$ with TES of 1.5litter of oil and 0.74kg of rock is effective to cook 1kg of rice by absorbing energy from $1.5m^2$ solar collectors.

As it is shown in the simulation section, the temperature of TES could be reached on the acceptable temperature (467K) after 6hours. Where as in the experimental result, due to many losses which are raised in the above, the energy reached to the cooker (pot) is 380K. Even if it has low energy, it can cook the required food by placing TES in the insulated tank during discharging.

Therefore, there were deviations between experiment and simulation because the model did not account the basic losses and frustration of solar radiation in case of numerical simulation. The model of the TES system was validated with experimental results and a brief reason was found between experiment and simulation for the charging cycle.

The discharging of TES is started after it is lifted from the focal point of the compound parabolic solar collector and loaded by pot with water. The maximum temperature of water is 355K (82°C) reaches after 40 minutes, which is nearly boiling point.

5.2. Recommendations

The basic recommendations to enhance the efficiency TES are;

- ✓ There is high variation between experiential result and numerical result due to many losses. Therefore, it is better if an absorber is covered by special light transparent insulation during charging. The parabolic solar collector should be made from high reflective material to enhance its reflectivity.
- ✓ An absorber with TES, after it is lifted from solar collector, should be covered by highly effective insulated material to minimize the loss of TES to the surrounding.
- ✓ An absorber with TES should be optimized numerically, and select the best size and shape for an experiment.

Future works;

- Detail optimization of absorber by software and selection of the best size and shape for fabrication.
- Analyze the discharging of TES by numerical and experimental and validation of them.
- The economic analysis of overall system.

REFERENCES

- [1]. Soteris A. Kalogirou; “Solar thermal collectors and applications”; Progress in Energy and Combustion Science 30 (2004) 231–295
- [2]. Ahmed Bensenouci, and Ahmed Medjelled; “Thermodynamic and Efficiency Analysis of Solar Steam Power Plant Cycle”; International Journal of Renewable Energy Research Vol.6, No.4, 2016
- [3]. Soteris A. Kalogirou, Sotirios Karellas, Konstantinos Braimakis, Camelia Stanciu, and Viorel Badescu; “Exergy analysis of solar thermal collectors and processes”; Progress in Energy and Combustion Science, Article (science direct), 2016
- [4]. Balkeshwar Singh and Anil Kumar Mishra; “Utilization of Solar Energy for Driving a Water Pumping System”; International Research Journal of Engineering and Technology Volume: 02 Issue: 03 | June-2015
- [5]. Vanita Thakkar; “Status of Parabolic Dish Solar Concentrators”, International Journal of Enhanced Research in Science Technology & Engineering, Vol. 2 June-2013, pp: (42-50),
- [6]. Yahuza I, Rufai YA and TanimuL, Design; “Construction and Testing of Parabolic Solar Oven”; Journal of Applied Mechanical Engineering, 2016
- [7]. Yi-Mei Liu, Kung-Ming Chung, Keh-Chin Chang and Tsong-Sheng Lee; “Performance of Thermosyphon Solar Water Heaters in Series”, Article, Energies 2012.
- [8]. Mansi G. Sheth, Dr.P.K.Shah; “Design And Development Of Compound Parabolic Concentrating Solar Collector With Flat Plate Absorber”; International Journal of Innovative Research in Science, Engineering and Technology, Vol. 2, Issue 8, August 2013
- [9]. Muhammad Umair, Atsushi Akisawa and Yuki Ueda; “Optimum Settings for a Compound Parabolic Concentrator with Wings Providing Increased Duration of Effective Temperature for Solar-Driven Systems”; A Case Study for Tokyo; Article on Energies 2014, 7, 28-42; doi:10.3390/en7010028,
- [10]. Mohammadreza Sedighi, Mostafa Zakariapour; “A Review of Direct and Indirect Solar Cookers”; Sustainable Energy, 2014, Vol. 2, No. 2, 44-51
- [11]. Thanakom Soontornchainacksaeng; Strojnikivestnik; “Experimentation and Simulation of Thermal Energy Storage System with Non-Phase Change Materials”; Journal of Mechanical Engineering 51(2005)7-8, 534-537

- [12]. Dr.Tewolde Berhan G Egziabher; “Renewable Energy Projects in Ethiopia”.
- [13]. Ndiaga Mbodji and Ali Hajji, Mbodji and Hajji Energy: “Modeling, testing, and parametric analysis of a parabolic solar cooking system with heat storage for indoor cooking”; Sustainability and Society 2017.
- [14]. Rajendra C. Patil Mahesh M. Rathore Manojkumar Chopra; “An Overview of Solar Cookers”; 1st International Conference on Recent Trends in Engineering & Technology, Mar-2012 2, Issue 8, August 2013
- [15]. Hitesh Panchal, Jay Patel & Sudhir Chaudhary: “A comprehensive review of solar cooker with sensible and latent heat storage materials”; International Journal of Ambient Energy, (2017) DOI: 10.1080/01430750.2017.1392357
- [16]. Lof GOG. Recent investigation in the use of solar energy for cooking. Solar energy 1963; 7:125-33.
- [17]. Mohammadreza Sedighi, Mostafa Zakariapour; “A Review of Direct and Indirect Solar Cookers”; Sustainable Energy, 2014, Vol. 2, No. 2, 44-51;
- [18]. Klemens Schwarzer, Maria Eugênia Vieira da Silva: “Solar cooking system with or without heat storage for families and institutions”; Solar Energy, 2003
- [19]. Rajendra C., Patil Mahesh M. And Rathore Manojkumar Chopra: “An Overview of Solar Cookers”: 1st International Conference on Recent Trends in Engineering & Technology, Mar-2012
- [20]. AmósVeremachi, Azher Zia, Boaventura C. Cuamba, Jorgen Lovseth& Ole Jorgen Nydal: “Parabolic Dish Concentrating Collector for Indirect Solar Cooking”; Global Journal of Science Frontier Research: Volume 17 Issue 1 Version 1.0 Year 2017
- [21]. Harish Ronge, Vyenkat Niture, and Mr. D.S.Ghodake : “A Review Paper on Utilization of Solar Energy for Cooking”; Imperial International Journal of Eco-friendly Technologies Vol. - 1, Issue-1 (2016), pp.121-124
- [22]. Erdem Cuce, Pinar Mert Cuce; “A comprehensive review on solar cookers”; Article in Applied Energy · February 2013
- [23]. Mahesh M. Rathore, Dr. and Ravi M. Warkhedkar: “A REVIEW OF SOLAR COOKERS”; International Journal of Modern Trends in Engineering and Research; Date: 2-4 July, 2015

- [24]. Klaus Kunhnke, Marianne Reuber and Detlef Schwefel: “Solar Cookers in the Third World” Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH – 1990
- [25]. Mahesh M. Rathore and Dr. Ravi M. Warkhedkar: A Review of Solar Cookers: International Journal of Modern Trends in Engineering and Research (IJMTER) Volume 2, Issue 7, [July-2015] Special Issue of ICRTET’2015
- [26]. Ibrahim Ladan Mohammed: “Design and Development of a Parabolic Dish Solar Water Heater”; International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com Vol. 2, Issue 1, Jan-Feb 2012, pp. 822-830
- [27]. Amós Veremachi, Azher Zia, Boaventura C. Cuamba, Jorgen Lovseth & Ole Jorgen Nydal: “Parabolic Dish Concentrating Collector for Indirect Solar Cooking”; Global Journal of Science Frontier Research: Volume 17 Issue 1 Version 1.0 Year 2017
- [28]. B. Kanimozhi, A. Prabhu. M. Anish, P. K. Harish Kumar: “Review on Heat Transfer Enhancement Techniques in Thermal Energy Storage Systems”; Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 4, Issue 2 (Version 1), February 2014, pp.144-149
- [29]. S. Kalaiselvam and R. Parameshwaran: “Thermal Energy Storage Technologies for Sustainability; Systems Design”; Assessment and Applications, 2014
- [30]. M. Fatih Demirbas; “Thermal Energy Storage and Phase Change Materials”; An Overview, Energy Sources, Part B: Economics, Planning, and Policy 2006
- [31]. Sarada Kuravi, D. Yogi Goswami, Elias K. Stefanakos, Manoj Ram, Chand Jotshi: “Thermal Energy Storage for Concentrating Solar Power Plants”; Clean Energy Research Center, University of South Florida, Tampa FL 33620
- [32]. A. Andreozzi, N. Bianco, O. Manca, S. Nardini & V. Naso: “Numerical investigation of sensible thermal energy storage in high temperature solar systems”; WIT Transactions on Modelling and Simulation, Vol 48, © 2009 WIT Press
- [33]. P.M Diaz: Analysis and Comparison of different types of Thermal Energy Storage Systems: A Review; Journal of Advances in Mechanical Engineering and Science (JAMES), 08 June 2016
- [34]. Abhishek Saxena and Varun Goel: Review Article; “Solar Air Heaters with Thermal Heat Storages”; Chinese Journal of Engineering Volume 2013, Article ID 190279, 11 pages

- [35]. Mawire A, McPherson M, Van den Heetkamp RRJ: “Simulated energy and exergy analyses of the charging of an oil-pebble bed thermal energy storage system for a solar cooker”; *Sol Energy Mater Sol Cells* 92:1668–1676. 2008
- [36]. Schwartzer K, Silva MEV: “Solar cooking system with or without heat storage for families and institutions”; *Solar Energy* 2003
- [37]. Mussard M A: “solar concentrator with heat storage and self-circulating liquid”; Ph.D. Thesis 2013, Norwegian University of Science and Technology, Trondheim, Norway
- [38]. Ashmore Mawire, Abigail Phori, and Simeon Taole: “Performance comparison of thermal energy storage oils for solar cookers during charging”; *Applied Thermal Engineering*; Available online 23 August 2014
- [39]. Ramalingam Senthil And Marimuthu Cheralathan: “Thermal Performance of Solid and Liquid Energy Storage Materials in A Parabolic Dish Solar Cooker”; *Int. J. Chem. Sci.*: 14(4), 2016, 1977-1983
- [40]. Mawire A.*, Phori A.T. and Taole S.H.: “Characterisation Of Edible Sunflower as A Heat Storage Medium for Solar Cooking”; *Third Southern African Solar Energy Conference* 11–13may 2015
- [41]. D. Buddhi and L. K. Sahoo, “Solar cooker with latent heat storage: design and experimental testing,” *Energy Conversion and Management*, vol. 38, no. 5, pp. 493–498, 1997.
- [42]. S. D. Sharma, T. Iwata, H. Kitano, and K. Sagara, “Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit,” *Solar Energy*, vol. 78, no. 3, pp. 416–426, 2005.
- [43]. K. Schwarzer, M. E. V. Silva, and L. L. P. Santana: “Recent Developments of the Solar Cooking System with or without Heat Storage for Families and Institution”s, 2006.
- [44]. A. Saxena, S. Lath, and V. Tirth, “Solar cooking by using PCM as a thermal heat storage,” *MIT International Journal of Mechanical Engineering*, vol. 3, no. 2, pp. 91–95, 2013.
- [45]. M. Mussard, A. Gueno, and O. J. Nydal, “Experimental study of solar cooking using heat storage in comparison with direct heating,” *Solar Energy*, vol. 98, pp. 375–383, 2013.

- [46]. Asfafaw H.: Experimental Investigation of a Concentrating Solar Fryer with Heat Storage; Thesis for the degree of Philosophiae Doctor; March, 2015
- [47]. Rainer Aringhoff, et.al., “Exploiting The heat from the sun to combat climate change”; Greenpeace, 2005
- [48]. Delaney, D., “Scheffler’s community solar cooker” <http://www.solar-bruecke.org>, 2003.
- [49]. Swisher, J.H., “Division of Energy Storage Systems”; ERDA Washington, D.C.,20545. 2003.
- [50]. Prabagar Subramaniam, Kalya Subasinghe, W. R. Keerthi Fonseka; Wood Ash As An Effective Raw Material For Concrete Blocks; International Journal of Research in Engineering and Technology; Volume: 04 Issue: Feb-2015
- [51]. Georgia State University, “Hyper physics Insulating Material Thickness” 2005.
- [52]. The Thermal Insulation Association of Southern Africa, “Thermal Insulation Handbook” 2001.
- [53]. YunusCengel, A., “Heat transfer: A practical Approach” 2nd Ed ; Tata McGraw-Hill, 2003.
- [54]. American Thermal Insulation Manufacturers Association (ATIMA), “Energy Saving Guide,” 2005.
- [55]. Saša Pavlović, Velimir Stefanović, Darko Vasiljević and Emina Petrović: Optical Design of a Solar Parabolic Concentrating Collector Based on Trapezoidal Reflective Petals”; Journal of Energy and Power Engineering 9 (2015) 714-720
- [56]. Bhattacharya K.R., Sowbhagya C.M., and Swamy Y.M.I. “Some Physical Properties of Paddy and Rice and Their Interrelations”. Journal of the Science of Food and Agriculture, Vol. 23, Issue 2, John Wiley & Sons Ltd., 1972.
- [57]. Mahavar S., Rajawat P., Marwal V.K., Punia R.C. and Dashora P: “Modeling and On-field Testing of a Solar Rice Cooker”; Energy, No. 49, 2013, pp 404 – 412.
- [58]. Edward D.: “Solar Cooking Recipes”; May, 2013 – last update. Available: www.cookwiththesun.com/recipes.htm.
- [59]. Green D. Rice: Cooking Tips, Measurement Conversions www.cooksinfo.com/rice. Retrieved on 2013.
- [60]. Nguyen A.: “How to cook Perfect Rice”. Viet World Kitchen 15th; Retrieved on 2013.

- [61]. Magal B.S.: “Solar Power Engineering”; Tata Mc-Graw Hill Publishing Company Limited, New Delhi, 1993. 4
- [62]. Fareed. M. Mohamed, Auatf.S.Jassim, Yaseen. H. Mahmood, Mohamad A.K.Ahmed; Design and Study of Portable Solar Dish Concentrator; International Journal of Recent Research and Review, Vol. III, September 2012
- [63]. Ashmore Mawire, Abigail Phori, Simeon Taole: Performance comparison of thermal energy storage oils for solar cookers during charging; Applied Thermal Engineering 73 (2014) 1323e1331
- [64]. Lavinia Gabriela SOCACIU: Seasonal Sensible Thermal Energy Storage Solutions; Leonardo Electronic Journal of Practices and Technologies Issue 19, July-December 2011
- [65]. O. Ercan Ataer: Energy Storage Systems – Storage of Thermal Energy

Appendix

Temperature variation result of TES for each Time by COMSOL software

Time (min)	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140
T _{oil} (K)	291	291	293	295	298	315	325	345	355	365	375	383	385	390	393
T _{rock} (K)	291	291	292	293	295	296	298	310	320	325	325	346	347	348	350

Time (min)	150	160	170	180	190	200	220	240	260	280	300	320	340	360
T _{oil} (K)	400	405	410	412	415	420	430	450	455	465	480	490	500	505
T _{rock} (K)	351	352	353	353	354	354	355	355	357	358	369	369	362	365

Average Charging temperature of solar cooker

Time (hr)	3:00	3:30	4:00	4:30	5:00	5:30	6:00	6:30	7:00	7:30	8:00	8:30	9:00	9:30	10:00	10:30	11:00
Temp. Abs. surface (K)	291	297	315	324	333	339	351	357	366	384	411	431	447	462	475	476	475
Temp. Oil (K)	291	294	298	303	315	325	333	339	345	357	363	375	383	399	407	411	411
Temp. Rock (K)	291	291	295	298	309	315	322	328	336	345	345	348	349	351	353	354	354.5

Discharging temperature of TES and boiling temperature of water

Time(min)	0	10	20	30	40	50	60	70	80	90	100	110
Oil Tem.(K)	410	405	395	285	270	355	330	320	300	295	293	291
Rock tem. (K)	354	352	350	345	338	330	320	305	295	293	292	291
Water tem (K)	291	308	330	350	355	353	352	345	335	320	300	297



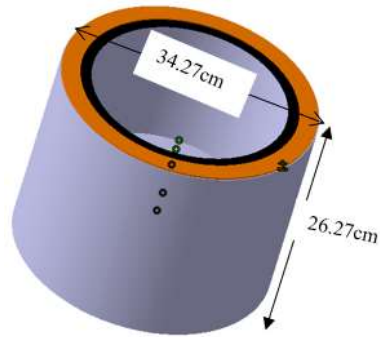
a, placing an absorber on the focal point

b, filling used engine oil in the absorber

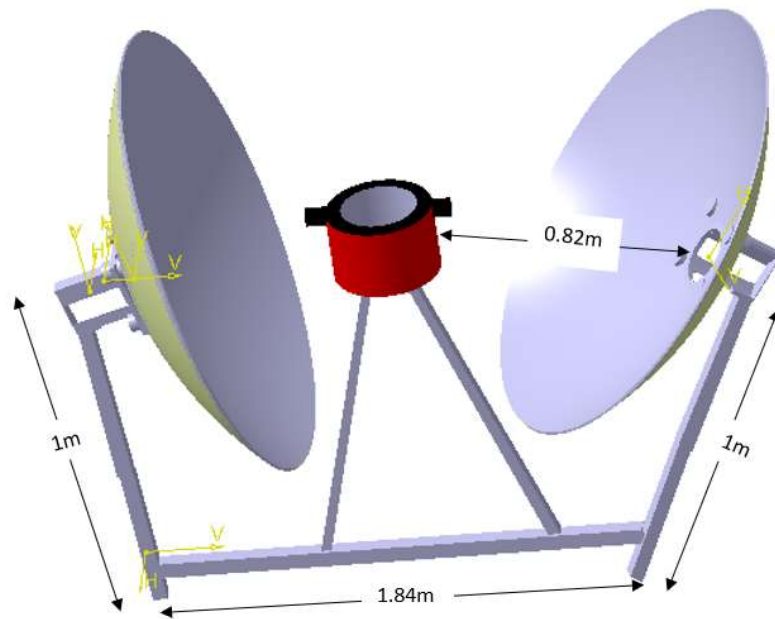


Boiling of water

Detail Drawing

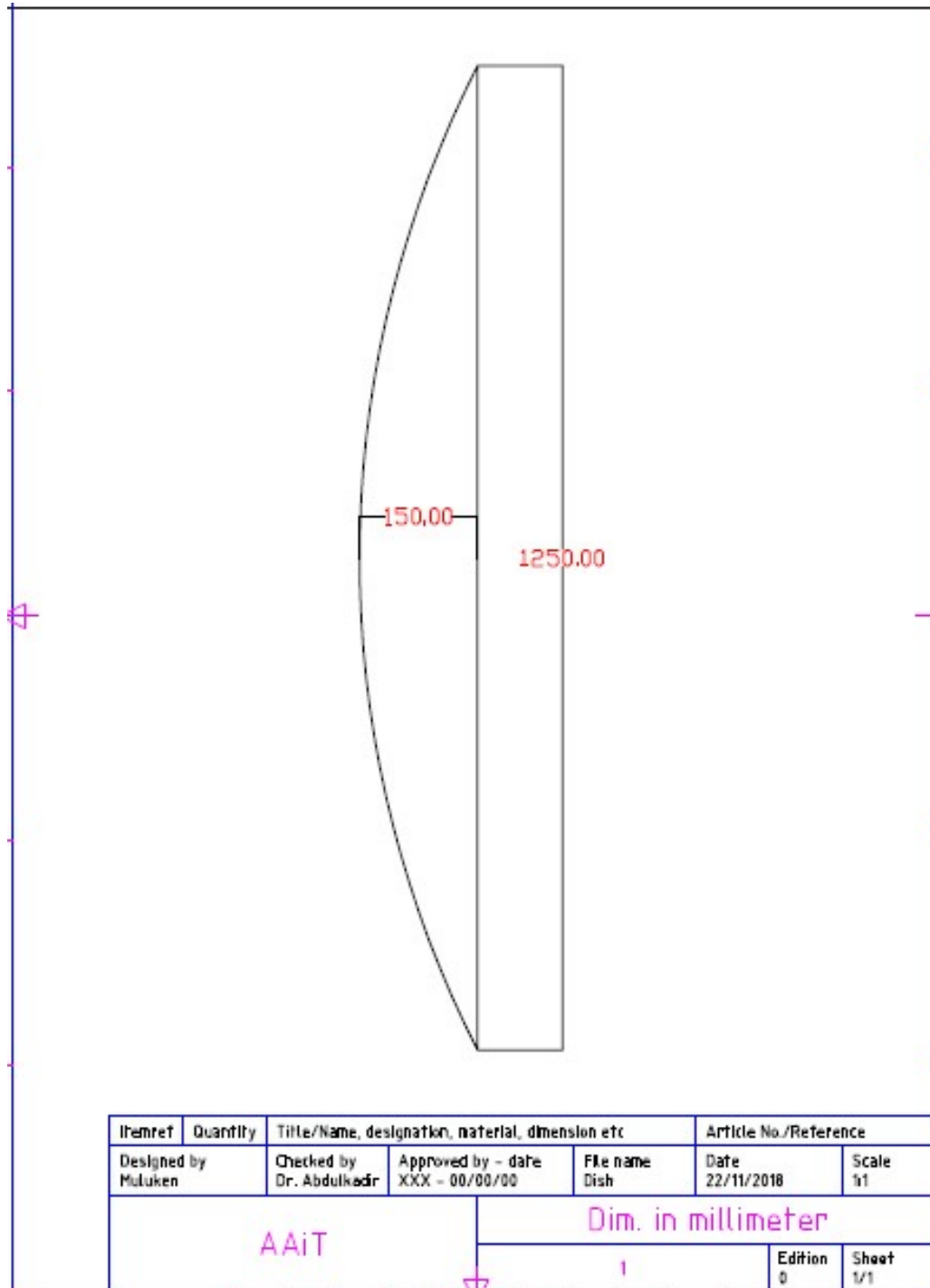


a, solar absorber with TES

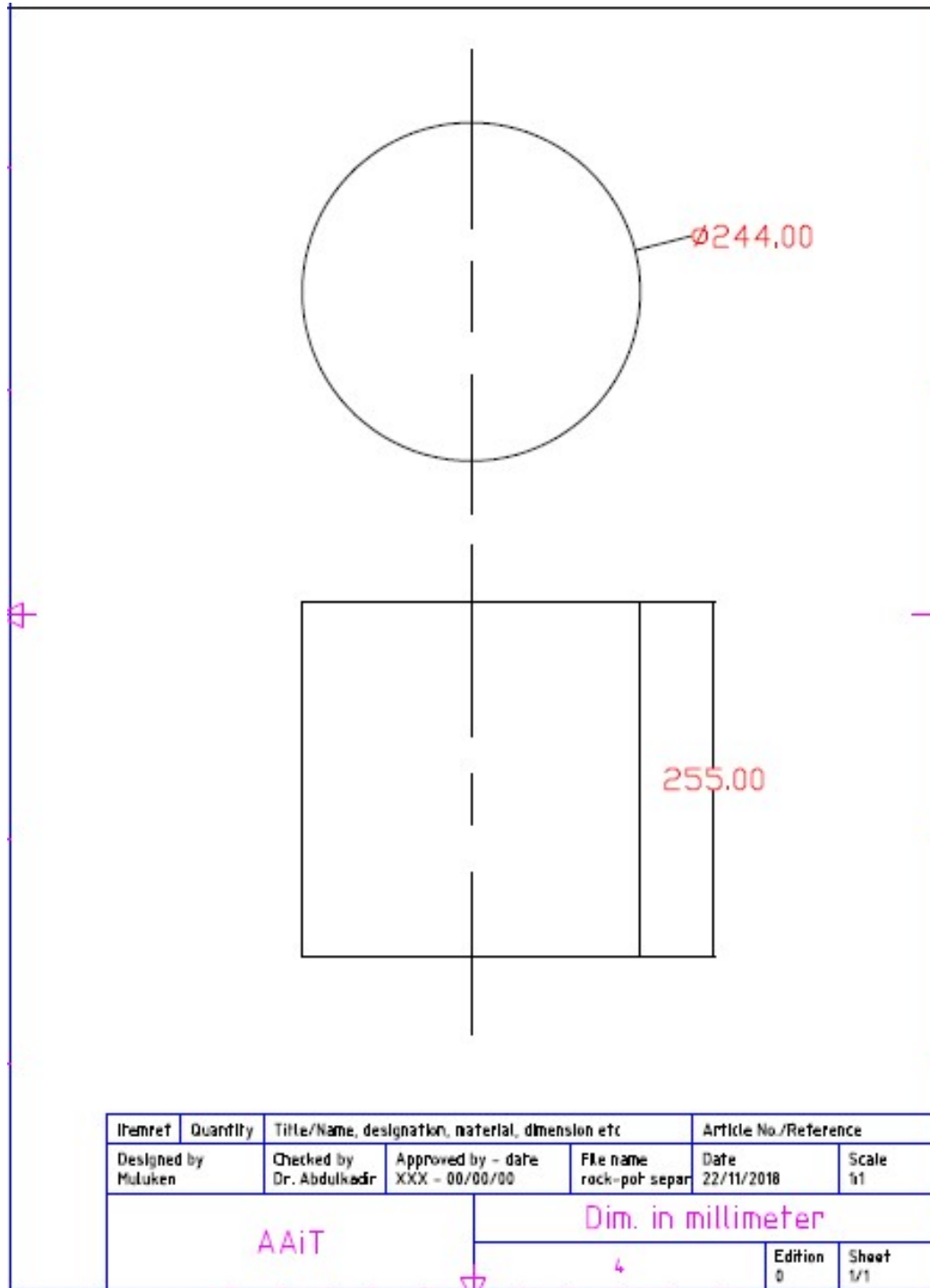


b. assembly of overall system

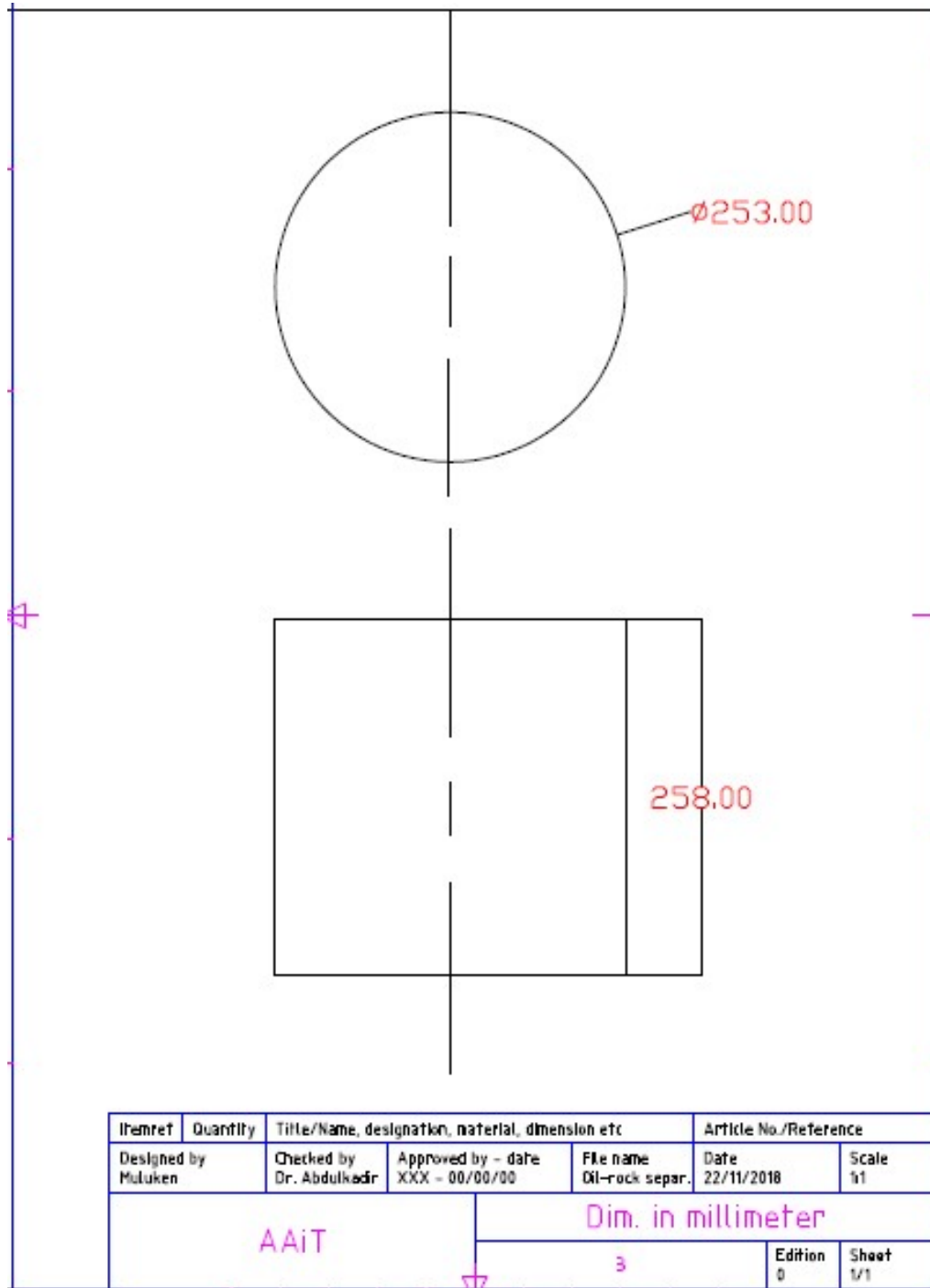
Annex



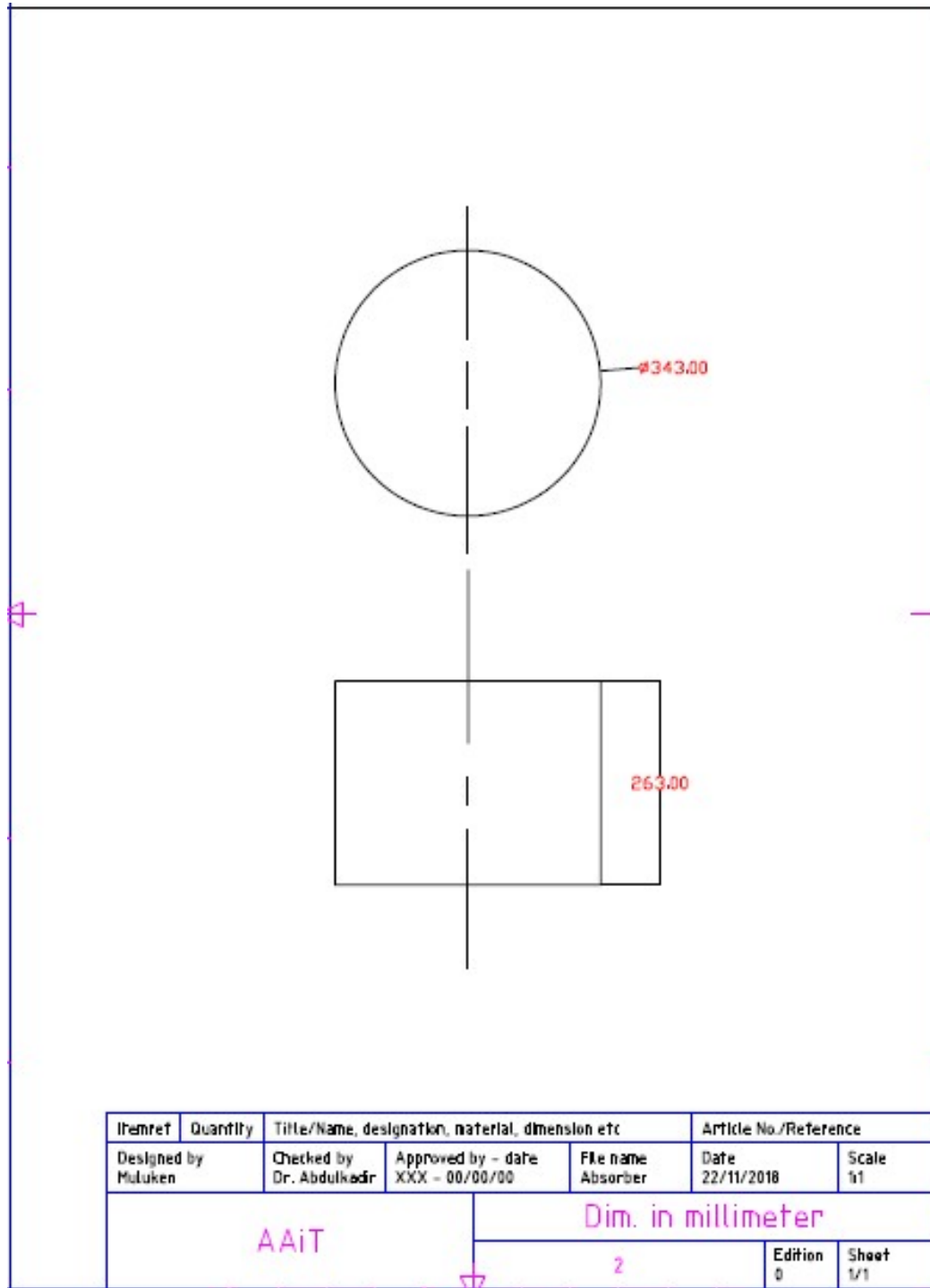
Figure; Dish



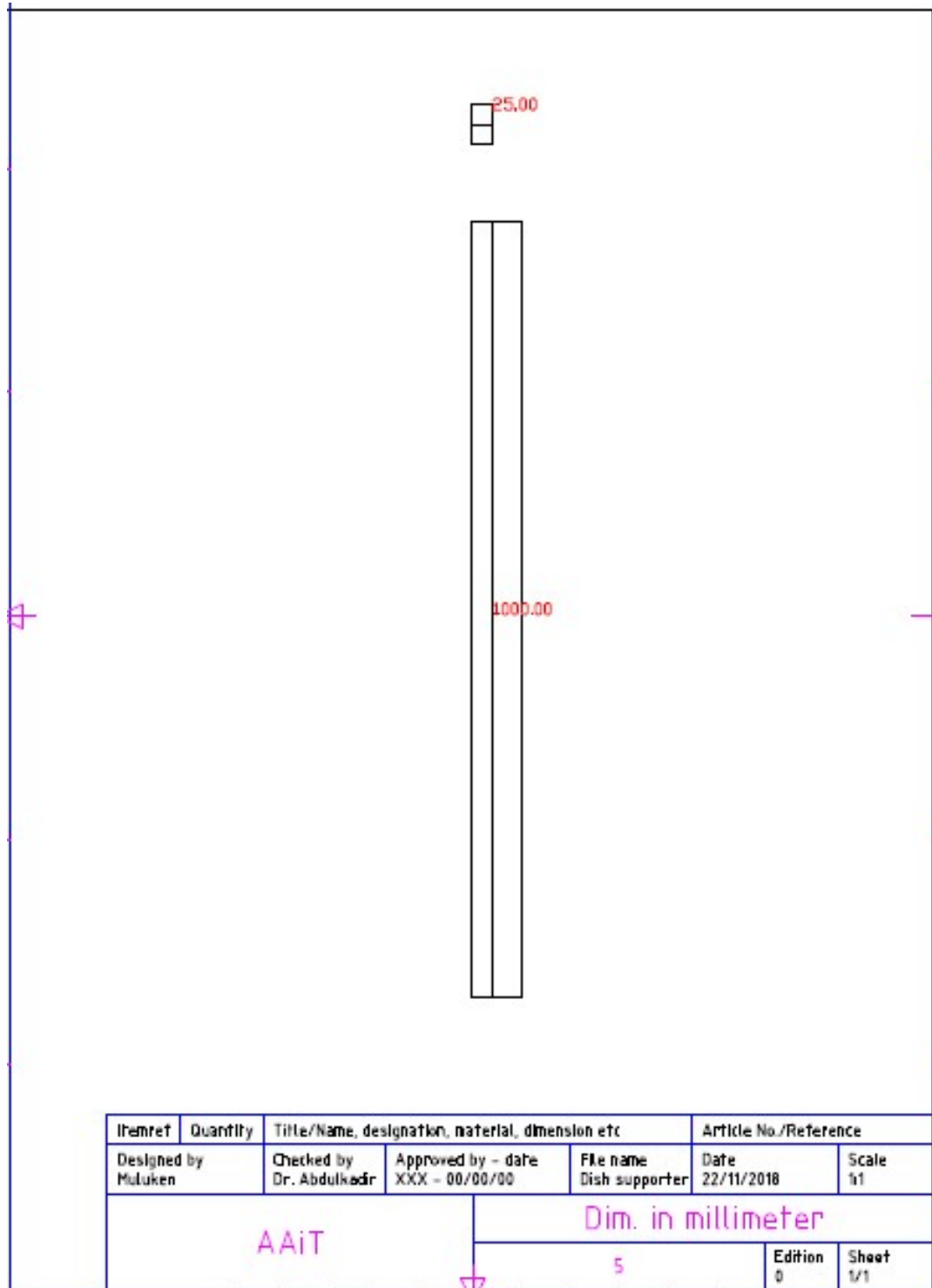
Figure; rock- pot separator



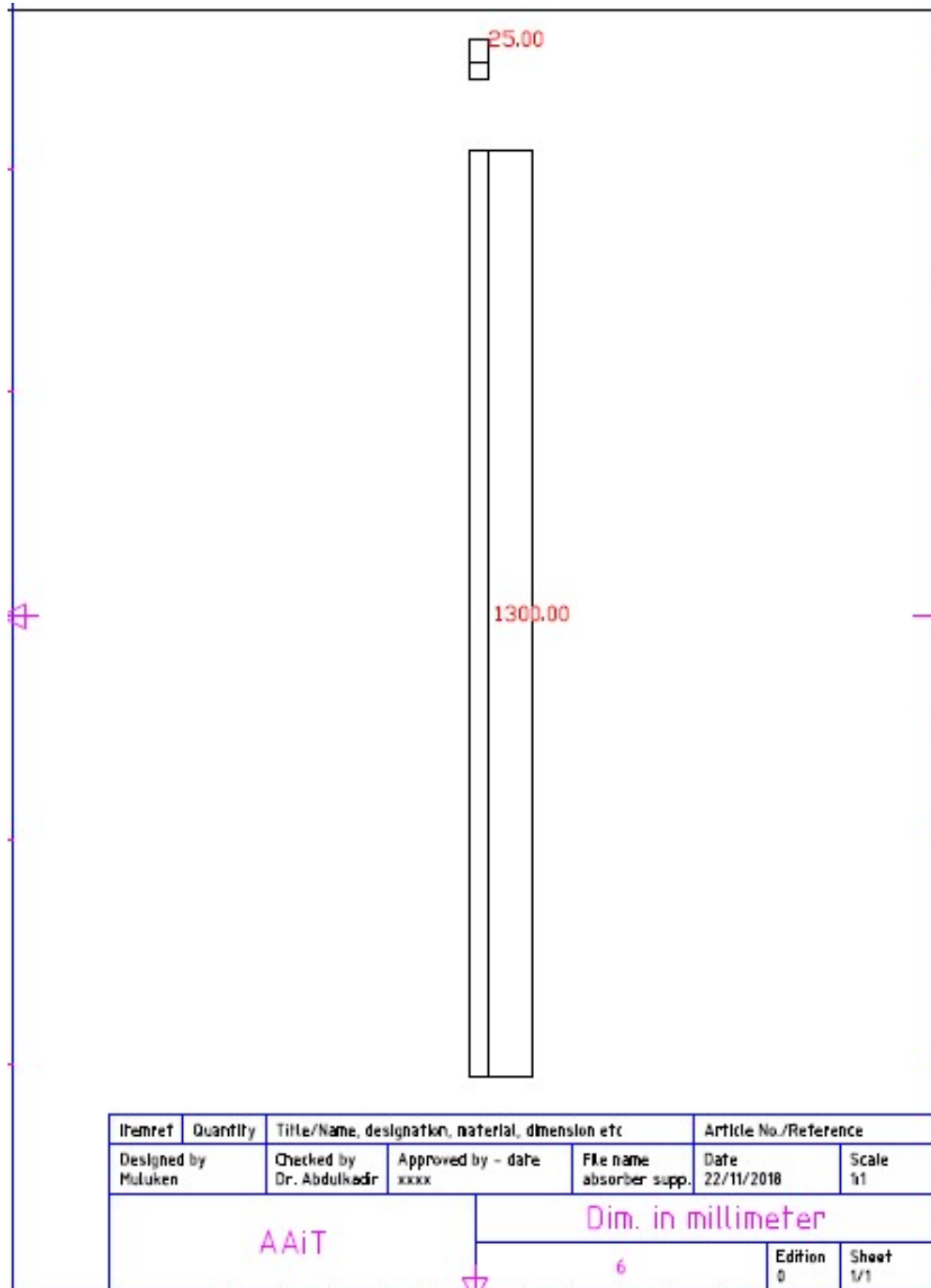
Figure; oil-rock separator



Figure; absorber



Figure; dish supporter bar (2 pieces)



Figure; absorber supporter bar (2pieces)