



Addis Ababa University

Addis Ababa Institute of Technology

**Integration of Scheffler Concentrator and
Thermal Storage Device for Indoor Injera
Baking**

By

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April 2013

Addis Ababa, Ethiopia

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Storage Device for Indoor Injera Baking**

By
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A Thesis Submitted to
School of Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements for the Degree of
Masters of Science in Thermal Engineering

Advisor: Dr. - Ing. Demiss Alemu

April 2013
Addis Ababa, Ethiopia

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SCHOOL OF MECHANICAL AND INDUSTRIAL
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Abstract

Women and children spend much of their time in collecting fire wood to cook Ethiopian common food item, Injera and they are the main groups exposed to smoke inhalation while cooking. Deforestation of biomass for cooking is damaging the rural household economy as well as contributing for local and global environment change; i.e. environmental pollution and health problems.

The aim of the research work is to integrate Scheffler concentrator with thermal storage system via a secondary reflector for solar cooking to make cooking indoor convenient and avoid the problems that are caused due to carbon inhalation and deforestation. Thus, solar thermal powered Injera baking system is designed. The system consists of the primary concentrator (Scheffler), secondary reflector and thermal storage system with the cooking (pan) assembly.

SolTrace software is used to model and simulate the Scheffler concentrator and secondary reflector. The solar power reaching the storage device is determined from the software. The storage device involves sensible heat storage mechanism with Hitec heat transfer salt as a storage medium. The heat retention capacity of the storage system is determined from heating and cooling curves generated by Ansys software modeling and simulation.

Based on the results obtained, any convenient indoor cooking device shall be designed especially for rural areas where there is no grid connection; and the result of this research work will alleviate problems related to carbon inhalation and deforestation.

Acknowledgement

I would like to express my genuine gratefulness to my Advisor, Dr.-Ing. Demiss Alemu and my Co-advisor Abdulkadir Aman (PhD Candidate) for their support and encouragement during the progress of this thesis work. Their important comments helped me to reach at this point. I must also express Abdulkadir's role in availing me the Software which solved the crux problem of the thesis work.

I should also thank all my instructors who gave me the theoretical base during the course work in my specialization; and the staff members of the department who have contributed to this work directly or indirectly.

I am also very grateful to Air Force Technical College for sponsoring my MSc Study at the School of Mechanical and Industrial Engineering, AAiT.

My special thanks go to W/ro Yirgedu Getaneh for her overall encouragement and support.

Melkamu Yayeh

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List of Symbols

A	Contact area (m^2)
BHS	Bond Heat Storage
C	Specific heat (J /kg.K)
h	Convection coefficient (W /m^2K)
L	Length (m)
k	Thermal conductivity (W/m.K)
LHS	Latent Heat Storage
m	Mass (kg)
Q	Heat lost or gained (J)
T	Temperature (K)
TES	Thermal Energy Storage
SHS	Sensible Heat Storage
R	Radius (m)
R	Thermal resistance (K/W)
t	Time (s)
V	Volume (m^3)
ΔT	Temperature change (K)

Greek letters

C_g	y- intercept of a line
C_z	y-intercept of a parabola
E	Energy (J)
m_g	Slope of a line
m_p	Slope of a parabola
R	Property of Insulating Material (m^2K/W)
δ	Stefan–Boltzmann c
ϵ	Emissivity of surface and has a value between
ϵ	Emissivity
ρ	Density (kg m^3)
σ	Stefan- Boltzmann constant = $5.67 \times 10^{-12} W/cm^2.K^4$

Chapter One

Introduction

1.1 Background of the Study

Food is a universal need, which requires energy for its preparation. Preparing and consuming food is subject to many cultural considerations. It is known that, the energy requirements for cooking in developing countries is largely met through wood collection from forests and from agricultural wastes, and the options for cooking food are limited, most of the time they rely on wood as a fuel for cooking open fire stove [26] [27].

Technical advances in energy efficiencies can be used in developing countries, where biomass fuels such as wood, charcoal and agricultural residues are used for house hold fuel. Fuel wood fire cause indoor air pollution that causes health problems due to carbon monoxide and soot inhalation and require lots of time to fetch. Over use of fuel wood has led depletion of the forest and degradation of the environment in most developing countries which will in long term result in considerable global warming and greenhouse effects [27].

The sun is an inexhaustible source of energy; the amount of solar energy an area receives depends on the time of day, the season of the year, the cloudiness of the sky, and how close the area is to the earth's equator. Ethiopia is close enough to the equator and gets plenty of solar energy.

Ethiopia receives a solar irradiation of 5000 – 7500 Wh/m² according to region and season and thus has great potential for the use of solar energy [9]. The average solar radiation is more or less uniform, around 5.2kWh/m²/day. The seasonal variation is from 4.55-5.55 kWh/m²/day and with location from 4.25 Wh/m²/day in the extreme western lowlands to 6.25kWh/m²/day in Adigrat area in Northern Ethiopia [41].

The use of solar power in Ethiopia is increasing from <5% since the early 1990s to 15 – 20% in the last few years. Until recent times use of solar Photovoltaic (PV) for meeting off-grid power needs was confined to projects funded by donors. The solar PV market is still at its early stage [41] [53].

UN organizations such as UNICEF and WHO are few examples that had supported projects that use PV based technologies (distance-education radios and vaccine fridges) in remote rural areas of Ethiopia. Moreover, the Government of Ethiopia (GoE) with technical as well as financial assistance from Italian government had executed a PV-based rural electrification project in the mid 1980s [53].

The rural electrification project was later abandoned and looted, during change of government in 1991, by the very people it was intended to serve. Such donor-driven projects proved unsuccessful or at least unsustainable primarily because the requisite of commercial infrastructure (awareness, skilled technicians, financing mechanism, market linkages, and supportive policies) was lacking [53].

Ethiopian Telecommunications Corporation (ETC) is the major user of PV solar in the country. ETC uses PV solar to power its remote rural telecom installations and this application has grown several times in recent years [41].

Next to the PV solar home systems, there is also a need for solar water heating (SWH) systems that use solar irradiation to heat up water, which can significantly reduce fuel wood and electricity consumption. Solar thermal is another application with considerable potential in Ethiopia. Although of more recent, phenomenon compared to PV, SWH is an application that is growing steadily in Addis Ababa in recent years. There are both imported and locally manufactured models of solar thermal water heaters in the market [34]. Unlike PV systems, SWH systems have not been monitored in the past and thus accurate data is missing. Nevertheless it is estimated that 5,000 units are installed, which is equivalent to an area of 10,000 m² [22] [27].

The 2010 – 2015 Growth and Transformation Plan of the Ethiopian government furthermore includes the dissemination of 153,000 SHSs and 3 million solar lanterns [22] [41].

The use of solar energy for the purpose of cooking food presents a viable alternative to the use of fuel wood, kerosene, and other fuels traditionally used in Ethiopia. While certainly solar cookers cannot entirely halt the use of combustible fuels, it can be shown that properly applied solar cooking can be used as an effective mitigation tool with regards to global climate change, deforestation, and economic debasement of the world's poorest people.

Solar collectors convert solar radiation into heat and they rely on an energy source that is free, abundant and renewable, but the reason that they are not widely spread as needed is because of the draw back that cooking must be done when, and where the sun is shining [21].

1.2 Statements of the Problem

The basic food in Ethiopia, Eritrea, Somalia and the Sudan is a large, flat thin type of bread similar to 'kitta'. It is called 'Injera' in Ethiopia and Eritrea. Injera has a diameter of 60 cm in Eritrea / Ethiopia, in Somalia 35 cm and in the Sudan somewhere in between the two [53].

In Ethiopia, Injera baking requires a bulk of domestic energy. In most households, Injera baking system is carried out using an open fire /three stone/ stove which is inefficient and wasteful of energy. To bake Injera, the heat supplied to the baking pan comes usually either from burning fire wood, animals dung or agricultural residue in biomass cookers using the traditional Mitad stoves for centuries. A serious disadvantage concerning Injera baking is that the mitad consumes considerable quantities of firewood, which is estimated to be at least 50% of the biomass energy consumption per household per year [48].

Due to the growing scarcity of wood fuel, people are forced to travel long distance from their homes to fetch wood; this struggle is carried almost entirely by women and children.

Recent field observation shows that improvements in air control and firebox design is currently the most effective and socially acceptable stove design modifications (eg. Miret stove) [27]. However, their usefulness with regard to saving the resource base from depletion is limited in the face of growing population and urbanization because they use fire wood as the source of energy. In addition to the mentioned, wood firing causes health problem due to inhalation of carbon monoxide and smoke and emission of Carbon dioxide to atmosphere which results in green house.

The extensive use of biomass in traditional, open air inefficient stoves and use of petroleum fuels for cooking causes environmental pollution and restrains economic and social development. To avoid or curtail these problems and the increased concerns over the local, regional and global environmental impacts of conventional energy systems; transition to renewable energy resources is necessary [27].

Thus to reduce and avoid the addressed problems, it is important to look for a new means of fuel source by utilizing energy from the sun. Converting the sun's radiant energy to heat is the most common and well developed solar energy conversion technology to alleviate the stated problems [24] [27].

In Addis Ababa Bereket (Bereket Injera) has developed a number of outdoor solar cooker prototypes, but the right model has yet to be found. Ultimately the plan is to be able to set up Injera bakeries; the so-called "Injera group" has been set up by The Netherlands Foundation

of Solar Cooking, SUPO and Solar Cookers for Developing Countries. A new prototype is being developed in collaboration with other funds and technical support by Bereket [53].

One challenge facing the widespread use of solar energy is reduced energy production when the sun sets or is blocked by clouds or in rainy days and cooking is outside home; thermal energy storage provides a workable solution to this challenge. Thermal storage allows a means to extend cooking into the evening [39] [24] [42].

In concentrating solar thermal system, the sun's rays are reflected onto a receiver, which creates heat. If the Scheffler receiver is integrated with indoor thermal storage device via a secondary reflector, then the thermal energy can be stored for later use so that it would be convenient indoor cooking which minimizes both social and economic consequences. Properly designed and insulated thermal storage gives the probability of cooking when there is no radiation of the sun (i.e. night, cloudy, rainy day, etc) [39] [45].

Therefore, to reduce the problems associated with using biomass, kerosene, or liquefied petroleum gas, solar powered Injera baking mitad with thermal storage device design is expected in this thesis.

1.3 Objective of the Thesis

1.3.1 General Objective

The general objective of this thesis is to design an indoor solar thermal Injera baking system having a thermal storage system integrated with Scheffler reflector.

1.3.2 Specific Objectives

The specific objectives are to:

- *Design the Integration of Scheffler concentrator with thermal storage system for indoor Injera cooking;*
- *Model and simulate the Scheffler concentrator and secondary reflector using SolTrace software to determine the heat flux reaching the thermal storage;*
- *Integrate thermal storage (molten salt) system and Injera baking mitad;*
- *Determine the optimum volume of thermal storage system mathematically; and*
- *Simulate heat retention capacity and see heating and cooling property of the thermal storage.*

1.4 Significance of the Thesis

The majority of Ethiopia's population live in rural areas. Women and children spend much of their time in collecting fire wood and they are exposed to health problems due to smoke inhalation from the burning wood while cooking. The use of solar power Injera baking system where there is no other alternatives like electric power, helps to conserve time that can be used for production purpose and avoids the health problems that may be caused by smoke inhalation.

The solar baking system is expected to solve the problem of energy sustainability by replacing the current dependency on fire wood, cow dung, crop and petroleum oil residues and this contributes reduction in air pollution and green house gas emissions in the long range through avoidance of forest deforestation.

1.5 Research Methodology

The methods employed to achieve the objectives of the research work are the following:

1.5.1 Literature Survey

Literature survey of relevant materials on Injera baking methods, basics of solar energy, solar radiation concentrators and reflectors, thermal storage mediums and devices, thermal conductivity, insulation materials and selection, etc, are collected and revised from books, journals, electronic Medias, and catalogue to lay good scientific foundation of the thesis work.

1.5.2 Modeling and Simulation

After a Scheffler concentrator and the secondary reflector are designed for medium size family cooking, it is simulated using SolTrace software to determine the solar power reaching the thermal storage system placed indoor, so that integration is possible for an indoor cooking. The storage system is modeled and simulated using Ansys software and heating and cooling curves are generated.

1.5.3 Results and Discussion

Simulating the Scheffler concentrator and secondary reflector establishes a relationship between the expected performances of generation of power from solar radiation and from the actual electrical backing methods in order to make a comparison between the two methods. The heat retention capacity or efficiency of the storage system is analyzed from the heating and cooling curves.

Discussion is done on the results obtained from the simulation. The discussion involves comparison of results from the analysis and from the actual Injera baking methods like electrical Injera baking system.

1.5.4 Conclusion and Recommendation

The recommendation and conclusion are presented according to the results obtained. The result of simulation is discussed thoroughly and relevant conclusion and recommendations are duly addressed in such a way that it would be a spring board for future works practical works.

1.6 Application of Results

The outcome of the thesis would not be restricted in designing indoor Injera backing, but it will be useful to design different types of convenient indoor solar cooking devices of any size which will eliminate social problems due to carbon inhalation. It will also be helpful in reducing deforestation which is the main cause of global warming. Moreover, it will serve as a source for further study in this area.

1.7 Limitation of the Thesis

There was an intention to extend this work to integrate the purchased Scheffler concentrator to a designed and manufactured indoor Injera baking with thermal storage; but it was impossible to get the Scheffler concentrator. Thus the thesis work is restricted to be desktop analysis using different software packages.

1.8 Organization of the Thesis

The structure of this thesis work is categorized in to six chapters preceded by the preface of the research which shortly describes the summary of the whole work.

The first chapter introduces the research paper describing the background of the work, statement of the problem, objectives of the thesis, significance of the thesis, the methodology involved in order carryout the research, application of results and finally limitation of the thesis.

In the second Chapter, reviews of related literatures from books, journals and different websites are offered. The methods of baking Injera, basics of solar energy and concentrating it for cooking are discussed. The Scheffler concentrator, the solar thermal energy storage mechanisms, thermal insulating material and finally modes of heat transfer are discussed thoroughly.

The third chapter elaborates the mathematical approaches in the design of Scheffler concentrator from paraboloid surfaces and secondary reflector device for indoor cooking is dealt. The chapter also deals with the method of tracking the sun for efficient concentration is also presented.

The fourth chapter describes the design of thermal energy storage system. It contains the basic procedures for the design of storage device including tank size determination and selection of storage medium, thermal insulation material and thickness based on different approaches is elaborated.

The fifth chapter combines the third and fourth chapters. The result obtained from simulation of Scheffler concentrator and secondary reflector using SolTrace software is used to determine the heat flux reaching the storage device. The capacity and efficiency of the storage system is analyzed using Ansys software in this chapter too.

Finally, the last chapter summarizes the basic findings of the research and conclusions are made. Recommendations based on the research findings of the thesis work are also forwarded in this chapter.

Chapter Two

Review of Related Literature

2.1 Introduction

Energy development must provide us with the possibility and thus the foundation of technology, skill and production base for rapid exploitation of the sustainable options. This chapter discusses the preliminary issues related to this fact. In this chapter reviews of related literature will be discussed. The different methods of Injera baking in Ethiopia like electrical heating, open fire wood, and the Merete Injera baking methods are discussed. The basics of solar energy, solar cooking methods and types of concentrating solar power (CSP) are dealt. Scheffler solar concentrator, its design and its working principle are discussed. Concepts used for solar thermal storage systems design and selection are also reviewed. Design criteria of solar thermal energy storage system, Thermal insulation systems; their advantages, types of insulating materials are also elaborated thoroughly. Finally the three modes of heat transfer are presented.

2.2 Methods of Injera Baking

Injera has a diameter of 56 to 60 cm in Ethiopia and Eritrea, in Somalia 35 cm and in Sudan somewhere in between [5]. Most Ethiopians eat Injera at least two times a day and it is being exported to North America and Middle East [47]. Preparation of Injera is a long process; it usually takes two to four days from mixing to cooking. It can be produced from almost any staple grain, with sorghum, millet and teff being the most common in Ethiopia. The teff flour is mixed with water and left to ferment for two to four days, but can take less than this time in warmer locations. Starter (left-over batter from the previous baking time) may be added to trigger fermentation. Approximately four to six hours before baking, a layer of bitter fermentation product is removed and hot water is added to reactivate fermentation, then the batter is poured on top of the hot baking pan surface [40].

To bake Injera, the heat supplied to the baking Mitad either comes from burning fuel wood, cattle dung or agricultural residue in biomass cookers, from electrical resistance in the electric baking pan. Heating thermal storage system for solar baking pan as in this case is also another option. The heat is then conducted through the baking pan to the surface where the batter is cooked. The heat supplied to the Injera baking pan is used for raising the temperature of the batter on the pan surface from room temperature (20 to 25°C) to around boiling point of

water and evaporate considerable portion of water in the batter. (In Addis Ababa, boiling point of water is about 92°C). Conventional baking pans are 58 - 60cm in diameter [27]. The following methods will describe the methods of Injera backing usually applied in Ethiopia.

2.2.1 Baking Using Open Fire System

In most of the households of the country, Injera baking is carried out using an open fire (three stone, 'Gulecha') baking system and the fuel is biomass. The heat supplied to the mitad in this system is lost through a variety of paths such as: through the sides, through the exhaust gases from the fuel, through convective and radiative heat losses from the pan surface. The fraction of energy that flows into the Injera batter is very limited and therefore this technique is inefficient and wasteful; and also is unhealthy because of carbon inhalation to the lungs and irritation of eyes [40] [45].



Figure 2.1 Open fires (Gulicha method) Injera baking system

2.2.2 Miret Injera Stove

It is prefabricated stove from cement and local aggregate such as sand panels or the oven can be made by pressing clay around the mould. The stove is suitable for mass production by casting light concrete. Each Miret saves approximately 5 kg of wood per Injera baking session for an average household. Most household bakes Injera twice a week. Thus, the Miret saves at average per household nearly 260 kg of wood per year. This is a significant savings for the average Ethiopian urban household. However, the Miret saves commercial Injera bakers over 3.5 tons of fuel wood per year [26] [27] [45].

Even though the Miret stove is better and efficient compared to the open fire baking system; it has the following drawbacks:

- Since it uses biomass (wood or animal dung) it has contribution to deforestation and limits advantage of dung as plant fertilizer.
- It may also produce smoke and may result in producing pollution if baking is in door.



Figure 2.2 Mirte Injera baking stove [27]

2.2.3 Electrical Injera Baking Method/Pan

The other type of technology for Injera baking is an electric 'Mitad'; which is mainly used by people in the urban and near urban areas where electric power is available. Thus, the majority of population (more than 80%) in Ethiopia uses wood or biomass fuel for Injera baking. Though this system reduces the problem of carbon inhalation and deforestation; it has certain disadvantages like [27] [40]:

- If the source of energy (power plant) is diesel fuel, it needs high cost and has contribution to air pollution and GHG emission.
- People in rural areas do not have the access to electricity. Hence, the electric baking system is used only in urban areas.
- There is high heat loss due to non-optimum of insulation through the sides and bottom.



Figure 2.3 Electrical Injera baking Method

2.2.4 Solar Cooking Method

Solar cooking uses an arrangement of reflectors to concentrate solar energy on a cooking vessel so that solar energy will be changed in to heat energy for cooking. A number of innovative designs have been developed now a day and are being used in many parts of the world [45].

Comparing the advantages and disadvantages of each baking methods, the solar baking system is the most suitable technique due to the following basic advantages:

- No smoke production, free of air pollution and therefore safe to health and environment
- Does not cause resource depletion
- Can be used anywhere, wherever there is radiation
- Uses abundant, free and renewable energy source hence no exhaustion of the source
- Requires initial investment only

2.3 Basics of Solar Energy

The source of all solar energy is the sun and all life on the earth depends on solar energy. Knowledge of the quantity and quality of solar energy available at a specific location is of prime importance for the design of any solar energy system. Although the solar radiation (insolation) is relatively constant outside the earth's atmosphere, local climate influences can cause wide variations in available insolation on the earth's surface from site to site. In addition, the relative motion of the sun with respect to the earth will allow surfaces with different orientations to intercept different amounts of solar energy [40].

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and is 1.5×10^{11} m from the earth, on the average. The earth revolves around the sun every 365.25 days in an elliptical orbit, with a mean earth-sun distance of 1.496×10^{11} m (92.9×10^6 miles) defined as one astronomical unit (1 AU). This plane of orbit is called the ecliptic plane. The earth's orbit reaches a maximum distance from the sun, or aphelion, of 1.52×10^{11} m (94.4×10^6 miles) on about the 3rd of July. The minimum earth-sun distance, the perihelion, occurs on about January 2nd, when the earth is 1.47×10^{11} m (91.3×10^6 miles) from the sun [10]. Solar energy will provide an ever-increasing fraction of our future energy requirement. Although sunlight or solar radiation is abundant and renewable, it is diffuse. The temperature from this diffuse source is sufficient to provide domestic hot water or home heating, but much higher temperature is necessary to displace fossil fuels for production of electricity or other industrial applications. Thus solar radiation must be concentrated to produce this elevated temperature; it must also be collected and moved to the point of use. The use of solar energy to cook food presents a viable alternative to the use of fuel wood, kerosene, and other fuels [26] [10].

2.4 Potential of Solar Energy and Its Range of Applications

Solar energy has the greatest potential of all the sources of renewable energy and if only a small amount of this form of energy is used, it will be one of the most important supplies of energy. Energy comes to the earth from the sun. Solar energy keeps the temperature of the earth above that in colder space, and causes current in the atmosphere and in the ocean, and the rain-cycle, and generates photosynthesis in plants [10] [21].

The solar power at the earth's atmosphere is 10^{17} watts, whereas the solar power on earth's surface is 10^{16} watts. The total world-wide power demand of all needs of human activities is

10^{13} watts. Therefore, the sun can give 1000 times more power than what we need. If we can use 5% of this energy, it will be 50 times what the world will require. Attempts have been made to utilize energy in raising steam which may be used in driving the prime movers for the purpose of generation of electrical energy. However on account of large space required, uncertainty of availability of energy at constant rate due to clouds, winds, mist etc. there is limited application of this source in the generation of power. Now a days the drawbacks as pointed out that the energy cannot be stored and it is a dilute form of energy etc are out dated arguments, since the energy can be stored by producing hydrogen, or by storing in other mechanical or electrical thermal storage devices, or it can be stored in containers of chemicals called phase changing solutions. These solutions store large quantities of heat in a relatively small volume [10] [39].

The facts speak in favor of solar energy, that world's reserves of coal, oil and gas will be exhausted within a few decades. Nuclear energy involves considerable hazards and nuclear fusion has not yet overcome all the problems of even fundamental research, compared with these technologies, the feasibility of which is still uncertain and contested. The applications of solar energy which are enjoying most success today are [14] [39]:

- a) Heating and cooling of residential building
- b) Solar water heating and solar distillation on a small community scale
- c) Solar drying of agricultural and animal products
- d) Salt production by evaporation of seawater or inland brines
- e) Solar cookers
- f) Solar engines for water pumping
- g) Food refrigeration
- h) Wind energy, which is indirect source of solar energy
- i) Solar furnaces
- j) Solar photovoltaic cells, which can be used for conversion of solar energy directly into electricity or for water pumping in rural areas
- k) Solar thermal electric power generation by:
 - Solar ponds

- Steam generators heated by rotating reflectors (heliostat mirrors), or by tower concept
- Reflectors with lenses and pipes for fluid circulation (cylindrical parabolic reflectors) Etc.

2.5 Solar Cookers

Solar cookers can be classified in to the following main categories [21].

- i) **Direct Solar Cookers:** Direct solar cookers are cookers in which the cooking system uses direct solar energy to cook different types of foods. It is a direct-focusing cooker which uses a reflector to focus sunlight directly onto a cooking pot either suspended or set on a stand at the focal point. Numerous arrangements of this cooker have been devised for allowing the reflector to be tilted to always point toward with the pot remaining at the focal point. The most common types of direct solar cookers are
 - Box Cookers
 - Curved Concentrator Cookers and
 - Panel Cookers
- ii) **Indirect Solar Cookers:** In this case, the cooking vessel is physically displaced from the collector and a heat transferring medium is required to convey the heat to the cooking utensils. The heat transfer medium is circulating in a closed loop in an insulated pipe and container. Or a secondary reflector is used to transfer the heat from the primary reflector to the cooking place. These cookers are advantageous than the direct cookers because they provide high thermal power and allow indoor solar cooking.

2.6 Harnessing Solar Power

The most abundant and convenient source of renewable energy is solar which can be harnessed in methods, either Photovoltaic (PV) or Concentrating Solar Power (CSP) technology.

2.6.1 Photovoltaic systems

When certain semi-conducting materials, such as silicon, are exposed to sun light, they generate small amounts of electricity. This process is known as the photoelectric effect. The photoelectric effect refers to the emission or ejection of electrons from the surface of a metal in response to light. It is the basic physical process in which a solar electric or photovoltaic (PV) cell converts sunlight to electrical energy. Solar cells are just too expensive hence; photovoltaic can't compete economically with other conventional power generators. Moreover, if the photovoltaic system is assumed to have a 100% efficiency, then the maximum power that can be generated shall never get more than 1 kW per m² of solar cells. Thus it is not an effective method [10] [21].

2.6.2 Concentrating Solar Power (CSP)

It is a promising technology for power generation in which the solar radiation is concentrated to generate high temperature for producing a solar thermal power plant. With an average annual direct normal irradiance (DNI) of 2,000kWh/m² the area required to generate 100MW of power is about 2km². Ethiopia receives an average annual DNI of nearly 5000 – 7000 Wh/m² according to region and season and thus has great potential for the use of solar energy which is sufficient to operate concentrating solar power plants (CSP) [10] [16] [21].

2.6.3 Types of Concentrating Solar Power (CSP)

In concentrating solar power (CSP) technology, sun's direct normal irradiation is concentrated to produce heat with temperature ranging from 400°C to 1,000°C [8]. This heat is used to produce electricity by conventional steam cycle, or combined cycle, or Stirling engine or it is used in solar cooking. Based on the process of collecting and concentrating solar radiation, the CSP can be categorized into following major types [21] [52]:

- i) **Parabolic Trough:** Parabolic trough-shaped mirror reflectors are used to concentrate sunlight on to thermally efficient receiver tubes placed in the trough's focal line. A thermal transfer fluid, such as synthetic thermal oil, is circulated in these tubes. Heated to approximately 400°C by the concentrated sun's rays, this oil is then pumped through a series of heat exchangers to produce superheated steam. The steam then is converted to electrical energy [10].
- ii) **Central receiver or solar tower:** A circular array of heliostats (large individually tracking mirrors) is used to concentrate sunlight on to a central receiver mounted at the

top of a tower. A heat-transfer medium in this central receiver absorbs the highly concentrated radiation reflected by the heliostats and converts it into thermal energy to be used for the subsequent generation of superheated steam for turbine operation [10] [52].

iii) Linear Fresnel Reflector (LFR): A Linear Fresnel Reflector (LFR) array is a line focus system similar to parabolic troughs in which solar radiation is concentrated on an elevated inverted linear absorber using an array of nearly flat reflectors. An LFR can be designed to have similar thermal performance to that of a parabolic trough per aperture area, although recent designs tend to use less expensive reflector materials and absorber components which reduce optical performance and thus, thermal output [52].

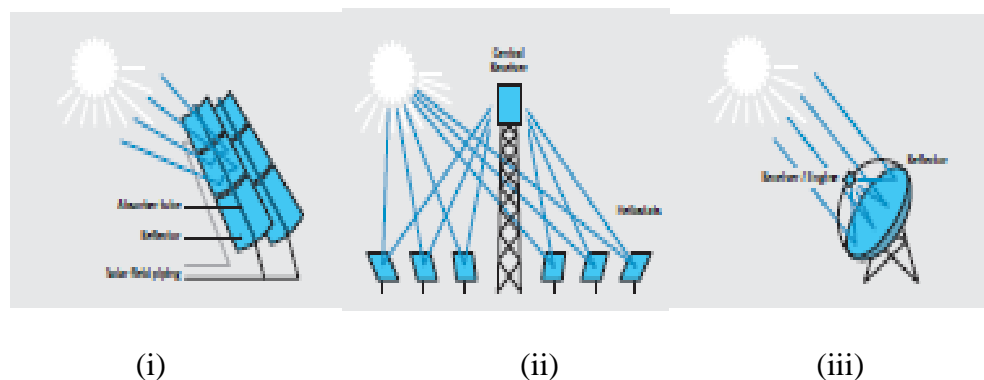


Figure 2.4 (i) Parabolic Trough, (ii) Central receiver and (iii) Parabolic dish

iv) Parabolic Dish (Scheffler Solar Concentrators): is a dish-shaped reflector used to concentrate sunlight on to a receiver located at the focal point of the dish. The concentrated beam radiation is absorbed into the receiver to heat a fluid or gas (air) to approximately 1020°C [10] [44] [52]. The following section deals about Scheffler concentrators.

2.7 Scheffler Concentrator for Solar Cooking

German scientist Wolfgang Scheffler has devised a parabolic concentrator set-up to harness solar energy using low cost set-up. A concentrating primary reflector tracks the movement of the Sun, focusing sunlight on a fixed place. The focused light is used to heat a very large pot, which can be used for baking breads, heating, steam generation, cooking, and water heating [51].

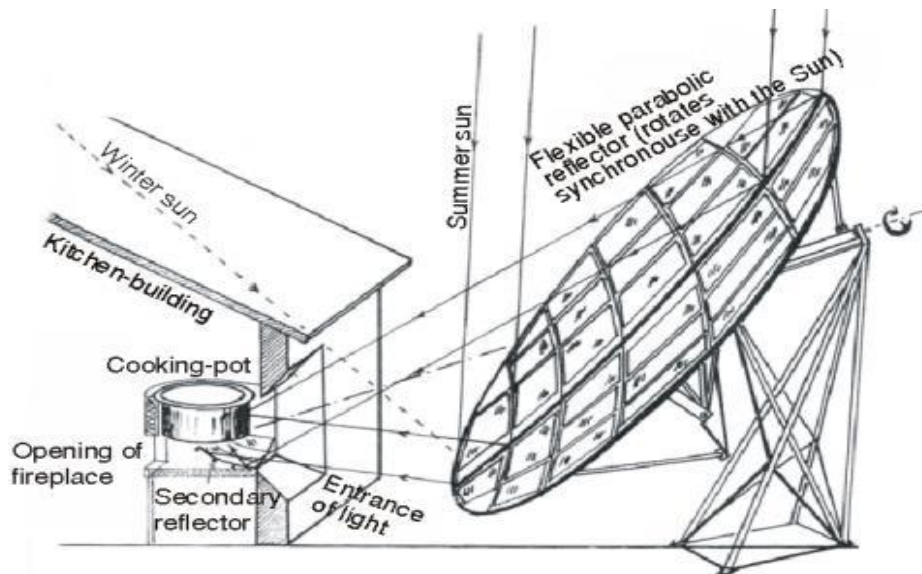


Figure 2.5 Flexible Parabolic Scheffler reflector integrated with indoor cooking pot via a Secondary reflector

Design and development of the Scheffler concentrator aims to make solar cooking comfortable as much as possible. Cooking is simple and comfortable as the cooking-place doesn't have to be moved and it may even be inside the house, while the concentrating reflector is outside, in the sun. The concentrator consists of an eccentric, flexible parabolic concentrator which rotates around an axis parallel to the earth's axis, synchronous with the sun. Additionally the reflector is adjusted to the seasons by tracking it in a simple way [44].

The tracking mechanism can be a combination of electronic and mechanical design which tracks the sun. Scheffler also can have an automatic tracking mechanism (counter weight driven clockwork) and due to the dish having flexible curvature gave fixed focus and thus offered a solution to both cooking in comforts in shadow of the kitchen and also being automatic with no need to be tracked manually. Daily tracking is achieved by a simple photovoltaic device located in the center of the reflector. Where this technology isn't available, mechanical clockwork is used for this purpose [44].

Scheffler concentrators have been built in very different sizes: as small as 0.5 square meters and as big as the 50 square meters reflectors, including medium sizes (2, 2.7, 8, 10, 9.7, 10, 12.6, and 16 square meters). The main construction of the concentrators (apart from the mirror surface) consists of steel. Profiles that are common in construction of furniture, water-installation and housing are used. This material is relatively cheaply available everywhere.

For the concentrator surface various materials can be used. Such as, silvered glass mirrors, aluminum sheet, aluminized materials are most common [44].

Parabolic Scheffler concentrators can provide high temperature for all types of cooking, steam generation and many other applications. Their specialty is a flexible surface curvature and a non moving focal area. In a 2.7 square meters concentrator, maximum temperature in the focus may reach 1020°C, and it is possible to boil 22 liters of water per day (with a solar radiation of 700W/m²). A 2.7 square meters reflector may lead 1.2 liters of water to boiling point in 10 minutes. A 9.7 square meters reflector may lead 4.5 liters of water to boiling point in 10 minutes. Thus, integration of Scheffler with thermal storage device may give a convenient indoor cooking with or without the presence of radiation [48].

2.8 Solar Thermal Energy Storage Concepts

2.8.1 Thermal Storage Systems

Developing efficient and inexpensive energy storage devices is as important as developing new sources of energy. The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. The TES is not a new concept, and it has been used for centuries. Energy storage can reduce the time or rate of mismatch between energy supply and energy demand, and it plays an important role in energy conservation [42].

Energy storage improves performance of energy systems by smoothing supply and increasing reliability. For example, storage would improve the performance of a power generating plant by load leveling. Higher efficiency would lead to energy conservation and improve cost effectiveness. Some of the renewable energy sources can only provide energy intermittently.

Although the sun provides an abundant, clean and safe source of energy, the supply of this energy is periodic following yearly and diurnal cycles; it is intermittent, often unpredictable and diffused. Its density is low compared with the energy flux densities found in conventional fossil energy devices like coal or oil-fired furnaces. The demand for energy, on the other hand, is also unsteady following yearly and diurnal cycles for both industrial and personal needs. Therefore, the need for the storage of solar energy cannot be avoided. Otherwise, solar energy has to be used as soon as it is received. In comparison, the present yield in energy gained by fossil fuels and hydro power amounts to about 70x10¹² kWh. But the technical use of solar energy presently poses problems primarily because of inefficient collection and storage.

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 [14].

If mass specific heat capacity is not small, denser materials have smaller volumes and correspondingly an advantage of larger energy capacity per unit volume. The space available is limited both in transport and in habitat applications. The volume occupied by the present available storage systems is considerable and may be an important factor in limiting the size of storage provided. The amount of energy storage provided is dictated by the cost. The cost of floor space or volumetric space should be one of the parameters in optimizing the size of storage.

The technology of thermal energy storage has been developed to a point where it can have a significant effect on modern life. The major nontechnical use of thermal storage was to maintain a constant temperature in dwelling, to keep it warm during cold winter nights. Large stones, blocks of cast iron, and ceramics were used to store heat from an evening fire for the entire night. With the advent of the industrial revolution, thermal energy storage introduced as a by-product of the energy production [15].

A variety of new techniques of thermal energy storage have become possible in the past. Heat storage at power plants typically is in the form of steam or hot water and is usually for a short time. Very recently other materials such as oils having very high boiling point, have been suggested as heat storage substances for cooking utilities. Other materials that have a high heat of fusion at high temperatures have also been suggested for this application. Perhaps the most promising application of thermal energy storage is for solar heated structures, and almost any material can be used for thermal energy storage [39].

2.8.2 Options in Thermal Storage Methods

Thermal energy storage can be classified by storage mechanism i.e. sensible heat storage (SHS), latent heat storage (LHS), and chemical or bond heat storage (BHS). Thus, this section is concerned with the modes of thermal energy storage (TES).

The sensible heat storage, SHS refers to the energy systems that store thermal energy without phase change. The sensible heat storage occurs by adding heat to the storage medium and increasing its temperature. Heat is added from a heat source to the liquid or solid storage medium [14] [39].

Latent heat storage, LHS is the energy system that store thermal energy by heating of a material that undergoes a phase change usually melting. The amount of energy stored in the LHS depends upon the mass and latent heat of the material. In the LHS, the storage operates isothermally at the phase change of the material.

The bond heat storage, BES works based on the principle that, when a chemical reaction is taking place, energy is either absorbed or librated, thus the storage will store this energy in the form of thermal energy. [39]

The following sections will present the three types of thermal storages options thoroughly.

i) Sensible Heat Storage

Thermal energy can be stored in the sensible heat (temperature change) of substances that experience a change in internal energy. The stored energy is calculated by the product of its mass, the average specific heat, and the temperature change. Besides the density and the specific heat of the storage material, other properties are important for sensible heat storage [24]:

- Operational temperatures
- Thermal conductivity and diffusivity
- Vapor pressure
- Compatibility among materials
- Stability of the storage media
- Heat loss coefficient as a function of the surface areas to volume ratio and
- Cost

The energy stored depends on the temperature change of the material and can be expressed in the form:

$$E = m \int_{T_1}^{T_2} C_p dT \quad [2.1]$$

Where:

m Mass of the storage media,

C_p Specific heat of storage media at constant pressure, and

T_1 and T_2 represent the lower and upper temperature levels between which the storage operates. The difference ($T_2 - T_1$) is referred to as the temperature swing.

a) Solid Media

For sensible heat thermal storage, solid medias usually are used in packed beds, requiring a fluid to exchange heat. When the fluid heat capacity is very low (e.g. when using air) the solid is the only storage material; but when the fluid is a liquid, its capacity is not negligible, and the system is called a dual storage system. Packed beds favor thermal stratification, which has advantages. Stored energy can easily be extracted from the warmer strata, and cold fluid can be taken from the colder strata and fed into the collector field [14].

An advantage of a dual system is the use of inexpensive solids such as rock, sand, or concrete for storage materials in conjunction with more expensive heat transfer fluids like Therminol oil. However, pressure drop and, thus, parasitic energy consumption may be high in a dual system. This has to be considered in the storage design.

b) Liquid Media

Liquid media maintain natural thermal stratification because of density differences between hot and cold fluid. To use this characteristic requires that the hot fluid be supplied to the upper part of a storage system during charging and the cold fluid be extracted from the bottom part during discharging, or using another mechanism to ensure that the fluid enters the storage at the appropriate level in accordance with its temperature (density) in order to avoid mixing. This can be done by some stratification devices (floating entry, mantle heat exchange, etc.) [14][43].

ii) Latent Heat Storage

Thermal energy can be stored nearly isothermally in some substances as the latent heat of phase change; i.e. as heat of fusion (solid-liquid transition), heat of vaporization (liquid-vapor), or heat of solid-solid crystalline phase transformation. All substances with these characteristics are called phase change materials (PCMs). Because the latent heat of fusion between the liquid and solid states of materials is rather high compared to the sensible heat storage systems, systems utilizing PCMs can be reduced in size compared to single-phase sensible heating systems. However, heat transfer design and media selection are more difficult, and experience low temperature salts has shown that the performance of the materials can degrade after a moderate number of freeze-melt cycles [24].

The amount of energy (E) stored in this case depends upon the mass (m) and latent heat of fusion (q_L) of the material. Thus,

$$E = mq_L \quad (2.2)$$

The storage operates isothermally at the melting point of the material. If isothermal operation at the phase change temperature is difficult, the system operates over a range of temperatures T_1 to T_2 that includes the melting point. The sensible heat contributions have to be considered and the amount of energy stored is given by:

$$E = m \left[\left\{ \int_{T_1}^{T^*} C_{ps} dT \right\} + q_L + \left\{ \int_{T^*}^{T_2} C_{pl} dT \right\} \right] \quad (2.3)$$

Where:

C_{ps} and C_{pl} represent the specific heats of the solid and liquid phases storage medias and T^* melting point of the storage media

iii) Bond or Chemical Storage

A third storage mechanism is by means of chemical reactions. For this type of storage it is necessary that the chemical reactions involved are completely reversible. The heat produced by the solar receiver is used to excite an endothermic chemical reaction. If this reaction is completely reversible the heat can be recovered completely by the reversed reaction. Often catalysts are necessary to release the heat. This is even more advantageous as the reaction can then be controlled by the catalyst. Commonly cited advantages of thermal energy storage in a reversible thermo chemical reaction (RTR) are high storage

energy densities, indefinitely long storage duration at near ambient temperature, and heat-pumping capability.

Drawbacks may include complexity, uncertainties in the thermodynamic properties of the reaction components, high cost, toxicity, and flammability [23] [24].

Using heat to produce a certain physicochemical reaction and then storing the products: Absorbing and adsorbing are two examples for the bond reaction. The heat is released when the reverse reaction is made to occur. In this case also, the storage operates essentially isothermally during the reactions. However, the temperature at which heat flows from the heat supply is usually different, because of the required storage material and vice versa. Of the above methods, sensible and latent heat storage systems are in use, while bond energy storage systems are being proposed for use in the future for medium and high temperature applications. The specific application for which a thermal storage system is to be used determines the method to be adopted. The following table shows overviews of the three storage methods with example [24].

Table 2.1 Overview of thermal energy storage

Energy storage	Functional Principle	Phases	Example
Sensible Heat	Temperature change of the medium with highest possible heat capacity	Liquid	Hot water, organic liquids (Thermia oil) , molten salt, liquid metals
		Solid	Metals, minerals, rocks ceramics
Latent Heat	Essentially heat of phase change	Liquid– Solid	Nitrides, Chlorides, hydroxides, Carbonates, Fluorides
		Solid – solid	Hydroxides
Bond or chemical energy	Chemical energy is absorbed and released due to shifting of equilibrium by changing pressure and temperature	Solid – Gas	CaO.H ₂ O, MgO.H ₂ O, FeCl ₂ /NH ₃
		Gas – Gas	CH ₄ H ₂ O
		Liquid – Gas	LiBr/H ₂ O, NaOH/H ₂ O, H ₂ SO ₄ /H ₂ O

2.9 Modes of Heat Transfer

Heat transfer, also known as heat flow, heat exchange, or transfer of thermal energy is the movement of heat from one place to another. When an object is at a different temperature from its surroundings, heat transfer occurs so that the body and the surroundings reach the same temperature at thermal equilibrium. Such spontaneous heat transfer always occurs from a region of high temperature to another region of lower temperature. There are three basic modes of heat transfer mechanisms defined as follows [43] [53]:

2.9.1 Conduction Heat Transfer Mechanism

Transfer of energy between objects in physical contact is the transfer of heat from a hot side to a cooler side through a dividing medium. The hot side heats the molecules in the dividing medium and causes them to move rapidly, heating the adjacent molecules until the cool side is heated. The transfer of heat stops when the temperature of the hot side equals that of the cool side. In heat transfer by conduction heat flow (Q) through the area A in a plane normal to the direction of heat transfer in time (δt) given by Fourier's law of conduction as [5] [6] [14] [18]:

$$\dot{Q} = -KA \frac{\delta T}{\delta X} \quad (2.4)$$

Conduction through a plane wall: The details of conduction are quite complicated but for engineering purposes may be handled by a simple equation, usually called Fourier's equation. For the steady flow of across a plane wall with the surfaces at temperatures of T_1 and T_2 where T_1 is greater than T_2 ; the heat flow Q per unit area A ; (the heat flux) is:

$$\frac{Q}{A} = K \left(\frac{T_1 - T_2}{x_1 - x_2} \right) = K \frac{\Delta T}{\Delta X} \quad (2.5)$$

Equation (2.1) can be written in a more general form if the temperature gradient term is written as a differential:

$$\dot{Q} = -KA \frac{dT}{dX} \quad (2.6)$$

Where:

\dot{Q} - is the heat flow (W)

k - Thermal conductivity (W/m °C)

A - Area perpendicular to heat flow (m²)

DT/dx - Temperature gradient in plane of heat transfer in the direction of heat flow ($^{\circ}C/m$)

The negative sign in the equation is introduced to account for the fact that heat is conducted from a high temperature to a low temperature, so that (dT/dX) inherently negative; therefore the double negative indicates a positive flow of heat in the direction of decreasing temperature.

2.9.2 Convection Heat Transfer Mechanism

Convection is transfer of energy between an object and its environment, due to fluid motion. Convection can be forced convection in which the flow is caused by a pump or a fan or it may be natural convection in which the flow is caused by density differences due to differences in temperature. It is found that the heat flux is approximately proportional to the temperature difference between the wall and the bulk of the fluid [5] [12] [18] [42].

$$\frac{Q}{A} \propto (T_f - T_s) \quad (2.7)$$

This causes to define a constant proportionality called “convection heat transfer coefficient” denoted by, h

$$\frac{Q}{A} = h(T_f - T_s) \quad (2.8)$$

Thus the rate of convection heat transfer is given by

$$\dot{Q} = hA\Delta T \quad (2.9)$$

Where:

h - convection heat transfer coefficient ($W/m^2 \text{ } ^{\circ}C$)

A - Surface area where convection takes place (m^2)

ΔT - Temperature difference between the fluid and the wall surface ($^{\circ}C$)

2.9.3 Radiation Heat Transfer Mechanism

Transfer of energy from or to a body by the emission or absorption of electromagnetic radiation. All objects with a temperature above absolute zero radiate energy at a rate equal to their emissivity multiplied by the rate at which energy would radiate from them if they were a black body.

According to Stefan-Boltzmann law, ideal radiators emit energy at a rate proportional to the fourth power of the absolute temperature [6] [12] [18]. And the net rate of exchange of energy between two ideal radiators A and B is expressed as:

$$\dot{Q} = \sigma A(T_A^4 - T_B^4) \quad (2.10)$$

Where:-

σ - Stefan- Boltzmann constant = $5.67 \times 10^{-12} \text{w/cm}^2 \cdot \text{k}^4$

T_A - Temperature of body A ($^{\circ}\text{C}$)

T_B - Temperature of body B ($^{\circ}\text{C}$)

In many physical situations, we are interested in radiation heat transfer from the surface of an object to the surrounding uniform temperature. Thus, the net radiation from a non-black surface to the surrounding is given by [42].

$$\dot{Q} = \varepsilon \sigma A(T_s^4 - T_{\infty}^4) \quad (2.11)$$

Where:

T_s - Body surface temperature ($^{\circ}\text{C}$)

T_{∞} - Surrounding or ambient temperature ($^{\circ}\text{C}$)

ε - Emissivity of surface and has a value between 0 to 1 for perfect reflector

$\varepsilon = 0$ and for a perfect emitter a so called “black body”, $\varepsilon = 1$.

2.10 Thermal Insulation System

Insulation is defined as a material or combination of materials, which retard the flow or loss of heat and is used in heating, air conditioning and refrigeration systems to insulate piping, ducts, vessels, thermal storage devices and equipments in order to conserve thermal energy, prevent surface condensation and control heat input to the contained fluids. Generally the thermal insulation can be used to control heat flow in wide temperature ranges when the appropriate insulating material is selected [2] [20].

2.10.1 Advantages of Insulation Systems

The following are the basic advantages of insulating systems [20] [45]:

Energy Savings: Substantial quantities of heat energy are wasted because of un-insulated heated surfaces. Properly designed and installed insulation systems will immediately reduce the need for energy and benefits to industry include enormous cost savings, improved productivity, and enhanced environmental quality.

Process Control: By reducing heat loss or gain, insulation can help maintain process temperature to a pre-determined value or within a predetermined range.

Personnel Protection: Thermal insulation is one of the most effective means of protecting workers from burns resulting from skin contact with surfaces of hot surface and equipment operating at higher temperatures. Insulation reduces the surface temperature of piping or equipment to a safer level, resulting in increased worker safety and the avoidance of worker downtime due to injury.

Fire Protection: Used in combination with other materials, insulation helps provide fire protection in fire stop systems designed to provide an effective barrier against the spread of flame, smoke, and gases at penetrations of fire resistance rated assemblies by ducts, pipes, and cables.

2.10.2 Thermal Conductivity and Thermal Resistance of Insulator

Thermal Conductivity (k): Is a specific material property. It represents the heat flow in watts (W) through a 1 m² surface and 1 m thick flat layer of a material when the temperature difference between the two surfaces in the direction of heat flow amounts to 1 Kelvin (K). The unit of measurement for thermal conductivity (k) is W/(m.K) [53] [20].

Thermal resistance (R): Describes the thermal insulation effect of a constructional layer. Thermal resistance of a material depends on the geometry and thermal properties of the insulator. The unit of measurement for thermal resistance (R) is (K/W). [53]

For cylindrical insulation (such as circular pipe insulation) of inner radius r_1 , outer radius r_2 , and length L having average thermal conductivity K ; if there is no heat generation in the layer the thermal resistance can be given by:

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi L K}$$

For a cylinder consisting of two layers, the thermal resistance is:

$$R_{\text{total}} = R_{\text{cyl},1} + R_{\text{cyl},2}$$

If the steady heat transfer is through two-layered composite cylinder of length L with convection on both sides (inner and outer sides of insulator cylinders) can be expressed as:

$$R_{\text{total}} = R_{\text{conv},1} + R_{\text{total}} + R_{\text{conv},2}$$

$$R_{\text{total}} = \frac{1}{2\pi L r_1 h_1} + \frac{\ln(r_2/r_1)}{2\pi L K_1} + \frac{\ln(r_3/r_2)}{2\pi L K_2} + \frac{1}{2\pi L r_4 h_2}$$

2.10.3 Insulating Materials

Most insulation is used to prevent the conduction of heat. In some cases radiation is a factor. A good insulator is obviously a poor conductor. Less dense materials are better insulators. The denser the material, the closer its atoms are together. That means the transfer of energy of one atom to the next is more effective. Thus, gases insulate better than liquids, which in turn insulate better than solids [45].

An interesting fact is that poor conductors of electricity are also poor heat conductors. Wood is a much better insulator than copper. The reason is that metals that conduct electricity allow free electrons to roam through the material. This enhances the transfer of energy from one area to another in the metal. Without this ability, the material-like wood-does not conduct heat well.

There are different types of insulation materials among those; fiber glass, cellular glass, foamed plastic and calcium silicate 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 [46].

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 422oC. A high temperature, flexible blanket can be used with temperatures up to 530oC [7] [29].

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 [29].

2.10.4 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 [20].

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 though 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 summer. 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 [20][50][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 [2][53].

Chapter Three

Design of Primary Concentrator and Secondary Reflector

3.1 Introduction

In this chapter, the design of Scheffler concentrator and secondary reflector are discussed. The chapter explains the complete principle and mathematical model to design an 8 m² Scheffler concentrator including calculation of depths and arc lengths for different crossbars. The materials used for reflecting surfaces both for Scheffler concentrator and secondary reflector are also discussed. Maintaining a small and hot focus in a fixed place by tracking the sun and moving with the sun during all time of the day and the year are also presented. Finally installation of the Scheffler concentrator on site and use of pivot points for reaching the required profiles of the Scheffler reflector are discussed.

3.2 Design of Scheffler Concentrator

Unlike a conventional paraboloid concentrator, the Scheffler fixed focus concentrator is a lateral part of a paraboloid as shown in Figure 3.1. While designing a parabola curve for the Scheffler concentrator, all calculations are made with respect to equinox with zero solar declination. In order to calculate the equation of the parabola curve, the calculations are made by considering the side view of the paraboloid. In this way, the paraboloid and reflector frame are drawn in the form of a parabola curve and straight line respectively. The basic parabola equations with its axis passing through the y-axis can be written in the following form [32] [48]:

$$P(x) = m_p x^2 + C_z \quad (3.1)$$

Where m_p is the slope of parabola and C_z is the y-intercept of the parabola.

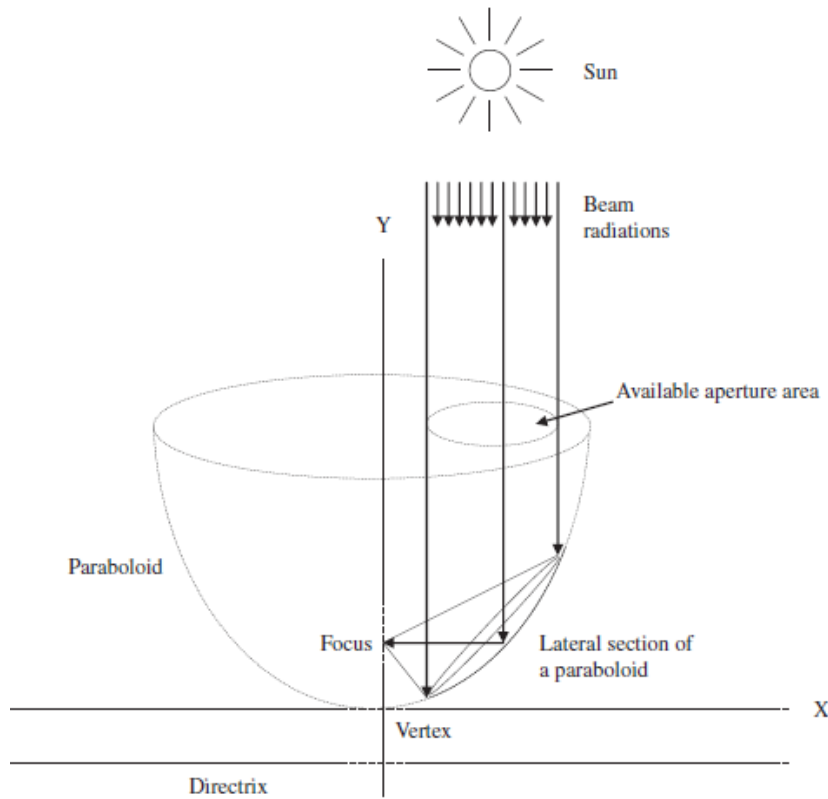


Figure 3.1 Section of Scheffler concentrator in a paraboloid

Taking first derivative of Equation (3.1) for the slope of parabola

$$P'(x) = 2m_p x \quad (3.2)$$

Commencing from a point P_n of the parabola curve in the positive coordinate axes where solar radiation is reflected at 90° as shown in Figure 3.2. At this point of the parabola curve, the tangent is cut at 45° angle and value of the y-coordinate is half that of the x-coordinate. In order to design the reflector parabola, the following aims and procedure have been considered.

3.2.1 Procedure to Design the Concentrator Parabola

The following are the basic steps in the design of concentrator parabola [1] [3] [32].

- i. Selection of x-coordinate of point P_n (x_p) in order to get a reasonable distance to the focal point; calculation of y-coordinate of point P_n (y_p) and slope m_p with the help of Equations (3.1) and (3.2).
- ii. Selection of X_{E1} and X_{E2} in order to get a surface of approximately $8m^2$ and a balanced collector; calculation of Y_{E1} , Y_{E2} and angle of the line joining the points E1 and E2.

- iii. Check if the two aims are roughly reached (calculation of surface area right and left of P_m and check their difference for balancing and their sum for collector surface); otherwise adapt a new set of P_n , $E1$ and $E2$.
- iv. Calculation of semi-major and semi-minor axis of the concentrator frame.

For a surface area of $8m^2$, the x-coordinate of the point P_n is taken as 2.87. (All calculations are based on the point P_n with x-coordinate as 2.86575 with five decimal places. This is however written in two decimal places as 2.87). This coordinate defines the distance of this point to the focal point, which is also an indicator to the average distance of the reflector surface to the focal point. A value is taken that keeps this distance small, but still leaves some space between the inner collector edge and the focal point in order to avoid shading from the building that usually exists around the focal point. Therefore, collectors with a higher surface area will generally have a point P_n with a higher x-coordinate.

The first derivative of Equation (3.1) at this point is equal to the slope at the point. The tangent cuts this point P_n at an angle of 45° with x-axis (directrix), so we can write:

$$P'(2.87) = \tan 45^\circ$$

$$P'(2.87) = 1$$

According to the definition of parabola, the coordinates at point P_n are given as:

$$P(2.87) = \left(\frac{1}{2}\right)(2.87)$$

$$P(2.87) = 1.43$$

By using Equation (3.2), the values of m_p are calculated as:

$$p'(x) = 2m_p x, \quad p'(x) = 1$$

Thus
$$m_p = \frac{1}{2(2.87)} = 0.17$$

Again from Equation (3.1)

$$p(x) = p(2.87) = 1.43 = m_p x^2 + c_p$$

$$c_p = p(x) - m_p x^2 = 0$$

The parabola equation for the equinox is given as:

$$P(x) = 0.17x^2 \tag{3.3}$$

In order to approximately construct a balanced reflector, two points X_{E1} and X_{E2} are chosen on a graph paper as 1.32 and 4.06. The reason of selecting these points is to construct a balanced parabola in order to rotate the reflector with a nominal force. In this way, the line joining these two points $E1$ and $E2$ of the parabola curve represents the cutting section of the elliptical frame of the Scheffler reflector. This line $E1E2$ is not parallel to the tangent at point P_n (which makes 45° angle with x -axis) but makes a 43.23° angle as shown in Figure 3.2. The structure is equilibrated and needs a little force to move the reflector.

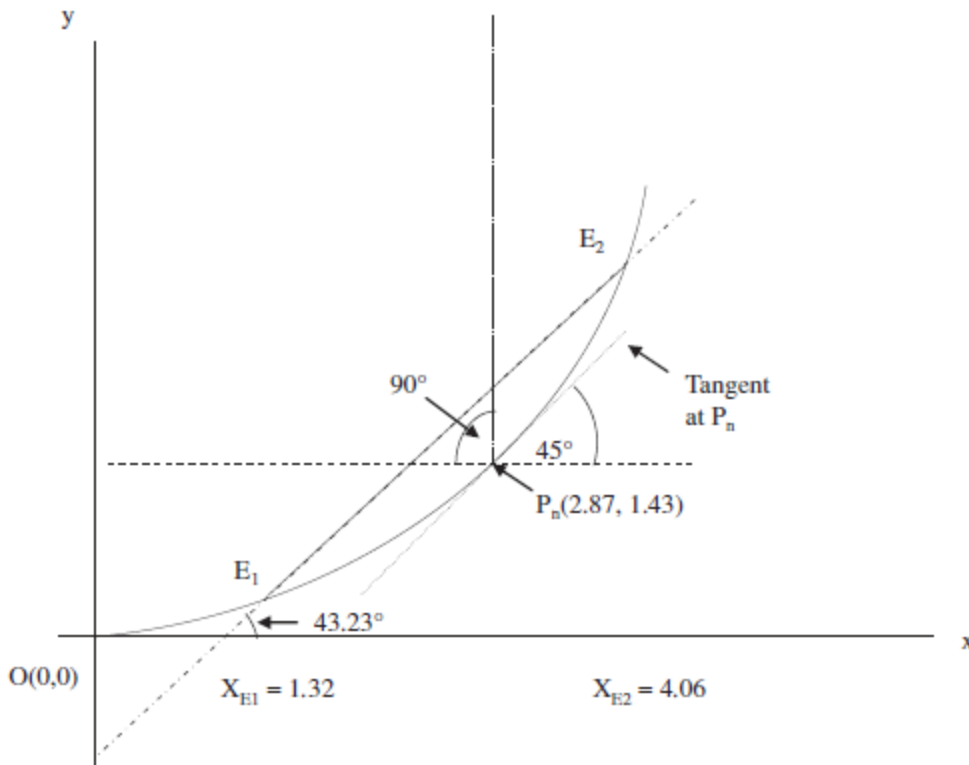


Figure 3.2 Description of parabola of a Scheffler Concentrator

As we can see in Figure above, the general equation of this straight line is given by:

$$G(x) = m_g x + C_g \quad (3.4)$$

Where m_g is the slope of the line and C_g is the y intercept of the line.

Differentiating Equations (3.4) with respect to x , gives

$$G'(x) = m_g$$

$$m_g = \tan 43.23^\circ$$

$$G'(x) = \tan 43.23^\circ$$

$$m_g = 0.94$$

The coordinate x of point E1 (X_{E1}) is selected to be 1.32 and the coordinate y is calculated to be 0.296 by using Equation (3.3). By substituting the values of x , y and m_g in Equation (3.4), the y -intercept (C_g) is calculated and becomes:

$$G(x) = m_g x + c_g,$$

$$0.296 = 0.94 * 1.32 + c_g$$

$$c_g = -0.94$$

Thus equation of the straight line is given by:

$$G(x) = 0.94x - 0.94 \quad (3.5)$$

The coordinate x of point E2 (X_{E2}) is calculated by comparing and solving Equations (3.1) and (3.4).

i. e, $p(x) = G(x)$ which gives, The general form of a quadratic equation is as follows:

$$x^2 - \left(\frac{m_g}{m_p}\right)x - \left(\frac{C_z}{m_p} - \frac{C_g}{m_p}\right) = 0 \quad (3.6)$$

Through solving Equations (3.6) with the help of a quadratic formula to get two points of intersection (X_{E1} and X_{E2}) of the Parabola curve and straight line, we get:

$$x_{E1} = \frac{m_g}{m_p} + 2\left[\left(\frac{m_g}{2m_p}\right)^2 + \frac{(C_z - C_g)}{m_p}\right]^{0.5} \quad (3.7)$$

$$x_{E2} = \frac{m_g}{m_p} - 2\left[\left(\frac{m_g}{2m_p}\right)^2 + \frac{(C_z - C_g)}{m_p}\right]^{0.5} \quad (3.8)$$

The straight line cutting the curve represents a cutting plane of an ellipse with axes ratio $a/b = \cos\alpha$, where “a” and “b” are the semi-minor axis and semi-major axis respectively. For a given paraboloid, the cutting section of the lateral part will make an ellipse and its projection on the ground (horizontal plane) will make a circle. So, the semi-minor axis of the ellipse and radius of projection on the ground will become the same. The projection of this ellipse on the horizontal plane (XZ -plane) is a circle with diameter of $2a$. The general equation for the diameter of circle ($2a$) is calculated for a Scheffler reflector by subtracting Equation (3.8) from Equation (3.7) and is given by:

$$2a = 4\left[\left(\frac{m_g}{2m_p}\right)^2 + (C_z - C_g)/m_p\right]^{0.5} \quad (3.9)$$

The semi-minor axis of the ellipse is 1.37 m and semi major axis of the reflector is calculated to be 1.88 m by dividing with axes ratio ($\cos 43.23^\circ$), using $a/b = \cos\alpha$, where $\alpha = 43.23^\circ$.

3.2.2 Distribution of Crossbars on the Concentrator Frame

For the construction of the Scheffler concentrator, it is necessary to know the exact position of the crossbars on the reflector frame. The frame of the Scheffler concentrator is elliptical in shape and this can easily be calculated by using the equation of ellipse which is given below [1] [48]:

$$\left(\frac{x}{b}\right)^2 + \left(\frac{y}{a}\right)^2 = 1 \quad (3.10)$$

Where, a is the semi-minor axis of the ellipse,

b is the semi major axis of the ellipse.

In order to locate any point “ y_n ” with respect to “ x_n ” on the elliptical frame, Equation (3.10) can be written as:

$$y_n = (\cos 43.23)(b^2 - x_n^2)^{0.5} \quad (3.11)$$

Equation (3.11) is used to calculate the position of crossbars on the elliptical frame of the Scheffler concentrator. A number of points can be taken but seven crossbars are sufficient to make the required section of the paraboloid for an 8m^2 Scheffler concentrator. Taking the centre of the ellipse as origin and major axis along x-axis, the middle crossbar passes through the origin. The other crossbars are located at a distance of ± 0.48 m, ± 0.96 m, ± 1.44 m from the origin along major-axis and the corresponding points on minor-axis are calculated as ± 1.37 , ± 1.32 , and ± 1.18 m respectively as shown in [Figure](#) below.

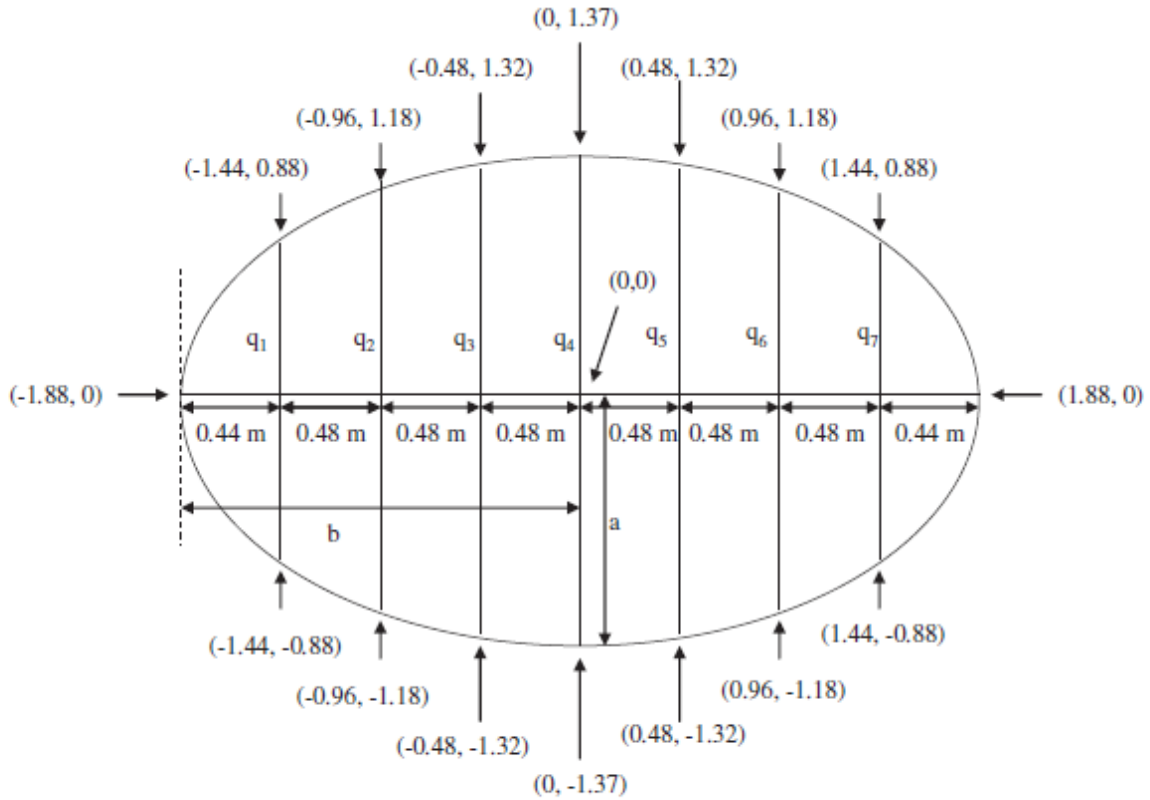


Figure 3.3 Intersection points of seven crossbars on an elliptical concentrator frame

After the construction work of the reflector frame, intersections points of the crossbars should be marked on the elliptical concentrator frame.

3.2.3 Calculation of Equations for Crossbar Ellipses

The cutting planes of the crossbars are perpendicular to the cutting plane of the reflector frame and are shown in the form of seven straight lines (q_1 to q_7) as shown in Figure 3.4. The inclination angle of the cutting plane of crossbars is found to be -46.77° by subtracting the angle of the cutting plane of the reflector frame from 90° . These cutting lines are also ellipses with axes ratio $(a_q/b_q) = \cos 46.77^\circ$. Starting from the middle crossbar (q_4 , passing through P_c), we take from the basic equation of the line and are given as [1] [48]:

$$q_4(x) = m_{q_4} x + C_{q_4} \quad (3.12)$$

Slope of the middle crossbar is calculated as:

$$m_{q_4} = \tan(-46.77) = -1.06$$

The x-coordinate of the point of intersection (C_f) of the middle crossbar and the reflector frame is the center of the line $X_{E1}-X_{E2}$ i.e., 2.69. The y-coordinate is calculated by substituting this value of x in Equation (3.5) and is given as follows:

$$q_4(x) = q_4(2.69) = 1.59$$

$$G(x) = 0.94x - 0.94, \quad x = 2.69$$

Substituting the values of m_{q4} , $q_4(x)$ and x in Equation (3.12), the y-intercept (C_{q4}) for the middle crossbar is calculated to be 4.46 and the equation of the middle crossbar (q_4) for $8m^2$ surface area of the Scheffler concentrator is given as:

$$q_4(x) = -1.06x + 4.46 \quad (3.13)$$

It is evident from Figure 3.4 that the slopes for all cutting crossbars are the same as these are perpendicular on the same cutting plane of the Scheffler frame. As the crossbars are equally distributed (from the center of the concentrator frame), so the difference between the two successive y-intercepts is calculated to be 0.70 by dividing 0.48 with $\cos 46.77^\circ$.

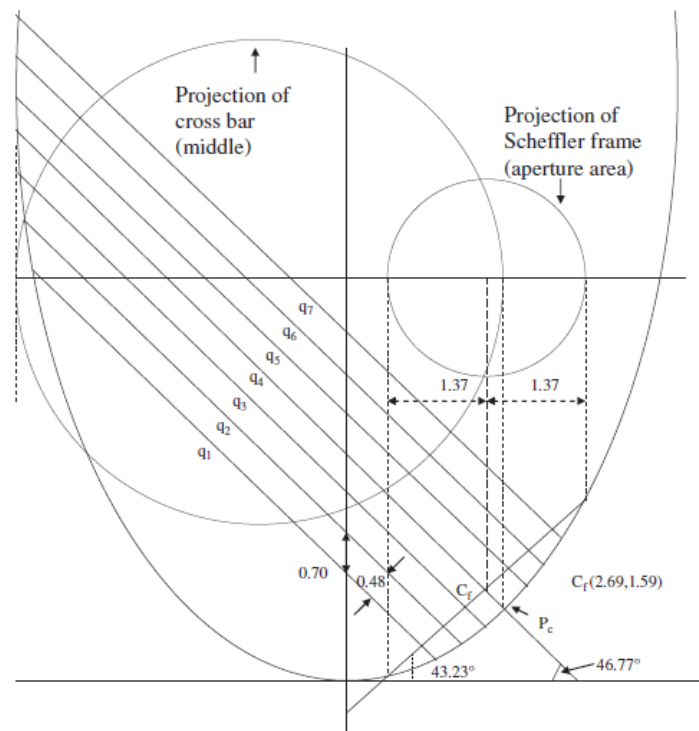


Figure 3.4 Description of Scheffler concentrator and crossbars on parabola curve

The equations for the 4th, 5th and 6th crossbars are calculated by adding 0.70, 2(0.70) and 3(0.70) in the y-intercepts values of Equation (3.13) respectively. Similarly, the equations for 1st, 2nd and 3rd crossbars are calculated by subtracting 0.70, 2(0.70) and 3(0.70) from the y-

intercepts values of Equation (3.13) respectively. The equations for all crossbars can be generalized as:

$$q_n(x) = m_q x + C_{qn}$$

Similarly, for a semi-minor axis (a_{qn}) of any crossbar ellipse Equation (3.9) can be modified for crossbars and the reflector frame and is generalized as:

$$a_{qn} = \left[\left(\frac{m_{qn}}{2m_p} \right)^2 - (C_z - C_{qn})/m_p \right]^{0.5} \quad (3.14)$$

Where subscript “n” represents the number of crossbars

Similarly, y-intercepts, equations of the cutting sections on the XY-plane, semi-minor axis and semi-major axis for all the seven crossbars are calculated and are given in Table 3.1.

3.2.4 Calculation of Depths and Arc Lengths of Crossbars

After the calculation of equations for different crossbars, the depths and lengths of arcs for different crossbars are calculated for the construction of the Scheffler concentrator. The depth of reflector for the nth crossbar (D_n) is calculated from the following formula and is explained in Figure 3.5 shown below [1].

Table 3.1 Semi-minor axis and semi-major axis of different crossbars

Crossbar, n	y-intercept C_{qn} (m)	Equation of cutting section Crossbars on xy- plane	Semi-minor axis a_{qn} (m)	Semi-major axis b_{qn} (m)
1	2.36	$q_{4(x)} = -1.06x + 2.36$	4.78	6.97
2	3.06	$q_{4(x)} = -1.06x + 3.06$	5.18	7.56
3	3.76	$q_{4(x)} = -1.06x + 3.76$	5.55	8.11
4	4.46	$q_{4(x)} = -1.06x + 4.46$	6.90	8.62
5	5.16	$q_{4(x)} = -1.06x + 5.16$	6.23	9.10
6	5.86	$q_{4(x)} = -1.06x + 5.86$	6.55	9.56
7	6.56	$q_{4(x)} = -1.06x + 6.56$	6.85	10.0

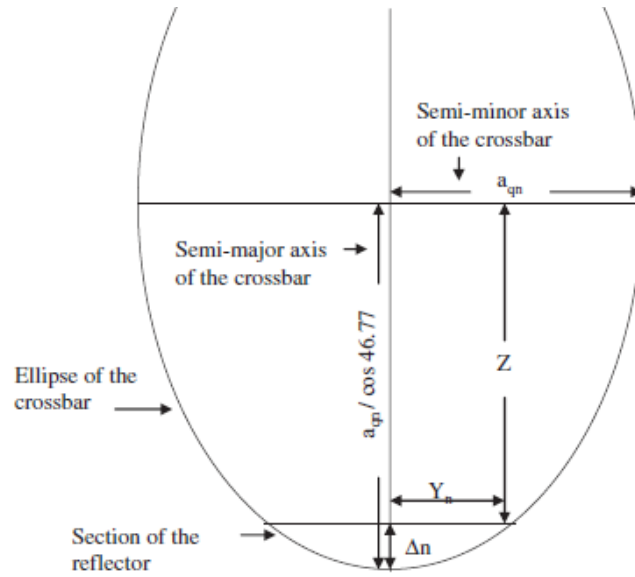


Figure 3.5 Ellipse of the crossbar for the Scheffler concentrator

$$\Delta n = \frac{a_{qn}}{\cos 46.77} - Z \quad (3.15)$$

Where $Z = \frac{(a_{qn}^2 - Y_n^2)^{1/2}}{\cos 46.77}$, (by using the basic formula for ellipse

By substituting the values of “Z” in Equation (3.15) we get:

$$\Delta n = \frac{\left[a_{qn} - (a_{qn}^2 - Y_n^2)^{1/2} \right]}{\cos 46.77} \quad (3.16)$$

We can see that all of the crossbars are the parts of the ellipses that differ slightly from the circle segment.

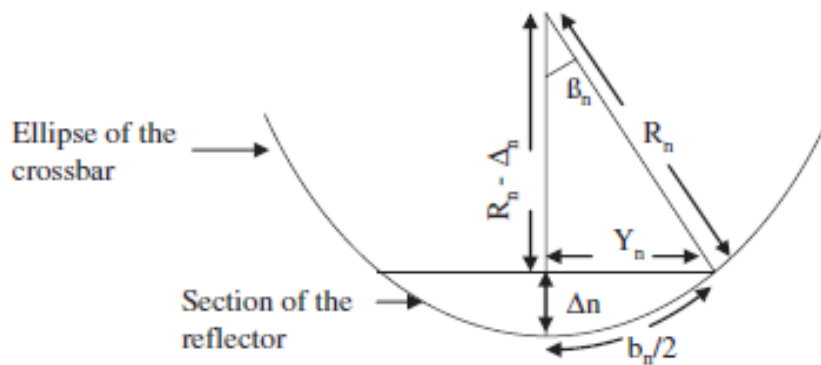


Figure 3.6 Radius, depth and arc length details for the n^{th} crossbar

For the solar concentrator optics, different approximations are valid to concentrate energy cheaply rather than to form a precise image. As the small segments are used for large ellipses, these small elliptical segments are taken as the parts of circle segments. In this case, since it is along the crossbar, a small placement deviation also means a small angle deviation. For an n^{th} crossbar, radius (R_n), depth (Δ_n), arc length (b_n) and angle made with half arc length (β_n) are shown in Figure 3.6 shown.

It is evident from Figure 3.6

$$R_n^2 = (R_n - \Delta_n)^2 + Y_n^2$$

By simplifying the above equation

$$R_n = \frac{\Delta_n^2 - Y_n^2}{2\Delta_n} \quad (3.17)$$

It is clear that from Figure 3.6,

$$\beta_n = \sin^{-1}(Y_n/R_n) \quad (3.18)$$

And
$$\left(\frac{b_n}{2}\right) = R_n \left(\frac{2\pi\beta_n}{360}\right) \quad (3.19)$$

The depth (Δ_n), radius (R_n) and arc length (b_n) of the n^{th} crossbar are calculated by using Equations (3.17) – (3.19) and are given in the table below.

Table 3.2 Depths and lengths of different arcs of crossbars for an 8m² Scheffler Concentrator
(all respective measurements are in meter and angle)

Crossbar,n	Y_n	Depth, Δ_n	Radius, R_n	Angle, β_n	Half arc length, $b_n/2$	Arc length, b_n
1	0.88	0.12	3.30	15.47	0.89	1.78
2	1.18	0.20	3.60	19.10	1.20	2.40
3	1.32	0.23	3.87	20.04	1.35	2.70
4	1.37	0.24	4.11	19.04	1.40	2.79
5	1.32	0.21	4.33	17.83	1.35	2.69
6	1.18	0.16	4.53	15.08	1.19	2.38
7	0.88	0.08	4.71	10.77	0.89	1.77

3.3 Design of Secondary Reflector

A secondary reflector is used to further reflect the beam radiations onto the bottom of the thermal storage system. The design of secondary reflector incorporates a parabolic dish to concentrate the primarily concentrated rays which are coming from the primary reflector (Scheffler concentrator) to a certain place where cooking is being taking place [32] [48].

In this way, the heat energy is supplied from the bottom side. The radiations are equally scattered onto the bottom of the storage system and solar thermal energy is best utilized like a conventional furnace under the storage. The secondary reflector is designed to converge the reflected radiations onto the bottom of the thermal storage system.

The secondary reflector is designed to receive all the solar radiations reflected from the primary concentrator and then further reflect it to the bottom of the storage system. The reflector can be placed on a fixed concrete foundation bed which facilitates the accurate position of the secondary reflector. The secondary reflector is designed using SolTrace in chapter five with following dimensions and properties.

Dish diameter=0.9m

Depth of the center=0.11m

Reflective Efficiency = 98%

Virtual property = 0

3.4 Reflective Materials for Reflective Surfaces

Highly reflective aluminum sheet materials are predominantly used as reflectors for lamps in office and industrial buildings [19]. Because of their mechanical properties and low cost compared to silvered glass mirrors, aluminized reflectors are finding applicability to high temperature solar concentrating technologies. Furthermore high reflectance aluminized sheet is already being successfully applied in low concentrating technologies like compound parabolic concentrator (CPC) troughs and day lightening. Of the material investigated, highly secular aluminium has an excellent chance to meet the requirements for medium concentrating technologies like parabolic troughs. For applications in humid climates, an additional polymer coating is necessary for durability. Standard anodized materials show satisfactory hemispherical reflectance properties after outdoor and accelerated exposure. Because of their manufacturing flexibility and their low costs, mirrors based on anodized or

coated sheet aluminum are a promising alternative as primary or secondary concentrators in a number of solar energy applications. They offer solar weighted reflectance of 88-91 %, good mechanical properties and are easy to recycle [19].

3.5 Tracking the Sun

The sun gives us the impression of movement basically because the earth is revolving under our feet. One way to stop moving while rotating is to locate our self in the center or axis of the rotation, the same way, the hot focus of the Scheffler concentrator can be kept at a fixed place in the axis of rotation of the reflector giving maximum convenience for utilization of solar energy [10].

For daily tracking, these reflectors rotate along an axis parallel to polar axis with an angular velocity of one revolution per day to counterbalance the effect of daily earth rotation. The daily tracking is accomplished with the help of a small self-tracking Photovoltaic system or clock-work operated by gravity which provide angular velocity at one revolution per day.

3.5.1 Bending and Flexing Feature of Scheffler Concentrator

This is the most important point of the design of the Scheffler concentrator, and is normally overlooked by people who see the reflector. In winter, the sun is low above the horizon, while in summer it moves high up into the sky. Under these changing conditions, having a different angle of the sunlight every day, it is difficult to maintain a small and hot focus in a fixed place during all the four seasons of the year. The design of the Scheffler concentrator provides the only widespread solution to this demanding situation. First it sounds almost unbelievable, but the concentrator is made to change the shape of its entire surface to adapt itself to the different angles of the sunlight. This way, a small and hot focus is achieved during all seasons. This sounds very complicated to make and to handle, but it turns out not to be so.

3.5.2 Moving with the Sun

Just as the earth spins around an axis through the North Pole and the South Pole, the Scheffler Reflector spins around an axis parallel to that, just in the opposite direction. (to counteract the earth's rotation), this is called polar mounting or mounting on a polar axis. The speed is one revolution per day, or, better, half a revolution in half a day, since we do not use it at night. In this way the concentrator keeps facing the sun in a constant manner [49].

The constant speed can be controlled with mechanical clockwork. For practical reasons, the shape of the reflector should be such that the hot focus is outside of the reflector, either on the north side or the south side. This way the hot focus can be even inside a building while the concentrator remains outside.

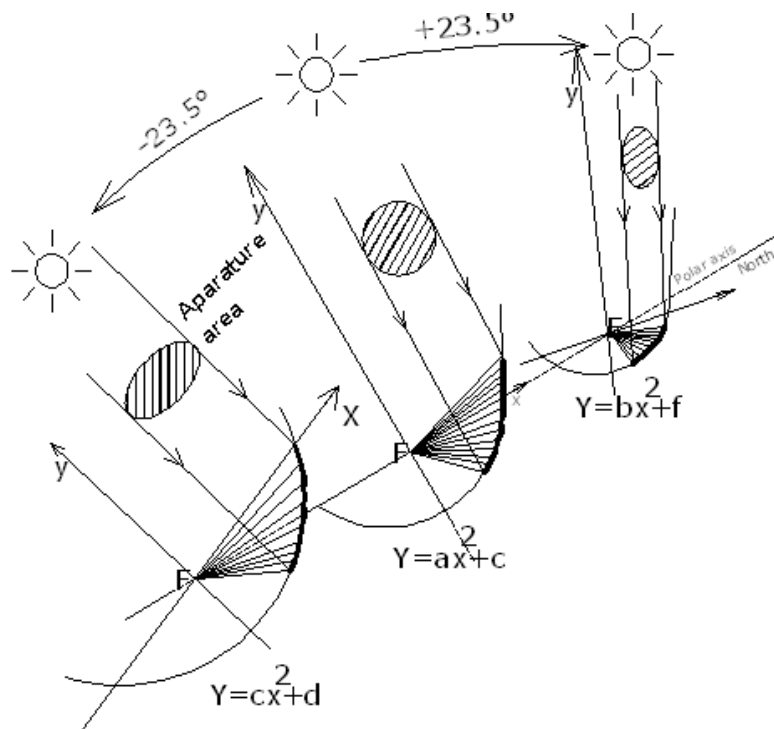


Figure 3.7 Parabolas focusing the sunlight at a fixed focus by moving with the sun

The incident light has to be always parallel to the Scheffler y -axis. Note that in moving with the sun there is a change in the aperture area, the focus F and the center of the Scheffler concentrator (black dot) remain stationary.

3.6 Installation of the Scheffler Concentrator

While installing a Scheffler reflector at any site, the axis of rotation is fixed very precisely at an angle equal to “the latitude of the site” with horizontal in north-south direction. For daily tracking, these reflectors rotate along an axis parallel to polar axis with an angular velocity of one revolution per day to counterbalance the effect of daily earth rotation [1].

Scheffler reflectors are classified as standing reflectors and laying reflectors depending upon the direction of the concentrator face. All standing reflectors face towards south in the northern hemisphere, and north in the southern hemisphere, as well as providing focus at ground level. But the laying reflectors face north in the northern hemisphere, and south in southern hemisphere, as well as providing an elevated focus. The installation detail for standing reflectors in the northern hemisphere (at \emptyset° latitude angle) is shown in Figure 3.8 below.

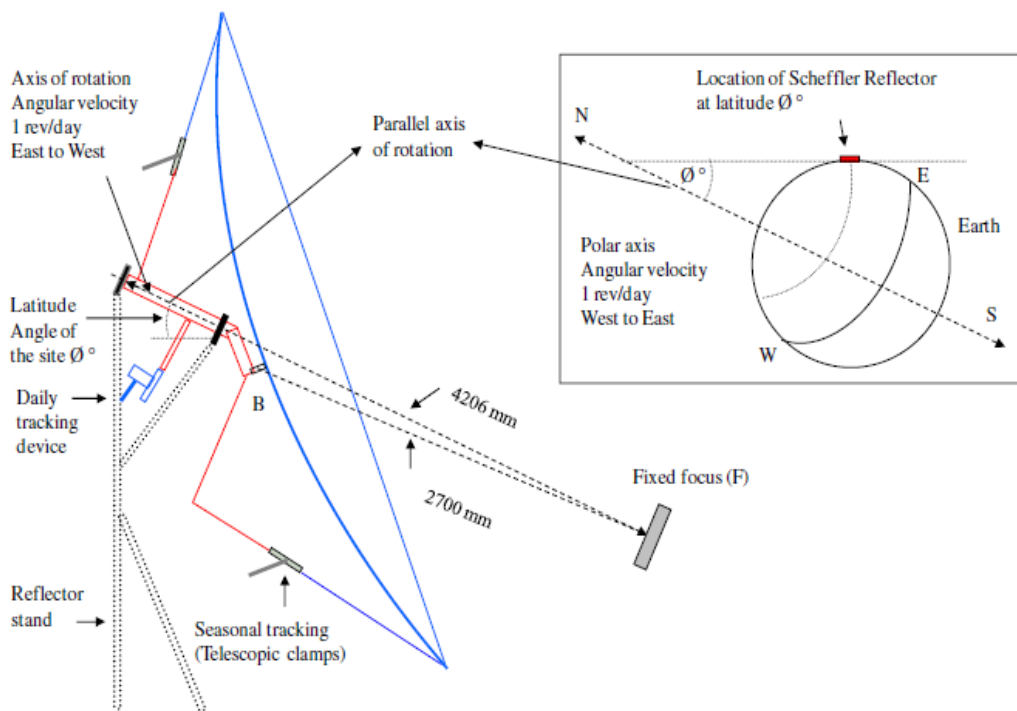


Figure 3.8 Installation and daily tracking details of Scheffler reflector (valid for standing reflectors in northern hemisphere)

Chapter Four

Design of Thermal Storage System

4.1 Introduction

The intermittent nature of solar energy and its diffused nature necessitate thermal energy storage systems for cooking to be in door and time independent. Most solar energy storage systems use sensible heat storage (SHS), though using latent heat storage (LHS) systems would have been considered too. There are many types of sensible heat storage for different applications; molten salt, rock, water, oil, concrete etc usually are used in low and medium temperature solar energy storage systems. In this chapter, the overall design of solar thermal storage system to bake Injera for one baking session of average family size starting from the selection of material for storage medium, volume, material for tank and appropriate insulator for the thermal storage system is discussed.

4.2 Design of Thermal Storage System for Injera Baking

4.2.1 Selection of Thermal Storage Mechanism and Media

In chapter two, the types and methods of selecting thermal storage media were discussed. In this section, the selection of storage medium for cooking purpose is discussed. From technical point of view, the crucial requirements while selecting a storage medium are [15][50]:

- High energy density (per-unit mass or per-unit volume) in the storage material
- Mechanical and chemical stability of storage material/media
- Compatibility between storage medium and other materials
- Complete reversibility for a large number of charging/discharging cycles or prolonged use
- Minimized thermal losses
- Ease of control

i) Sensible Thermal Storage Mechanism

Thermal energy can be stored in any heat storage medium that experience a change in internal energy. The stored energy could be determined by the product of its mass, the average specific heat and the temperature change that the medium undergoes. Besides, other properties like the density, thermal conductivity and diffusivity, vapor pressure,

compatibility among materials, mechanical and chemical stability, heat loss coefficient as a function of the surface areas to volume ratio; cost etc should also be considered in the selection of thermal storage medium [15] [36].

All these requirements and other previous works direct us to select sensible thermal storage medium (temperature change rather than phase changing) of substances [27] [33] [38] [42].

ii) Liquid Thermal Storage Media

Energy storage has been studied for concentrating solar power, CSP applications with sensible heat, latent heat, and thermo chemical reactions [32]. Of these methods, sensible heat storage in an excess volume of heat transfer fluid is preferred due to simplicity and low relative cost. During periods of high irradiance, excess heat will heat the liquid media and is stored for later use in the storage tanks. Thermocline tanks offer a low-cost means of realizing this concept by storing both the hot and cold liquid inside a single reservoir. Buoyancy forces, associated with the variation of the heat transfer fluid density with temperature, maintain stable thermal stratification of the two isothermal volumes. A narrow region of large temperature gradient exists at the interface of these liquid volumes, known as the thermocline or heat-exchange region [9].

The vertical location of this heat-exchange region varies in time as the heat is added and then extracted from the tank. When the heat-exchange region reaches the top of the heat exchanger, the supply of heat is exhausted and the power cycle is no longer supported by the storage system. Such a tank offers significant financial advantages over an alternative two-tank implementation [36].

In some technologies, sensible thermal storage by molten salt has been used. Molten salt is suitable medium for heat storage. It has been used in intermediate and high temperature solar power plants too. In addition to these criteria most solar energy storage systems use non-phase changing or only temperature changing storage Media [8] [15] [38].

A mixture known as heat transfer salt (HTS), which is composed of sodium nitrate and potassium nitrate at different proportion by weight, has been used commercially as a heat transfer fluid [50]. It has been suggested that this salt can be used to store thermal energy as sensible heat in the temperature range of 205 to 540⁰C. The application of molten salt storages has been tested in some solar power plants successfully [39] [42].

Hence, among the three storage methods discussed in chapter two, the sensible storage media by molten salt is selected due to the above reasons.

4.2.2 Properties of Heat Transfer Salts and Mixtures

The table below shows the property of various heat transfer salts with their limitations [29].

Table 4.1 Comparison properties of heat transfer salts for use at high temperatures

Salt Type	Practical temp. range (°C)	Cost (Birr/kg)	Melting point (°C)	Heat capacity (J /kgK)	Film Coefficient, h at 7.5 kw	Limitations
Dowther salt	180-370	6.4	13	2760	600	Leaks readily at seals and glands; poor rate of heat transfer; decomposition causes fouling
Hitec salt	205-540	12.8	142	1560	1400	Storages must be heated or steam traced because of freezing point
Draw salt	260-550	7.3	220	1495	1320	Storages must be heated or steam traced because of freezing point
Na salt	125-760	16.5	98	1300	4000	Requires sealed system; reacts violently with H ₂ O and other materials;
NaK salt	40-760	101.5	18	1050	3000	Requires sealed system; reacts violently with H ₂ O and other materials;
Lead salt	370-930	12.3	327	159	2080	Forms solid oxides that foul heat transfer surfaces and cause corrosion; needs high power; is toxic
Mercury	370-540	255.5	-39	138	1100	Very toxic; installation requires a high inventory Cost

Identification of potential salt for thermal storage system having lower melting points and higher energy density, in addition to being technically superior is the critical step in selecting molten salts for storage of thermal storage systems. This salt should be economically viable and achieve round trip efficiencies including recyclability and reduced environmental impact.

4.2.3 Properties of Hitec and Draw Heat Transfer salts

The heat transfer salts (HTS), Hitec, (marketed by Coastal Chemical Co. a Du Point subsidiary), contains 40% NaNO_2 , 7% NaNO_3 , and 53% KNO_3 by weight and the other heat transfer salt is Draw salt (eutectic) having a composition of 46% NaNO_3 and 54% KNO_3 by weight have been used industrially (e.g., Houdry fixed-bed cracking process used this mixture), practically the properties that have been determined for the 40-7-53 Hitec and 46-54 Draw salts are listed in table below [29].

Table 4.2 Properties of "selected" nitrate-based salts for thermal-energy storage

Property	Hitec	Draw salt (eutectic)
Composition, wt %	40 NaNO_2 , 7 NaNO_3 , 53 KNO_3	46 NaNO_3 , 54 KNO_3
Melting point, °C	142	220
Practical operating temperature range, °C	205-540	260-550
Density, kg/m^3		
At 260°C	1890	1921
At 540°C	1680	1733
Specific heat, $\text{J kg}^{-1}(\text{K})^{-1}$	1560	Not available
Viscosity, Pa/sec		
At 260°C	0.0043	0.0043
At 540°C	0.0012	0.0011
Thermal conductivity, $\text{W m}^{-1}(\text{K})^{-1}$	0.61	0.57
Heat transfer coefficient, $\text{W m}^{-2}(\text{K})^{-1}$	4600-16700	4300-15600

The Hitec mixture melts at 142°C, but appreciable changes in composition do not affect the freezing point markedly. Hitec heat transfer salts have essentially zero vapor pressure in the 142 to 450°C range, and its specific heat is appreciably lower than that of water (approximately 1/3). However, its thermal conductivity is approximately the same and its density is approximately twice as large. The viscosity of this heat transfer salt in its useful temperature range is greater than that of water and the liquid melts by an order of magnitude, but it compares favorably with other heat transfer fluids on the basis of heat-transport

capacity (i.e., the heat transfer per unit time, over a given range of temperature, for varying mass velocity) [30].

Hitec heat transfer salts possess most of the desirable attributes required for a heat transfer medium. Among its favorable "handling" properties are reasonable cost. Hitec heat transfer salt has a low melting point, although impurities formed by thermal decomposition (largely from NaNO_2) gradually elevate the melting point.

The salt mixture is stable in air and in the presence of moisture. It is relatively nontoxic and is nonflammable; however, the molten salt must be kept out of contact with easily oxidized organic materials.

Hitec does not explode spontaneously; however, the molten salt must be prevented from coming into contact with hot carbon since the mixture explodes. Therefore, solid fuel furnaces should not be used [23] [43].

It is known that the chemistry of the thermal stability and the decomposition of Hitec heat transfer salt proceeds via several significant reactions involving sodium nitrite (the least stable component of the three compounds that form Hitec heat transfer salt). However, the generally accepted overall reaction for its decomposition is:



Nitrogen evolution measurements and the above stoichiometry have been employed [38] to estimate the decomposition of Hitec heat transfer salt with time and as a function of temperature [11]. Although these data indicate that a Hitec heat transfer salt system operating between 260 and 520°C might require replacement of about half the nitrite in the mixture annually, industrial experience has been much more favorable. One circulating Hitec heat transfer salt system has been operated under a nitrogen purge at temperatures up to ~500°C for about five years with "minimal" incident and "minor" salt replacement [4]. Another installation [37] believes 10 years of operation at approximately 480 to 510°C under such conditions is achievable. It has been reported [35] that the decomposition of alkali nitrate-nitrite mixtures is catalyzed by iron above 520°C but not by stainless steel. Because the only long-term (18 to 30 months) quantitative data presented were obtained in carbon steel circulation loops, the long-term stability of Hitec heat transfer salt (of varying purity) should be investigated at elevated temperatures (450 to 550°C) in low-alloy steel and stainless steel systems. More specifically the selected salt has the following basic properties [50] [36]:

- Hitec exhibits a liquid operation range of 142–535⁰C
- Freeze prevention and recovery is essential in all salt-based systems to maintain the salt at elevated temperatures and to minimize component damage in the event of a change of phase.
- Low cost (relative to Therminol VP-1 heat transfer oils)
- Good thermal or chemical stability at $\geq 300^{\circ}\text{C}$
- Environmentally friendly (to replace VP-1 heat transfer oil)
- Very low vapor pressure for thermal energy storage
- Compatibility with materials of construction(storage tank)
- Excellent heat transfer fluid properties

On the other hand Draw salt exhibits almost the same physical and chemical property but its storages must be heated otherwise steam will be traced because of freezing point; of course this is a problem for both heat transfer salts but the draw salt container should be kept at a more elevated temperature (220⁰C) than Hitec salt (142⁰C). In addition to these, there is no sufficient physical and chemical available data for Draw salt.

Thus, from the above analysis and heat transfer molten salt properties, Hitec (40% NaN₀2, 7%NaN₀3, and 53%KN₀3 by weight) heat transfer molten salt is chosen for this particular solar thermal storage system design application.

4.3 Heat Required for Injera Baking

The heat used to bake Injera can be defined as the energy necessary to raise the batter to a particular temperature, and evaporate the amount of water that is observed to be lost during the baking process. To measure the energy utilized in cooking Injera, the initial mass of batter, and the total amount of Injera produced from this batter were measured. Thus the mass of water vapor can be obtained by subtracting the mass of the Injera produced from the initial mass of batter. It is assumed that the energy utilized in cooking the Injera is the energy required in raising the batter from room temperature to the boiling point of water which is called sensible heat, plus the energy required to evaporate the water which is called latent heat. It is also assumed that the heat capacity of Injera batter is the same as water in order to calculate the energy required to raise the batter temperature to boiling point of water [17].

Therefore, the utilized heat energy is

$$E_{\text{utilized}} = m_{\text{batter}} \times C_{\text{P water}} \times (T_{\text{boil}} - T_{\text{room}}) + (m_{\text{batter}} - m_{\text{Injera}}) \times h_{\text{vaporization}}$$

where:

m_{batter} - Mass of the batter = 400g

T_{boil} - Boiling temperature of water in Addis Ababa = 92°C

T_{room} - Room temperature in the baking room (Addis Ababa) = 20°C

C_p - Heat capacity of water = 4.187 kJ/kg.K

m_{Injera} - is the mass of the Injera produced = 320g

$h_{\text{vaporization}}$ - Heat of vaporization of water h_{fg} = 2260 kJ/kg

Thus:

$$E_{\text{utilized}} = 0.4\text{kg} \times 4.187\text{kJ/kg} \times (92 - 20)\text{k} + (0.4 - 0.32)\text{kg} \times 226 \text{ kJ/kg}$$
$$= 120.6 \text{ kJ} + 180.8 \text{ kJ}$$

$$E_{\text{utilized}} = \mathbf{301.38 \text{ kJ}}$$

By considering the energy loss in baking the required total energy can be calculated by assuming safety factor of 1.2[40] [17]. Thus the total energy required becomes 361.6 kJ. The time taken for cooking of Injera is about 3 minutes on average. The heat transfer rate (power) required for Injera baking can be calculated as [17]:

$$\dot{Q} = \frac{E_{\text{utilized}}}{\Delta T}$$

$$\dot{Q} = \frac{361.6 \text{ kJ}}{3 \times 60\text{sec}}$$

Thus heat transfer rate required for Injera baking is:

$$\dot{Q} \cong 2 \text{ kw}$$

This result corresponds to the value obtained from electrical mitad suppliers.

4.4 Estimation of Volume of Storage Medium and Tank

In order to determine the volume required to store heat energy for a session of Injera baking for an average family size for four days (about fifty Injera) involves the following steps [33]:

Step I Determination of total energy required for a session of Injera baking

- i. The amount of heat required to bake one Injera as calculated in the above section is
= 361.6 kJ

Total heat required for 50 Injera baking is:

$$= 361.6 \text{ kJ} \times 50$$

$$= 18080 \text{ kJ}$$

- ii. Amount of heat required for heating up a backing mitad (1.5cm thick and 60cm diameter) to a temperature of 220°C is about [3]

$$= 212.72 \text{ kJ}$$

Total heat required

$$= 18080 \text{ kJ} + 212.72 \text{ kJ}$$

$$= 18292.72 \text{ kJ}$$

- iii. Other heat losses or factor of safety [3][40]

$$= 18292.7 \text{ kJ} \times 1.5$$

$$= 27440 \text{ kJ}$$

Therefore, heat required for a single session of Injera baking for average family size is

$$= \mathbf{27440 \text{ kJ}}$$

Step II Determination of total mass of storage medium

- i. Amount of heat required in one session of Injera backing as determined above is

$$= 27440 \text{ kJ}$$

- ii. Latent heat of storage medium (HITEC molten salt) is [38]:

$$= 494 \text{ kJ/kg}$$

- iii. Mass of storage medium required for supplying desired amount of heat is:

$$= 27440 \text{ KJ} / 494 \text{ kJ/kg}$$

$$= 55.54 \text{ kg}$$

60kg of salt may be considered for the storage medium.

Step III Determination of total volume of storage tank

- i. The density of molten salt is 1740kg/m³ (at 400°C, the average working temperature of the molten salt)

- ii. The volume needed = $\frac{m}{\rho} = 60 \text{ kg} / 1740 \text{ kg/m}^3$

$$= 0.0473 \text{ m}^3$$

- iii. Taking into account the thermal expansion of molten salt and the thermal degradation, it can be assumed that the salt chamber may be four times this volume.

$$= 0.0473 \text{ m}^3 \times 4$$

$$= 0.1894\text{m}^3$$

Thus for a cylindrical storage tank of 0.6m diameter and a height of 0.67m, a cylindrical chamber of volume of **0.141m³** is obtained.

4.5 Thermal Storage Tank Material Selection

The storage should allow suitable baking since the mitad by itself is used as heat exchanger. The thermal storage should also be compatible with the baking Mitad. Thus, the tank side wall should be cylindrical shape made of cast steel with minimum carbon content to avoid vigorous reaction with the molten salt of 1.4mm sheet.

The baking Mitad will be above the storage system; but in order to avoid direct contact of the clay Mitad with the medium, cast steel with minimum carbon content having a thickness of 10mm flange will be placed in between to regulate heat transfer as temperature in the medium increases.

The lower bottom of the storage can be of thick cast iron flange of (about 12mm thickness) to resist the high temperature created during heating coming from the secondary reflector to the heat storage medium.

Removable heat insulating plugs shall be used at the lower flange allowing effective heat storage at night, while allowing charging in the sunlight during the day time. The whole system will be well insulated to avoid heat loss.

Table 4.3 Thermal properties of Cast Iron, Cast steel and aluminum

Metal	Temperature [°C]	Thermal conductivity [w/(mK)]	Selected for
Cast steel 1.5%C	20	36	Cylinder wall and upper flange
	400	33	
	1200	29	
Cast Iron	210	38-61	Lower flange

The cast steel 1.5%C is selected because the thermal conductivity decreases as temperature of the system is increasing. Where as pure aluminum is selected for lower flange in order to promote heat transfer to the medium due to its high thermal conductivity. Moreover, these metals are selected because they are available and durable with a reasonable cost. For the

sake of comparison lists of thermal conductivities at different temperature of other metallic materials is listed in the appendix.

When the storage tank is subjected to heat, the salt will start to expand and tries to displace the space occupied by the air over the salt. Hence to allow the outflow of air out of tank, small hole having a diameter of 1mm would be drilled on the sides of the storage tank just near the ceiling. When the salt completely displaces the space in the tank, the hole will be blocked by the salt due to its viscosity.

4.6 Design of Storage Tank

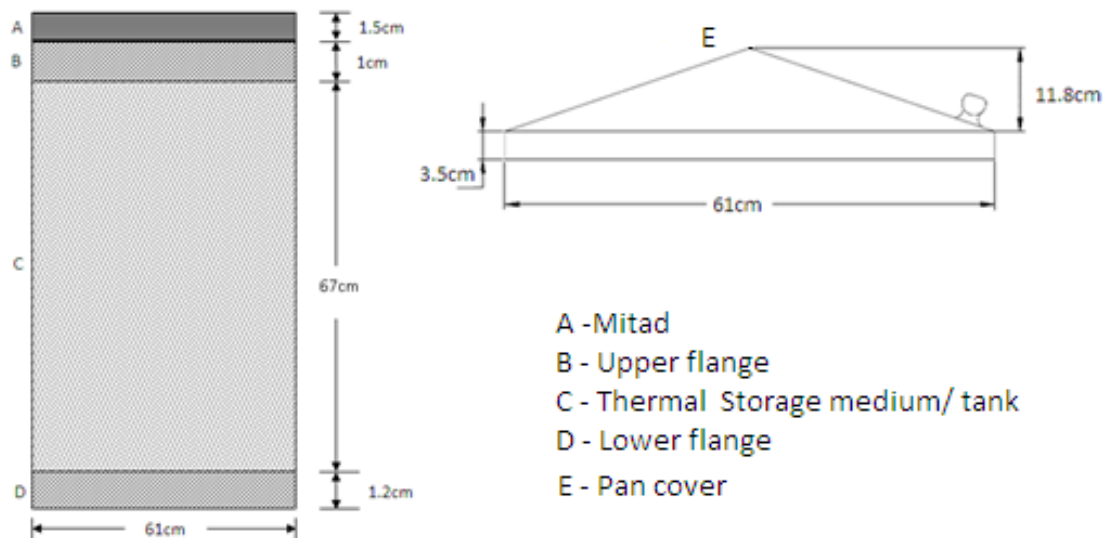


Figure 4.1 Design of Thermal storage system with mitad and its cover

4.7 Selection of Insulating Material

Insulation reduces the transfer of heat from the thermal storage to the surrounding. The basic requirement for thermal insulation is to provide a significant resistance to the flow of heat across the insulation material. To accomplish this, the insulation material must reduce the rate of heat transfer by conduction, convection, or any combination of these mechanisms that would occur during charging and/or backing. Type and thickness of insulation material are the basic parameters in thermal insulation selections. It is advisable to select the correct thickness and material type. The general criteria needed to make a choice among various thermal insulation materials are as follows [31] [50]:

- Surface temperature expected
- The R-value of the material

- Cost of the complete insulating system
- The reason insulation is needed
- The location where insulation will be needed
- Accessibility for the insulated area

4.7.1 Temperature of Working Surfaces

Temperature of the working surface is a decisive factor in the selection of insulating material thickness. The recommended insulation thickness based on upper limit hotness of surfaces at specified temperatures is given in the table below [2].

Table 4.4 Surface temperature and recommended insulation material thickness

Surface temperature (°C)	Insulation thickness (cm)
66	5.10
121	7.60
177	10.20
288	15.20
360	17.20
400	22.90
510	25.44

4.7.2 R-value of Insulating Material

The R-value [K/w] is the reciprocal of the amount of heat energy per area of material per degree difference between the outside and inside of the insulation. It is an indication of resistance to heat flow and is its ability to insulate; the higher the R-value, the better the insulation property will be [31] [53].

For cylindrical insulation (such as circular pipe insulation) of inner radius r_1 , outer radius r_2 , and length L having average thermal conductivity K ; if there is no heat generation in the layer the thermal resistance can be given by [53]:

$$R_{cyl} = \frac{\ln(r_2/r_1)}{2\pi L K}$$

For a cylinder consisting of two layers, the thermal resistance is:

$$R_{total} = R_{cyl,1} + R_{cyl,2}$$

The table shown below, shows list of common insulating materials with their R-value [20].

Table 4.5 R-values of different insulating materials

Material	R-value [m²k/watt]
Hardwood siding (1 in. thick)	0.91
Wood shingles (lapped)	0.87
Brick (4 in. thick)	4.00
Concrete block (filled cores)	1.93
Fiberglass batting (3.5 in. thick)	10.90
Fiberglass batting (6 in. thick)	18.80
Fiberglass board (1 in. thick)	4.35
Cellulose fiber (1 in. thick)	3.70
Flat glass (0.125 in thick)	0.89
Insulating glass (0.25 in space)	1.54
Air space (3.5 in. thick)	1.01
Drywall (0.5 in. thick)	0.45

4.7.3 Cost of Insulating Material

The other variable in the selection of insulating material is the cost per service time of the insulator. The optimum thickness can be determined by obtaining an expression for total cost which is the sum of the expressions for the lost heat cost and insulation cost as a function of thickness.

As thickness of insulation increases, the cost of material will go up. On the other hand, the energy cost savings also goes up, but at a slower rate of increase than the cost of materials and installation [53].

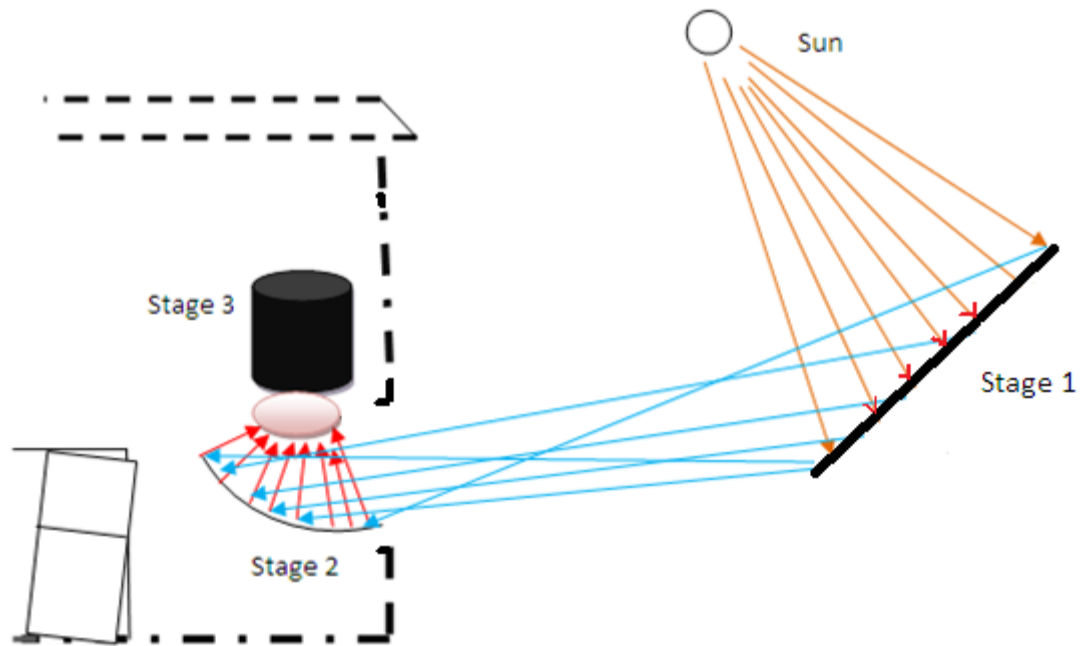
The average working temperature of the cooking system is about 300⁰C. This temperature requires 15 cm thickness in order to stop heat loss. Therefore, due to their availability, affordable cost and appropriate thermal insulating property, we can chose combined insulating material in order to achieve better insulation with minimized cost. These materials are Cellulose fiber and Fiber glass having a total thickness of about 15cm.

Chapter Five

Simulation and Results

5.1 Introduction

In this chapter, the modeling of the primary concentrator and the secondary reflector by SolTrace software and the heat flux that would reach to the thermal storage device will be discussed. The heat flux that would be obtained at the focal point of the secondary reflector or the heat flux reaching at the bottom of the storage will be an input to evaluate the performance (heat up time and heat retention capacity) of the thermal storage system. The performance of the storage system will be evaluated by Ansys software; discussions will be made based on the results. These and related points shall be discussed in this chapter. Figure 5.1 shows the whole set up that it is going to be simulated by SolTrace software.



Stage 1 Scheffler concentrator (optical element)

Stage 2 Secondary reflector (optical element)

Stage 3 Thermal storage system (virtual element)

Figure 5.1 The Scheffler concentrator integrated with the thermal storage via the secondary reflector

5.2 Simulation of Scheffler, Secondary Reflector and Thermal Storage System

5.2.1 The SolTrace

SolTrace is a software tool developed to model concentrating solar power optical systems and analyze their performance. Although originally intended for solar applications, the code can also be used to model and characterize many general optical systems including virtual systems.

It models optical geometries as a series of stages composed of optical elements that possess an extensive variety of available attributes including shape, contour, and optical quality. The software rapidly displays and saves data as scatter plots, flux maps, and can output data for subsequent analysis using other software packages.

5.2.2 Simulating Scheffler Concentrator

The Scheffler concentrator designed in Chapter Three is modeled using SolTrace software and integrated to a virtual storage via a secondary reflector.

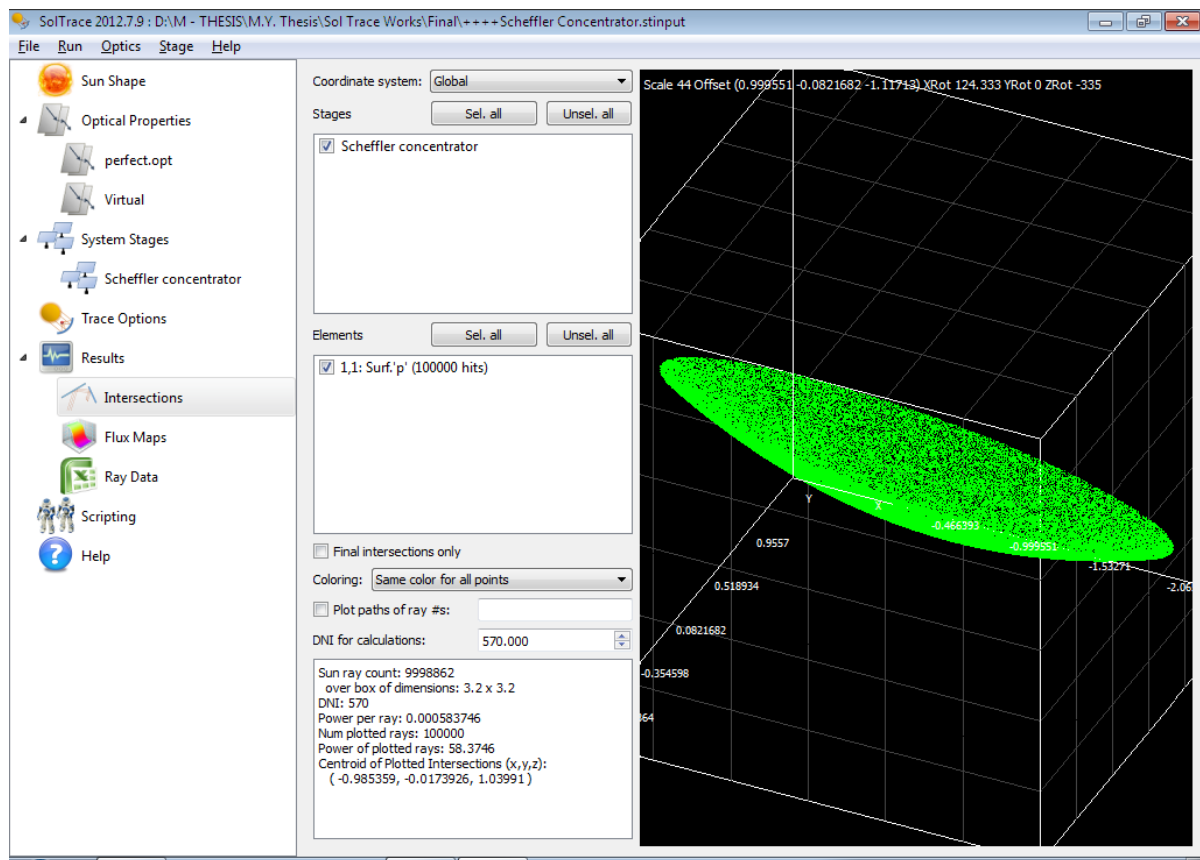


Figure 5.2 Simulation of Scheffler reflector using SolTrace

The mathematical geometry, optical and virtual property of each stage (the Scheffler, the secondary reflector and storage device including the elements in each stage) are inputs to the SolTrace software for particular latitude, solar hour and day of the year and the specific place under consideration.

From this information, the sun direction is determined assuming the z-axis of the global coordinate system pointing due north, the y-axis points towards zenith and the x-axis points due west. This is critical to remember when defining the stages and elements geometry. Figure 5.2 shown above shows simulation of the primary concentrator using SolTrace software with input dimensions and properties as dealt in chapter three.

5.2.3 Simulating Scheffler, Secondary Reflector and Thermal Storage

The simulation of the complete system, (primary concentrator, secondary reflector and thermal storage system) is based on their designs as discussed in the previous chapters.

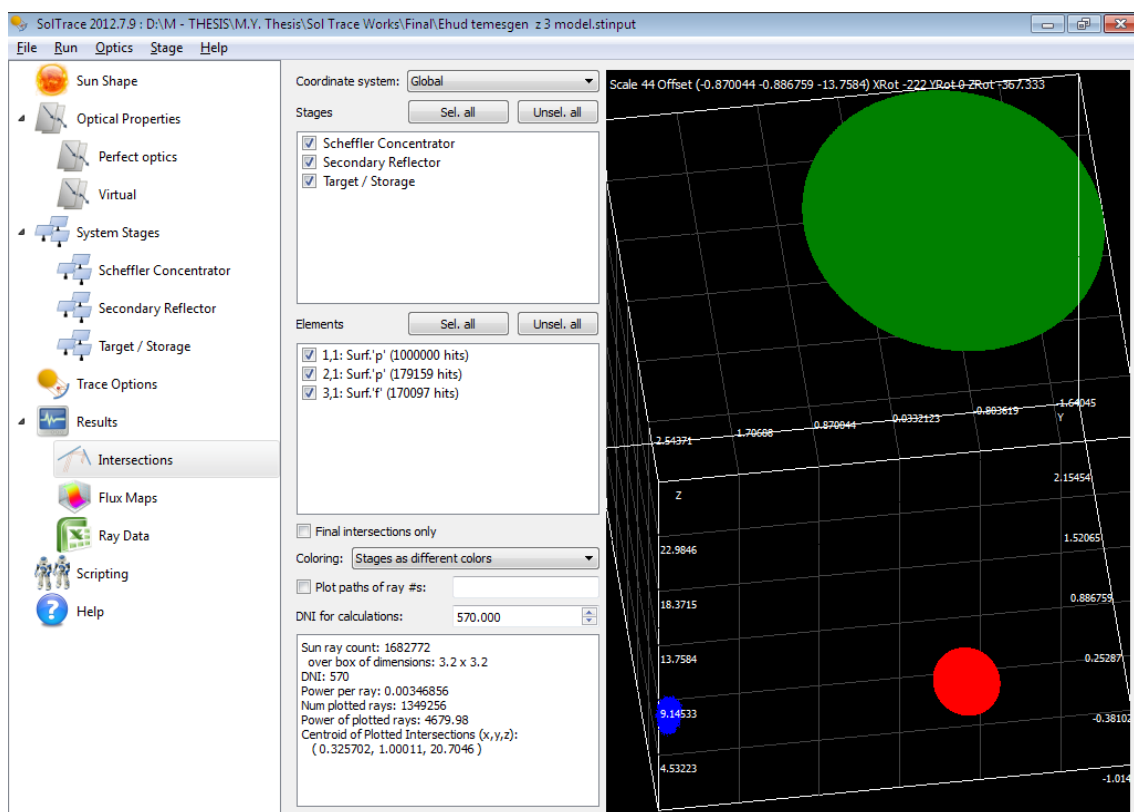


Figure 5.3 Simulation of stages (Green - Scheffler, Red – Secondary Reflector and Blue – Storage)

The above simulation represents for specific latitude, time and day of the year for Addis Ababa at 12:00 AM and the coordinates of the stages are fed as in the following way.

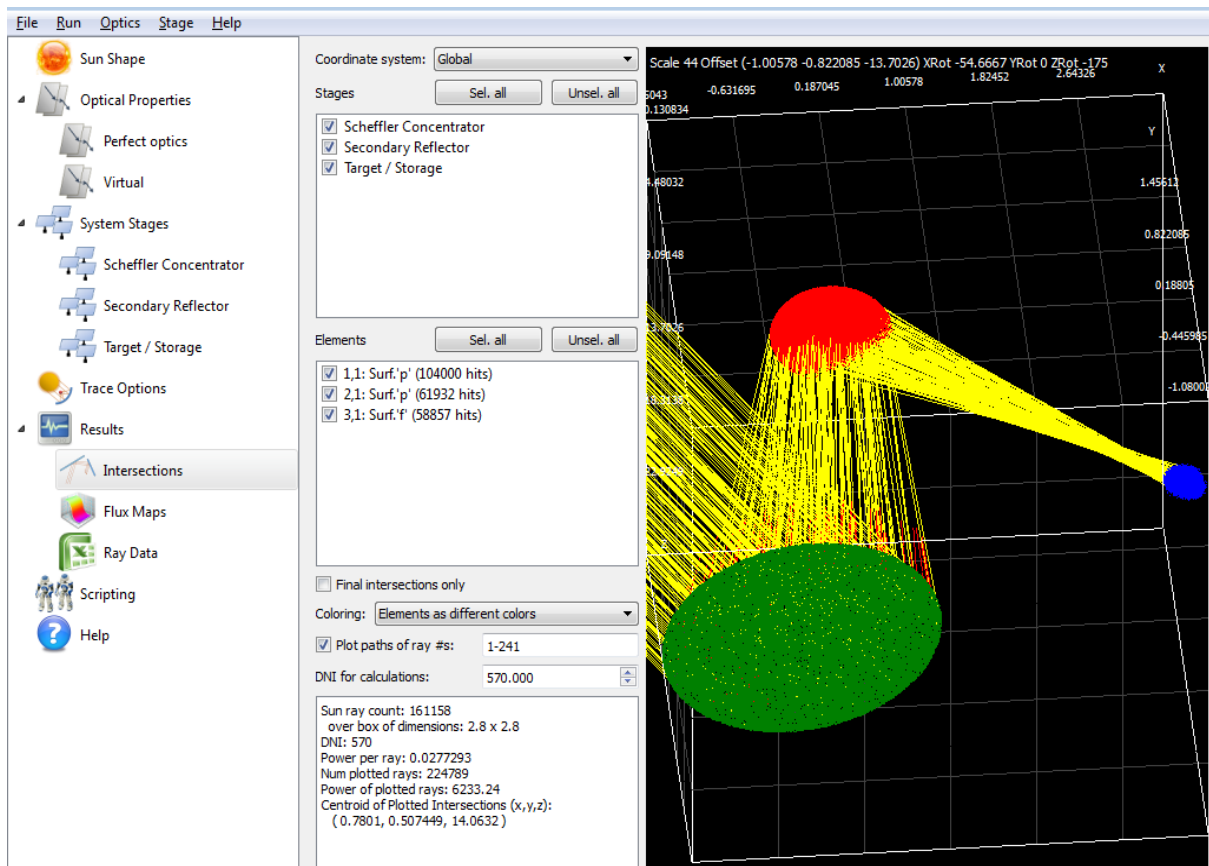
Scheffler= (0, 0, 0) its plane making 135° with the positive x-axis

Secondary Reflector= (2.87, 1.43, 0) its plane making 45° with the positive x-axis

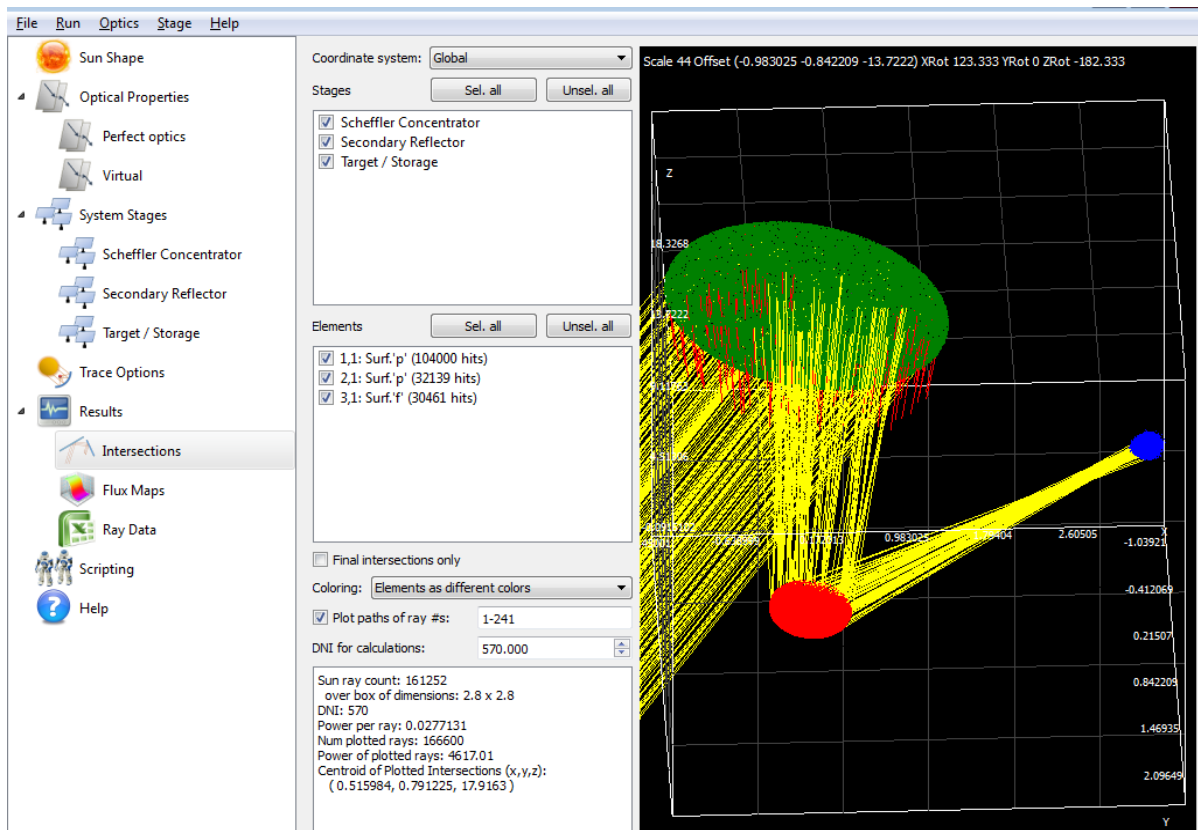
Virtual Stage = (5, 1.44, 0) just at focal point of the secondary reflector

The following figures show the Scheffler tracking the sun and pass on the concentrated ray to the secondary reflector. Then the ray will further be concentrated at the focal point.

The two figures are simulations from different perspectives.



(a)



(b)

Figure 5.4 Intersection plot for reflection and paths showing selected ray paths for certain ray numbers from different views

From the simulation we see red color rays reflected from the primary concentrator missing the secondary reflector along their path because the dimension of the secondary reflector is smaller for the space available in the kitchen and due to the amount of heat flux required for Injera backing. Had it been any other cooking, requiring higher heat flux than Injera backing, we would have made the size of the secondary reflector larger to trap much amount of rays reflected from the Scheffler.

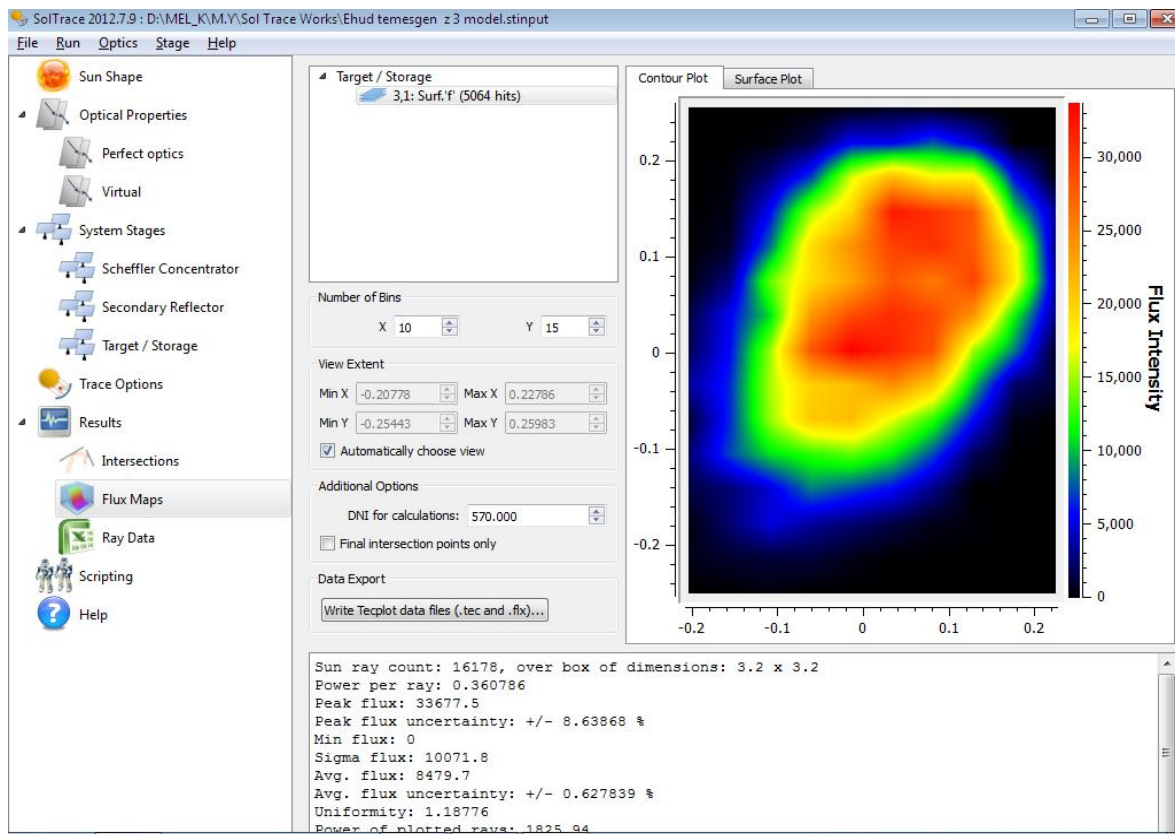
5.2.4 Heat flux at the Virtual Stage (Thermal Storage)

After complete modeling of the system, Direct Normal Irradiation (DNI) of the place (in this case Addis Ababa) which will be an input to find the heat flux reaching the virtual stage, thermal storage, at a given latitude and time of the day will have to be known.

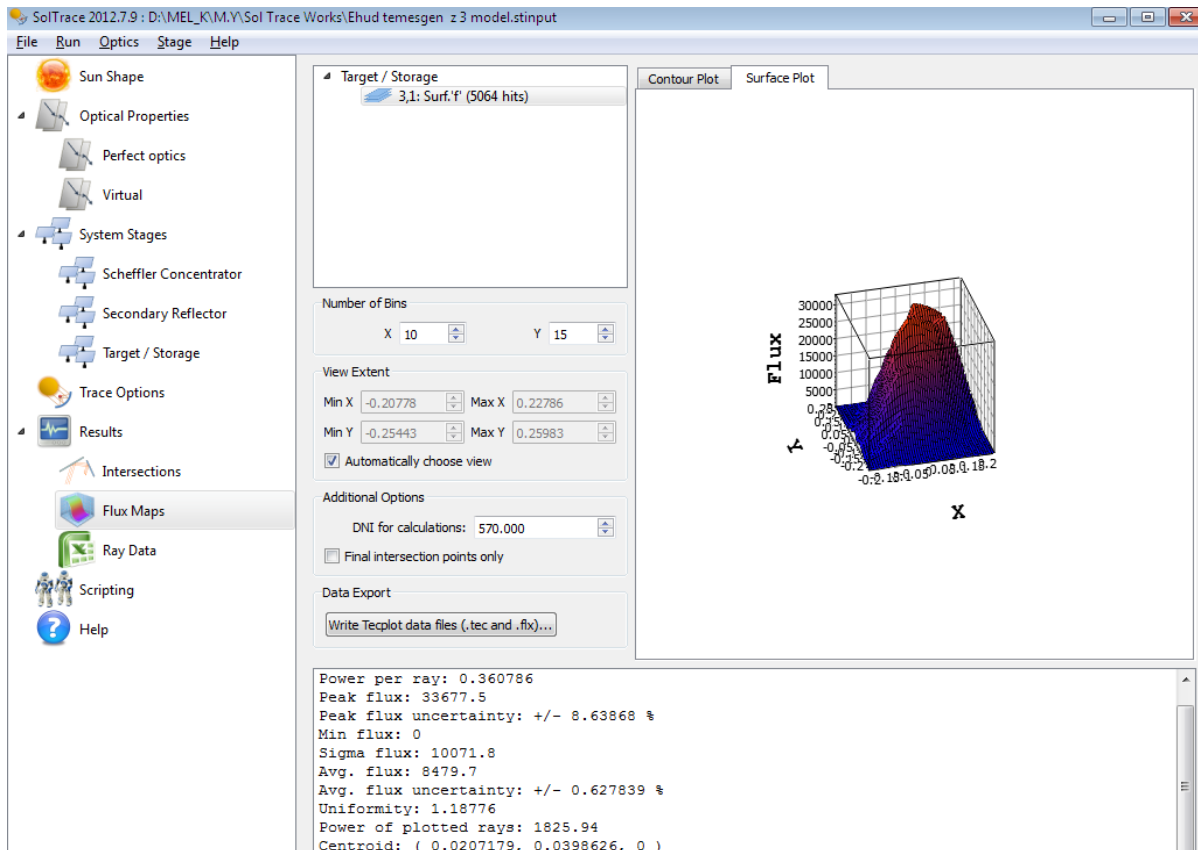
Ethiopia receives a solar irradiation of 5000 – 7000 Wh/m²/day according to the given region and season [16]. The average solar radiation is more or less uniform, around 5.2 kWh/m²/day. The values vary seasonally, from 4.55 to 5.55 kWh/m²/day and with location from

4.25kWh/m²/day in the extreme western lowlands to 6.25kWh/m²/day in northern area of Ethiopia.

The yearly average DNI value of Addis Ababa is 6kWh/m²/day which approximately equals to **570W/m²**. Using this value, the following SolTrace simulation results at the virtual stage (thermal storage system) at a radius of 30cm focal area are obtained. The result of the whole simulation shows: the peak flux, power per ray, peak flux uncertainty, sigma flux, average and minimum fluxes, etc. But the interest lies on the average flux reaching the virtual stage per unit time per unit area as shown below.



(a)



(b)

Figure 5.5 Simulation results (a) Contour Plot and (b) Surface Plot

Results Obtained:

The following results are taken from the flux maps (result) column, but the interest of the research is on the Average flux, ‘Avg. flux’.

Sun ray count: 16178, over box of dimensions: 3.2 x 3.2

Power per ray: 0.360786

Peak flux: 33677.5

Peak flux uncertainty: +/- 8.63868 %

Min flux: 0

Sigma flux: 10071.8

Avg. flux: 8479.7

Avg. flux uncertainty: +/- 0.627839 %

Uniformity: 1.18776

Power of plotted rays: 1825.94

Centroid: (0.0207179, 0.0398626, 0)

These results are obtained on October 1, 2012 at 12:00 AM of Addis Ababa. Similar works could have been done for each day of the year or at least for one representative day from each month of the year. But the DNI data obtained from SWERA for the whole year of Addis Ababa is the same i.e. **570 W /m²** and the different variable will only be the day of the year; thus simulating the system for a single variable i.e. due to days of the year will not result a significant change over the result obtained.

Therefore, for the sake of discussion the average flux found at the focal point of the secondary reflector (at the bottom of the storage device) is taken:

$$Avg. flux = 8479.7W/m^2$$

$$\dot{q}_{solar} = 8.48kW/m^2$$

In chapter four, the rate of heat transfer calculated for Injera baking, which corresponds to the value obtained from electrical mitad manufacturers was:

$$\dot{Q} = 2.0089kW$$

The heat flux per unit time per unit area for the baking mitad will be

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{\dot{Q}}{\pi r^2}$$

Where r is the radius of the backing mitad

Therefore, the heat flux is

$$\dot{q} = \frac{2.0089kW}{\pi(0.3)^2m^2}$$

$$\dot{q} = 7.1kW/m^2$$

When the heat fluxes obtained in the two cases are compared, the solar thermal heat flux obtained from the simulation ($\dot{q}_{solar} = 8.48kW/m^2$) is greater than the value obtained from electrical mitad manufacturers ($\dot{q} = 7.1kW/m^2$). Even though there is a slight difference; it is possible to use the solar power obtained for Injera baking purpose.

5.3 Simulating Performance of Thermal Storage System

The performance (heat up time and heat retention capacity or cooling rate) of the thermal storage system is simulated using Ansys software, because SolTrace does not allow in doing so. Hence equal amount of heat flux reaching the virtual stage (**8.48kW/m²**) will be supplied to the storage device at the lower cast iron flange of the storage system for about 7.5 hours

(the time represents the average daily presence of the source, sun radiation), and let it to cool for about 10 hours (the time shows absence or weak radiation of sun) having the design and material properties as discussed in the previous chapter.

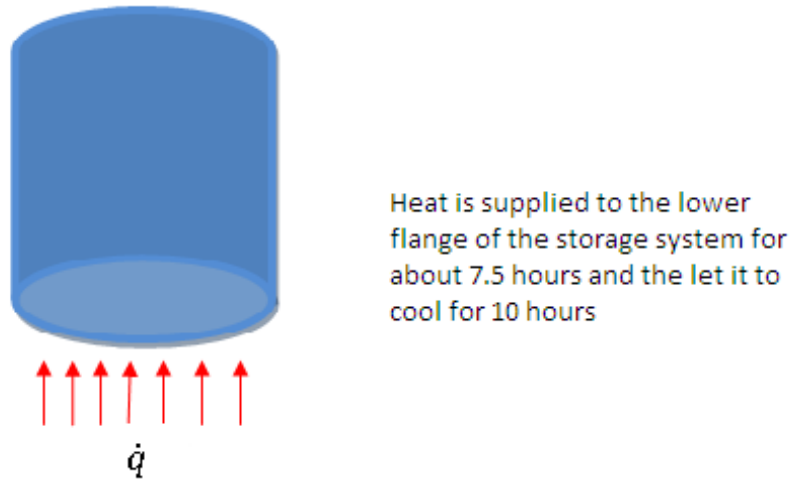


Figure 5.6 The storage system subjected to heat flux

5.3.1 Heating and Cooling of the Thermal Storage System

The thermal storage system is modeled and simulated by considering the following assumptions to see its heat up time and heat retention capacity.

- The heat flow is assumed to be in the vertical direction only
- There is no heat loss from the storage except on the upper surface, where there are convection losses.
- The contribution of the storage tank and both flanges during heating or cooling the storage is negligible as compared to the volume of the storage medium and thickness of the mitad.
- The lower surface of the storage is covered by a removable insulated flange when there is no solar charging; hence there is no heat loss when it is covered (night time).

i. Material properties

a) Salt, Hitec (M 1)

Table 5.1 Property of Hitec molten salt

Property	At 273 K	At 533 K	At 813 K
Thermal Conductivity [W/m K]	0.61	0.61	0.61
Specific Heat [J/Kg K]	1560	1560	1560
Density [Kg/m ³]	1920	1890	1680
Latent Heat [kJ/kg K]	492	492.8	496
Convection heat transfer coefficient [W/m ² K]	4,600-16,700		

b) Mitad, Fire clay (M 2)

Thermal Conductivity [W/m K] = 1.32

Specific Heat [J/Kg K] = 800

Density [Kg/m³] = 2400

ii. Initial Boundary Conditions

Temperature of salt, $T_s \sim$ = Temperature of Mitad, $T_m = 298K$

Heat Flux supplied to the storage = $8.48kW/m^2$

iii. Convection Boundary Condition

Convection Coefficient (Film coefficient) = $18.4W/(k.m^2)$

Ambient Temperature = 298K

iv. Interface Boundary Condition

The boundary conditions at an interface are based on the requirements that the two bodies in contact must have the same temperature at the area of contact. The interface between the storage medium (salt) and mitad cannot store energy, and thus the heat flux on the two sides of an interface must be the same. Thus the boundary conditions at the interface x_o of the salt and baking pan is

$$-K_s \frac{\partial T_s(x_o, t)}{\partial x} = -K_m \frac{\partial T_m(x_o, t)}{\partial x}$$

Where, K_s and K_m are thermal conductivities of salt and mitad respectively and T_s and T_m are temperature of salt and mitad respectively at a given time t .

v. Insulated boundary condition

Heat transfer through an adequately insulated surface can be taken as zero. Thus, the boundary condition on the sides of the storage tank and at the lower cast iron flange is zero (when there is no radiation the lower flange is covered by removable insulated flange); i.e. the temperature gradient in the direction normal to the insulated surfaces is therefore, zero.

$$k \frac{\partial T(0, t)}{\partial x} = \frac{\partial T(0, t)}{\partial x} = 0$$

5.3.2 Modeling Heat Storage Tank

Using the above material properties, boundary conditions and assumptions made previously, the storage system is modeled in Ansys workbench as shown below. Nodal temperature at the mitad surface for heating and cooling is simulated with respect to time.

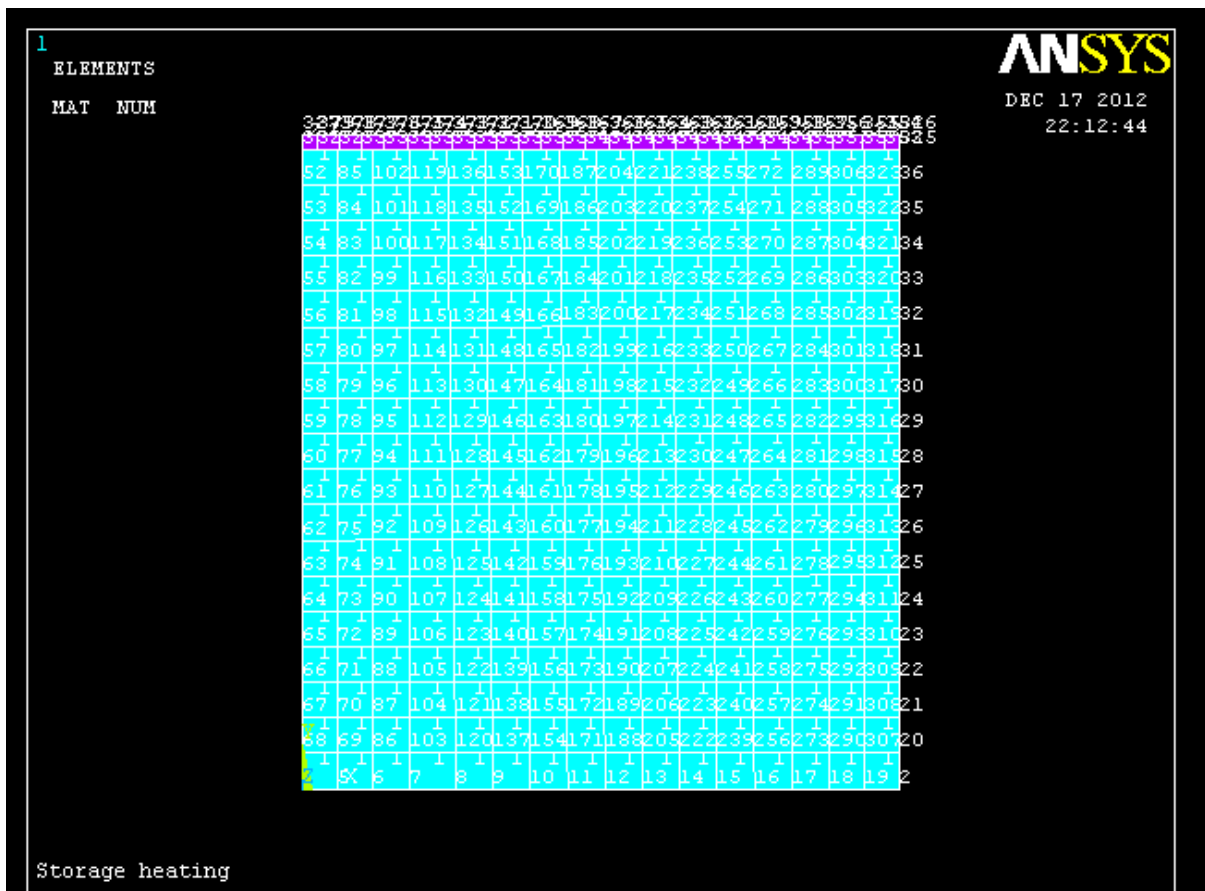


Figure 5.7 Modeling of the storage system and mitad

i) Heat up time (Charging)

During heating of the storage, a heat flux of 8.48kW/m^2 is applied at the bottom of the storage.

The graph shown below (figure 5.8) is temperature in K versus time in hr which shows the time required to reach the maximum temperature in the day time at the Injera backing pan (mitad) surface considering that the pan surface is exposed to convection heat losses.

Maximum temperature of 586K (313°C) is registered at the pan surface and the time required to reach this maximum temperature is about 1 hour only.

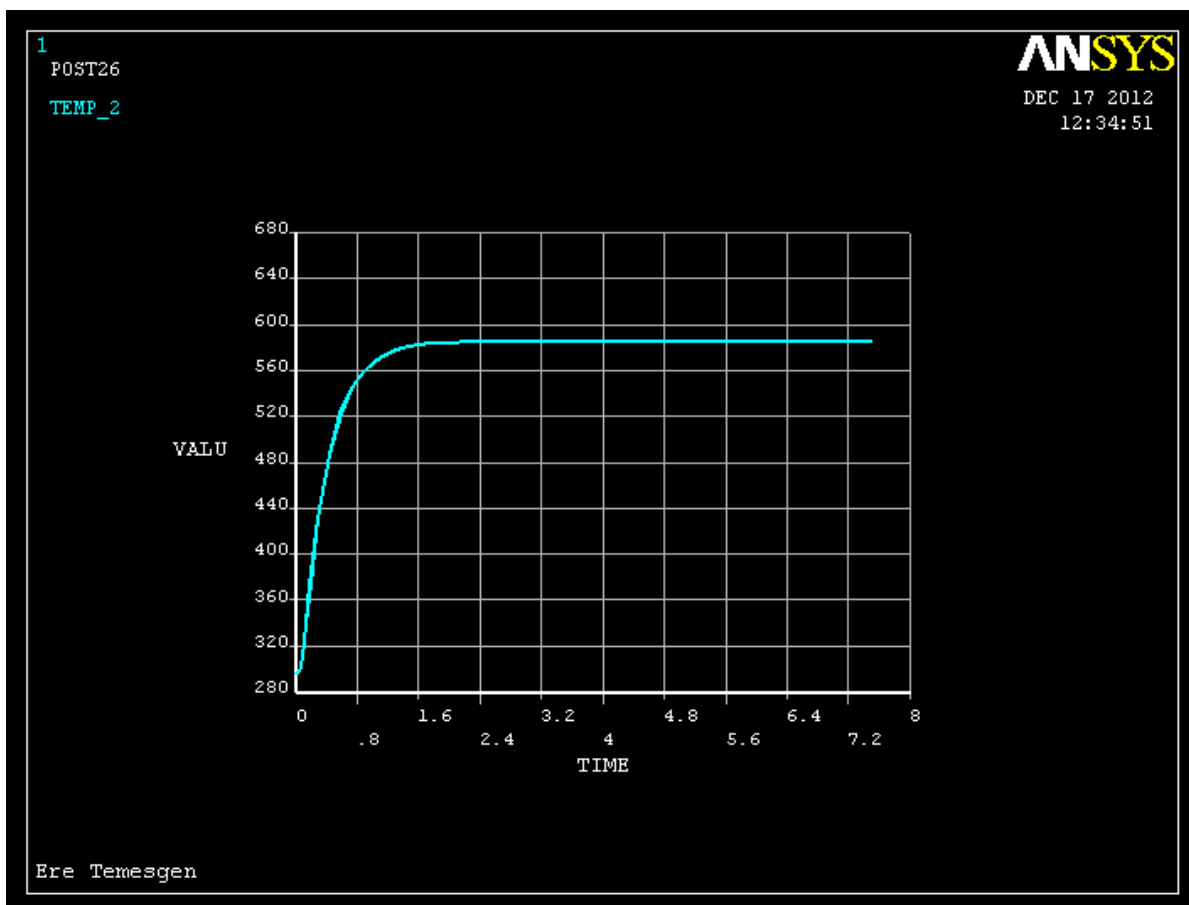


Figure 5.8 Temperature and heat up time of nodes at the surface of baking pan

ii) Heat retention Capacity (Cooling Rate)

To see the heat retention capacity of the storage, it is assumed that there is no solar radiation (for example the evening or the sun is covered by cloud etc); hence, the imposed heat flux is removed and the upper surface is left to cool by convection with constant bulk temperature of 15°C ; the lower surface is also covered by removable insulated plug to prevent heat losses.

During cooling, the system is constrained to an initial temperature of 586°K which is obtained during charging in the day time (heating phase) of the storage system and left to cool for 10 hours which represents absence of radiation (night time).

In this case, the temperature on the pan surface is assumed to be at a bulk temperature which is lower than the ambient temperature to represent the temperature of the batter which is about 15°C .

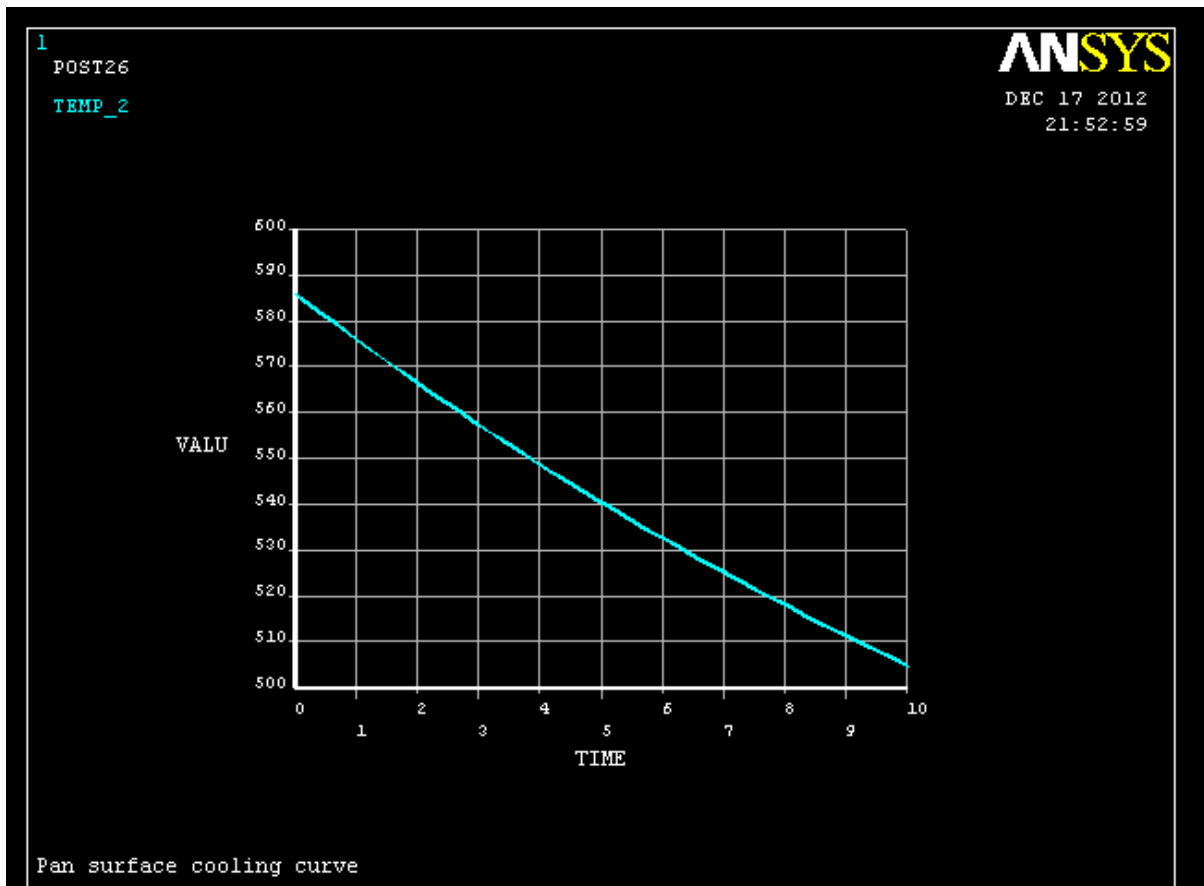


Figure 5.9 Temperature and cooling time of nodes on the surface of the pan

As we can see from the graph the cooling rate is about 8K per hour and the minimum nodal temperature obtained on the surface of the pan at the end of 10 hours is 506K (233°C).

The nodal temperature obtained at the pan surface at the end of cooling period is potential enough to bake Injera; since the temperature required to bake Injera is almost equal to the boiling temperature of water at Addis Ababa. Moreover, it is assumed that the heat capacity of Injera batter is the same as that of water in order to raise the batter temperature to boiling point of water. [17]

Chapter Six

Conclusion and Recommendation

6.1 Conclusion

The integration of primary concentrator, secondary reflector and the thermal storage helps to utilize solar energy in countries like Ethiopia, where there is adequate solar irradiation. This combination can be used for any kind of cooking both in the day as well as night time; thus, the solar cooker designed in this thesis has a potential to bake Injera when the radiation is low as compared to other solar cookers which are only capable of cooking whenever there is radiation only.

Hence the integration reduces the dependence on biomass fuels and their adverse environmental effects. Moreover, groups of society whom they are directly close to biomass fuel collection and utilization will be saved from both immediate and long term harmful effects of burning of fossil fuels.

The designed solar thermal storage system is consistent with the Injera baking system which will allow cooking to be done indoor, in addition to using it both in the day as well as in the evening.

The system only has an initial cost, and it doesn't produce any toxic gases and has no hazardous impact on the environment as a whole.

Hitec molten salt is very effective heat storage medium, tested due to its high operating temperature, high initial boiling point, low vapor pressure, non-corrosive, non-toxic, high heat transfer coefficient, thermal stability, and availability and relatively low cost. Moreover it has high heat retention capacity for a long time after the power source disappeared. The thermal storage system was also successfully designed and simulated indicating thermal retention times sufficient for cooking into the evening.

The maximum temperature obtained by simulation on the baking pan surface was seen to be about 313⁰C during charging and 233⁰C after cooling which can allow Injera baking for the average size of a family in one session of baking.

6.2 Recommendations

An interesting problem that would arise in practical sense is how to minimize heat loss when there is no cooking, and maximizing heat transfer when cooking is in progress. To this end, it will need both practical and computer optimization to get effective method of heat storage.

The heat flux obtained by the simulation would be greater for Injera baking; but it is possible to redesign the size of the secondary reflector during prototype development so that the heat flux required can be obtained.

This preliminary design can be taken as a spring board to produce a prototype. Within the given constraints, making a solar cooker with traditional means is not easy task.

However, this design though may face greater practical difficulties; it will be a starting point to do so. It is cost effective and the materials which would be used can easily be available.

To manufacture the whole setup using available materials, most of mechanical workshops can be used.

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Appendix

Thermal Conductivity of Some Common Metals

Thermal Conductivity (k) - is the quantity of heat transmitted, due to unit temperature gradient, in unit time under steady conditions in a direction normal to a surface of unit area.

$$1 \text{ Btu}/(\text{hr } ^\circ\text{F ft}^2/\text{ft}) = 1 \text{ Btu}/(\text{hr } ^\circ\text{F ft}) = 1.731 \text{ W}/(\text{m K}) = 1.488 \text{ kcal}/(\text{h m } ^\circ\text{C})$$

$$T(^{\circ}\text{C}) = 5/9[T(^{\circ}\text{F}) - 32]$$

Metal	Temperature, T ($^{\circ}\text{F}$)	Thermal Conductivity, k ($\text{Btu}/(\text{hr } ^\circ\text{F ft})$)
Admiralty Brass	68	64
Aluminum, pure	68	118
	200	124
	400	144
Aluminum Bronze	68	44
Antimony	68	10.7
Beryllium	68	126
Beryllium Copper	68	38
Bismuth	68	4.9
Cadmium	68	54
Carbon Steel, max 0.5% C	68	31
Carbon Steel, max 1.5% C	68	21
	752	19
	2192	17
Cartridge brass (UNS C26000)	68	69.4
Cast Iron, gray	70	27 – 46
Chromium	68	52
Cobalt	68	40
	68	223

Copper, pure	572	213
	1112	204
Copper bronze (75% Cu, 25% Sn)	68	15
Copper brass (70% Cu, 30% Zi)	68	64
Cupronickel	68	17
Gold	68	182
Hastelloy B	-	6
Hastelloy C	70	5
Inconel	70 – 212	8.4
Incoloy	32 – 212	6.8
Iridium	68	85
Iron, nodular pearlitic	212	18
Iron, pure	68	42
	572	32
	1832	20
Iron, wrought	68	34
Lead	68	20
	572	17.2
Manganese Bronze	68	61
Magnesium	68	91.9
Mercury	68	4.85
Molybdenum	68	81
Monel	32 - 212	15
Nickel	68	52
Nickel Wrought	32 - 212	35 – 52
Niobium (Columbium)	68	30
Osmium	68	35
Phosphor bronze (10% Sn, UNS C52400)	68	28.9
Platinum	68	42
Plutonium	68	4.6
Potassium	68	57.8

Red Brass	68	92
Rhodium	68	86.7
Selenium	68	0.3
Silicon	68	48.3
Silver, pure	68	235
Sodium	68	77.5
Stainless Steel	68	7-26
Tantalum	68	31
Thorium	68	24
Tin	32	36 – 39
Titanium	68	11 – 13
Tungsten	68	94 – 100
Uranium	68	14
Vanadium	68	35
Wrought Carbon Steel	32	34
Yellow Brass	68	67
Zinc	-	67
Zirconium	-	145

CANDIDATE’S DECLARATION

I, the undersigned, declare that this thesis entitled “Integration of Scheffler Concentrator and Thermal Storage Device for Indoor Injera Baking” is my own original work and has not been presented for a degree in any University, and that all the source of materials used for the Thesis has been duly acknowledged.

Melkamu Yayeh
(Candidate)

Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

Dr. –Ing. Demiss Alemu
(Advisor)

Date