Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Design, Simulation, Manufacturing and Testing of A Low-Cost Tube Type Direct Solar Oven

A Thesis Submitted to the School of Graduate Studies Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Mechanical Engineering (Thermal and Energy Conversion Chair)

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This is to certify that the thesis presented by Yonael Tesfaye Aragaw, titled as "Design, Simulation, Manufacturing and Testing of a Low-Cost Tube Type Direct Solar Oven" and submitted to the School of Mechanical and Industrial Engineering in the partial fulfillment of the requirements for the award of the degree of masters of science in Thermal Engineering with the regulations of the university, and meet accepted standards with respect to originality and quality.

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Declaration

I hereby confidently declare that the work which is being presented in this MSc thesis entitled as "Design, Simulation, Manufacturing and Testing of a Tube Type Direct Solar Oven" is the original work of my own, has not been presented for a degree of any university and all the resource of materials used for this thesis have been duly acknowledged.

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ABSTRACT

Ethiopia is rated as number four country in the world for solar cooking potential by the Solar Cookers International (SCI) in 2020. The country had an estimate of 24,200,000 people who live in areas that have good solar cooking power potential but with fuel scarcity. Shortage of electrical coverage in most parts of the country has led to high biomass dependency for energy demand. The household baking accounting for more than half of this energy, the country faces a great deforestation scale of around 200,000ha per year. Indoor pollution and hard labor of women and children are also results of this situation. Thus, this research focuses on designing, simulating, manufacturing and testing of a tube type direct solar oven which is low cost and easy to manufacture at the local markets of Ethiopia. The tube type direct solar oven is designed to bake 1kg of bread dough. It has a cylindrical oven inside an air tight transparent tube that acts as an insulation for the oven. For low cost and ease of fabrication the air tight transparent outer cover is a square prism made of 4 plastic (acrylic) plates. The solar oven is made of light materials which are easy to find locally. Thus, it has the advantage of being portable and affordable. Simulation of the solar ray's trajectory using COMSOL Multiphysics showed that all the incidence rays falling on the parabolic trough will reflect back on to the receiver for a 0^{o} incidence angle. And the bread baking simulation using COMSOL took 35min to bake 1kg of bread dough which is 5minutes longer than the analytical design. Tests conducted on the manufactured solar oven showed that the standard cooking power of the solar oven at $700W/m^2$ is 98W. The actual bread baking time of the oven was longer than the designed and simulated results due to quality in manufacturing and quality of materials used. But the economic analysis showed that the tube type direct solar oven is al low-cost effective baking tool with a short payback period resulting in an initial investment of $100 and a maximum payback period of 4months and 24days. Thus, the tube type direct solar oven is an easy to manufacture, easy to use low-cost direct solar oven that has a potential of being widely accepted by the Ethiopian society for its economic and environmental advantages.

Keywords: *Tube type direct solar oven, air tight cover, MATLAB, COMSOL Multiphysics, standard cooking power, thermal efficiency, utilization efficiency and payback period*

Table of Contents

CHAPTER ONE

INTRODUCTION

1.1. Background

We use energy for everything in the house and outside the house and basically to perform daily tasks. Long term survival and well-being of humans and societies highly depend on access to energy. Thus, with increase in population and the development of a community (or a country) energy demand increases greatly. Due to this, developing countries have showed a great increase in energy demand during the recent years. The International Energy Agency (IEA) projects thatdemand for energy will increase from about 13,400 million tons of oil equivalent (Mtoe) in 2012 to 18,300 Mtoe in 2040—a 37 percent increase, with most of the growth coming from developing countries (World Bank, 2016).

Ethiopia, being a country with fast economic growth, with an average of 10.8% growth rate in the past 15 years, is experiencing an enormously growing energy demand which is expected to rise 10-14% by 2037 (World Bank, 2016). Due to this, the Ethiopian government has tried to expand electricity grid to nearly 60 percent of the country with in the past five years but the total electricity coverage of Ethiopia was 48.27% in 2019 (World Bank, 2019). Thus, with more than 60 million people without access to electricity. Ethiopia still has the second largest energy access deficit in Africa (World Bank, 2019). Thus, the countries energy demand remains highly dependent on biomass. Households and transportation segments were the two-leading energy-consuming sectors. About 93% of the overall primary energy consumption is used by households, followed by transportation (5%), industry, and services share 1% each. Commercial energy consumption for farming is insignificant owing to a subsistent farming method driven by animal and human power (Mekonnen et al., 2020; Tucho et al., 2014).

This has led to a deforestation scale of around 150,000ha - 200,000ha per year (Gashaw et al., 2015). And with baking accounting for more than 50% of household energy consumption (SNV, 2016), biomass has become the main cooking fuel in Ethiopia. The high dependency on biomass results in large in-house pollution, hard labor of women and children, desertification, loss of biodiversity and famine. Due to this, the government together with international partners have launched many projects in order to reduce the use of biomass in households. Many improved stoves have been distributed in the country since 2006 which includes Mirt Stove and Tikikil Stove, which were able to save 300-575kg of wood per household per year (EnDev Ethiopia, 2014).

Ethiopia is rated number four country in terms of solar cooking potential and the estimated number of people in Ethiopia with fuel scarcity but ample sun in 2020 is 24,200,000 (Solar Cookers International, 2020). Ethiopia receives a solar irradiation of 5000 – 7000 $Wh/m^2/day$ according to regional and seasonal data. Thus, the country has great potential for the use of solar energy. The average solar radiation is more or less uniform, around 5.2 $kWh/m^2/day$. The values vary seasonally, from 4.55-5.55 $kWh/m^2/day$ and with a location from 4.25 $kWh/m^2/day$ in the extreme western lowlands to 6.25 $kWh/m^2/day$ in Adigrat area. But not even 10% of this energy have been harnessed yet (Bogale et al., 2017). Due to this, different introductory programs and trainings on solar technologies were conducted in the country through universities and other governmental institutions by NGOs (Solar Cooking Wiki, 2020). But solar technology is still at its infancy at the household level in Ethiopia.. REEEP in its 2014 report noted that it faced great difficulties in distributing solar irrigation pumps in Ethiopia compared to other countries. The report mentioned that Ethiopia proved to be a challenging environment for private sector development. Some of the major reasons for this being, import regulations, high in-country manufacturing cost, limited manufacturing capacity in terms of facilities and lack of skilled manpower. These conditions prevented the establishment of a production facility for the product in Ethiopia (REEEP, 2014).

But in many cases, globally, the demand for biomass fuels far outweighs sustainable supply which leads to deforestation, land degradation and desertification. Also, dwindling resources lead to an additional workload for women and children as they have to spend more time searching for firewood. The fuel they find is often of a lower grade and thus burns with more smoke and less heat which creates an indoor pollution which is a cause of death for 4.3millions of people around the world every year (WHO, 2017). The Fuelwood is often collected on a daily basis and has no time to dry before use. This makes the use less efficient as some heat is wasted to drive the moisture out of the wood. Also, the moist fuel results in more smoke. All these urges us to use the highly available solar energy resource in the country and come up with a reliable, affordable and simple solar cooking and baking technology, which has the potential to be widely accepted by the household sector.

Many researches and projects conducted by different universities of Ethiopia and abroad shows that solar thermal baking technologies have potential in penetrating in to the society. The different findings of these researches are discussed in the literature review part of this thesis. Thus, it is a necessity to develop a reliable solar baking technology that is affordable and easy to manufacture, if we want to reduce the excessive use of biomass in the country. This can be achieved by using previous researches as a foot step and combining their different findings in developing a reliable solar baking technology.

1.2. Statement of the problem

Ethiopia is a country with high solar cooking potential (Solar Cookers International, 2020), but not even one percent of this energy has been exploited (Hailu et al., 2020). One of the many reasons for this is limited manufacturing capacity in terms of facilities and skilled man power in the privet sector and import regulations concerning foreign currency (REEEP, 2014). Cooking in the country is still highly dependent on biomass with 99% of the rural and 80% of urban households using biomass as their main energy source for cooking (EnDev Ethiopia, 2014). This has led to an indoor air pollution which is responsible for the death of more than 5,000 people yearly in Ethiopia and which is also a cause for nearly 5% of the burden of disease in the country (Sanbata et al., 2014). Thus, an effective solar baking technology that is low cost and easy to manufacture locally in Ethiopia will have the potential to reduce the use of biomass in the household sectors of the country. And this will reduce the indoor air pollution by substituting it with clean energy.

1.3. Objectives

The general objective of the research is to manufacture a low-cost tube type direct solar oven for bread baking application in Ethiopia.

The Specific objectives include;

- Design of a tube type direct solar oven using MATLAB.
- Perform simulation using COMSOL Multiphysics 5.5.
- Develop a prototype and evaluate its performance.
- Perform economic analysis of the solar oven.

1.4. Significance of the research

The research aims to reduce the use of biomass for household cooking by introducing a low cost direct solar baking technology that is easy to manufacture. Thus, this research focuses on designing and manufacturing of a tube type direct solar oven which is affordable and able to be produced locally in Ethiopia. And such a technology has the potential to gain wide acceptance by the society and be able to penetrate in to their livelihoods easily. Therefore, the dependency of the society on biomass can be reduced, which in turn results in a decrease of indoor air pollution and deforestation. It will also reduce hard labor of women and children. The cooking and baking of food with renewable energy like solar will also have some impact on the cost of food, as it reduces the cost of energy in the baking process. At the same time, the introduction of a widely acceptable solar technology for baking will increase the interest of the Ethiopian society in renewable energy and encourage many researchers to participate in this area and bring forward other reliable technologies for the society.

1.5. Limitations

Even though, the research aims to manufacture a solar thermal baking technology that can be applicable in different rural and urban parts of Ethiopia, due to lack of time and data the research will focus only on the applicability of the technology in Addis Ababa. The other limitation is that the solar oven is designed for household cooking and baking application of different meals, but the research scope will only focus on the oven's performance to bake bread for household and commercial uses, due to lack of time. The accuracy of the simulation output will also be limited by the exactness of the input data to the experimental setup, as it is difficult to develop a prototype which has the exact material and geometry.

1.6. Organization of the research

The structure of the research is organized as follows: chapter one discusses about the introduction of the research which includes background of the research, problem statement and objective of the research. Chapter two discusses reviews of different researches in this area. Chapter three discusses about materials and methods used for the research, while chapter 4 shows the design and simulation of the research. Manufacturing and testing of the prototype are included in chapter 5 and data analysis along with discussions are included in chapter 6. The final chapter discusses about conclusions and recommendations for future works.

CHAPTER TWO
LITERATURE REVIEW

2.1. Bread Baking

Bread baking is a process that requires very high temperatures, typically between 160 and 250°C. Thus, it is one of the most energy demanding processes. It is estimated that baking bread consumes two to five times more energy than other thermal treatments normally applied to food, with an average consumption rate of around 4MJ/Kg (Le-Bail et al., 2010). A bread can be made with different ingredients and the flour can also be wheat, rice, potato, maize or other. Therefore, with different composition the demand in energy for baking and the temperature required is also different. But the focus of this review section will be solely on the energy requirements for baking a wheat bread, since the thesis focuses on solar baking of a white wheat bread.

The heat transfer in bread making can be seen in two parts, surface heating and core heating. The surface temperature quickly reaches 100 ºC and then approaches slowly to oven air temperature. This rapid increase in surface temperature is to the low thermal conductivity of bread dough which limits the bread core from reaching high temperature at the same time. Due to this, the heating rate at the crust can reach up to 14.4ºC/min while the heating rate at the core is below 3ºC/min (Vanin et al., 2009). And the slow rise in temperature at the crust after 100ºC is because of difference in water content between the surface and the core: water evaporates from the surfaces more quickly than it can be transported from the core; in addition, due to the evaporation-condensation-diffusion mechanism, water content remains almost constant at the core. The crust will finally have a water content which is below 20% by mass than at the core (Vanin et al., 2009). A bread is considered ‘baked’ when its core temperature reaches 92°C - 95°C (Cauvain et al., 2007).

Baking of industrial panned-wheat bread using the conventional tunnel oven takes about 27 minutes to bake and the baking process can be seen in four stages (Stear, 1990). The initial stage has a temperature setting of 203°C for a period of 7min, which is 25% of the total baking time. In this stage the outer layer of the crumb increases in temperature at an average rate of 5°C/min. The second and third stages takes about 14 minutes, which is around 50% of the total baking time. Oven temperature is held constant at these stages at 240°C and the crumb-temperature increases at the rate of about 5·5°C/min. during the second stage, until it acquires a level of 98 to 99°C at the commencement of stage three, thereafter remaining constant. After the surface temperature reaches 100°C, all the water at the bread surface evaporates and crust starts to form. When the crust temperature reaches 150 to 206°C the crust acquires the typical brown coloration due to caramelization. Over 200 aroma and flavor development substances have been identified. The final stage is maintained at a constant temperature of 221- 240°C, serving to firm-up the cell walls, and produce the desired crust color intensity. This stage amounts to 25% of total baking-time.

(El-Adly et al., 2015) conducted experiments on energy requirements of three types of breads, Mawi Baladi, Magr Baladi and French breads. The first two are thin Egyptian traditional breads made of whole wheat. The specific thermal energy required to bake the breads was found to be 2990.50KJ/Kg, 2786.10KJ/Kg and 4752.89KJ/Kg for Magr Baladi, Mawi Baladi and French breads respectively.

Baking time depends on baking temperature. Thus, by varying the temperature and time of baking we can have different quality, crust formation and size of bread form a common dough composition and size. (Peluola-Adeyemi et al., 2016) conducted a research on different baking temperature and time of bread which has a composition of 90% wheat and 10% cocoyam flour. The final result showed the bread which was baked at 186°C for 45min gained more preference than the breads baked at temperature ranging from 174.82°C to 240°C and time ranging from 30min to 48.11min.

In order to determine the heat required for baking a bread, the specific heat capacity of dough at different temperature of baking need to be evaluated. (Budžaki et al., 2015) conducted an experiment on some physical properties of Croatian unleavened flat bread, Mlinci, which is produced from wheat flour (68.2%), water (30.5%), vinegar (0.9%), and salt (0.4%). The dough is prepared by a method similar to that used for “Chapati” (Indian flat bread). The result showed that thermal conductivity and specific heat of the dough at different temperature can be closely estimated by the following regression equations shown in Table 2.1 and Table 2.2.

Table 2.1: Equation for specific heat capacity of bread dough at different temperature

Temperature range (ºC)	Specific heat capacity (kJ/kg_ºC)
34.3°C – 44.6°C	$0.58604 + 0.07138\ T$
44.6°C – 56.2	$41.67779 - 1.55354\ T + 0.01574\ T^2$
56.2°C – 95.8	$1.77318 + 170.7269 \exp((-0.09439)\ T)$

Table 2.2: Equation for Thermal conductivity of bread dough at different temperature

Temperature range (ºC)	Thermal conductivity (W/m_ºC)
26.9°C – 46.2	$0.13910 + 0.00782\ T$
46.2°C – 55.7	$6.91785 + 0.25405\ T - 0.00249\ T^2$
55.7°C – 124.2	$0.30070 + 16.43008 \exp((-0.07883)\ T)$

2.2. Solar Cookers

Solar cookers can be generally categorized in to two groups, indirect and direct solar cookers. Thermal heat storage units can be incorporated in both types but are mostly suitable for indirect solar cookers. Indirect solar cookers use a heat transfer media to transport the solar radiation heat to the cooking stove. The media can be air, water (steam), oil or other fluid. Most of the time additional pump or fan is required to drive these mediums but some of them use natural draft by placing the stove at a higher place than the solar heater. But direct solar cookers place the pot or the oven in direct sunlight and uses reflectors to increase the solar radiation gain (heat gain). While, it is possible to cook food indoor with the Scheffler direct and indirect solar cooking options, the use of direct cookers necessitates to cook outdoors in the open sun. However, the cost per unit aperture area is minimum for direct designs. And for using Scheffler (direct) or indirect steam cooking options skilled manpower would be required (Indora et al., 2018). Over the past few decades many researches have been conducted on solar cookers, but this chapter will only focus on some of the recent researches to identify where the solar cooking technology is currently, especially in Ethiopia.

2.2.1. Indirect Solar Cookers

Even though there are a lot of researches in this area, this literature review focuses only on three research topics which show the current stage of the technology. The first topic is on Designing and Development of a Steam Based Solar Thermal Injera Baking (Tesfay et al., 2013). This research is a recent success on developing a practical indirect solar baking technology for Injera baking in Ethiopia, starting from the parabolic dish up to the baking plate. The research was made in Mekelle university in collaboration with NTNU. The researcher used a standard readymade 6 petal, Ø 1.8m and focal length of 0.684m parabolic dish filmed with MICRO-SUN reflective and having an aperture area of $2.54m^2$, a concentration ratio of 325.5, a solar tracker powered by PV, 10mm pipe taking the steam from the receiver to the baking plate in the kitchen, and the steam travelled through pipes by natural convection.

Final test results of the constructed Solar Steam baking showed that Injera can be baked at a lower temperature than what is suggested on most literature. Because the researchers were able to bake it at 135-160ºC. But still the Solar Mitad took longer time for baking compared to the electric Mitad and direct biomass burning Mitad. And also, since the Solar Mitad directly depends on solar radiation, its performance varies throughout the day, showing high performance around noon. But during its high-performance time also the Solar Mitad took 10-15 min for baking 1 injera and 45min-1hr to regain its surface temperature, where the electric and biomass Mitads only took a total average of 2.5min for 1 injera.

So, even though the research showed that it is possible to cook high temperature demanding foods indoors with Solar Technologies, it also showed that the technology needs a lot of improvement to gain acceptance and be favored by the society.

Next, we will look at a research in South Africa made on an indirect parabolic solar cooker (Omotoyosi et al., 2017). The cooker uses a Ǿ 2m parabolic dish reflector to focus the sun rays to a frustum shaped receiver that was placed at its focus. The cooker has an insulated cooking/heat storage tank which was separated from the dish and cavity receiver system. The heat transfer fluid was distributed through the system with the aid of Ǿ 10mm copper tube. Thus, 40m copper tube was required to cover the receiver coil, the indoor heating coil and the distance between the two. A stainless-steel conical cover is used at the receiver, while a mild steel container insulated with ceramic wool is used at the indoor heating and storage unit. The heat transfer medium is Shell Oil. Its water boiling test was conducted 4 times using 1.5kg of water. And the boiling time recorded for the four tests, after oil pre-heat, was found to be 13min, 17min, 28min and 38min respectively. From the tests its efficiency was found to be 39%.

Thirdly, we will look at novel indirect solar cooker (Hussein et al., 2008). The cross-sectional view of the cooker is shown below. It consists of three main components: an outdoor flat-plate solar collector, an indoor PCM cooking unit and a closed loop wickless heat pipes network made of copper tube. The evaporator section of the wickless heat pipes network is incorporated into the outdoor collector, while its condenser section is incorporated into the indoor PCM cooking unit as shown in Figure 2.1. Two cooking pots of 3L and 4 L capacities were built in the inner box of the indoor cooking unit inside the helical condensing coil. The space between the pots and the inside surface of the inner box was filled with magnesium nitrate hexahydrate (Mg(NO3)26H2O) as PCM.

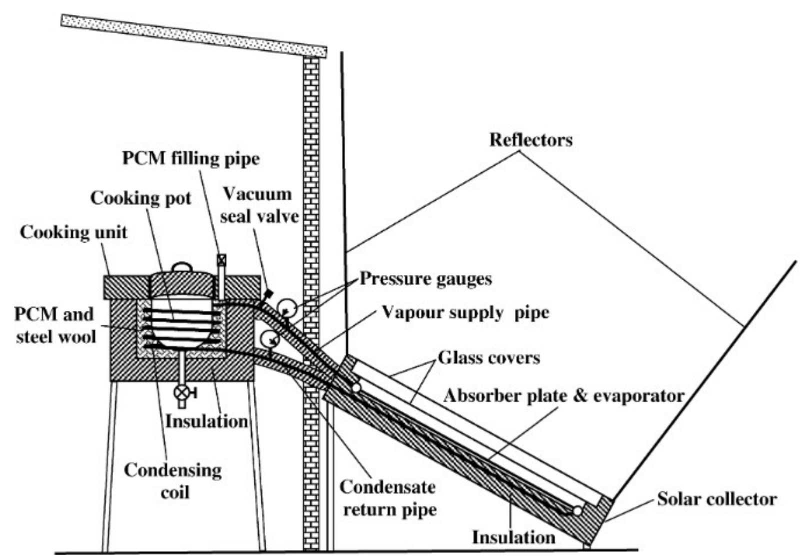

Figure 2.1: Section view of an indirect Novel solar cooker (Hussein et al., 2008)

Test results on this stove shows that by filling both the pots to their full capacity with water, it took 80min (from 1pm to 2:20pm, which is the peak performance time of the stove) to bring the water from 31°C to 100°C with a heating power of around 420W.

Thus, even though indirect solar cookers are able to give us a clean indoor cooking, they are more costly, require large space and their many parts require skilled manpower power for manufacturing and maintenance compared to direct solar cookers. These together with its low mobility and flexibility makes the stoves less practicable in developing countries.

2.2.2. Direct Solar Cookers

Direct solar cookers are the most common type available due to their ease of construction and low-cost material. Commercially successful direct type cookers are box type and concentrating type cookers (Sedighi et al., 2014). But furthermore, we can classify direct solar cookers as box type, panel type, parabolic type and non-imaging type solar cookers (Mejía et al., 2020).

Box type solar cooker is an insulated container with a multiple or single glass cover. This kind of cooker depends on the greenhouse effect in which the transparent glazing permits the passage of shorter wavelength solar radiation, but is opaque to most of the longer wavelength solar radiation coming from relatively low temperature heated objects (Muthusivagami et al., 2010). The inner part of the box is painted black in order to maximize the sunlight absorption. A double-walled insulated box can also serve to hold the heat inside the cooker. Mirrors may be used to reflect additional solar radiation into the cooking chamber.

Table 2.3 shows a list of some solar box cookers evaluated by their first figure of merit (F1), stagnation temperature and time to reach this temperature. The first figure of merit is defined as the ratio of optical efficiency to the overall heat loss coefficient. That means, the desired higher figure of merit could be achieved when the optical efficiency is higher and the heat loss is lower (Mekonnen et al., 2020).

Table 2.3: List of different box cookers and their performance

No.	Author	Cooker Type	F1	Stagnation Temperature	Time to Reach S.T.
1	(Adewole et al., 2015)	Reflector Based Solar Box Cooker	0.08	76°C	200 min
2	(Sonali et al., 2015)	Typical Box Type Solar Cooker	0.1061	100°C	240 min
3	(Saravanan et al., 2014)	Double exposure box-type solar cooker	0.1131	102°C	180 min
4	(Mekonnen et al., 2020)	Box Type Solar Baking Oven	0.1204	121.1°C	150 min
5	(Harmim et al., 2013)	Box type solar cooker with parabolic concentrator as booster-reflector	0.152	127.7°C – 165°C	180min

In addition, a box type solar cooker for rice cooking, Figure 2.3c, was developed in India which has a different feature compared to its predecessors, as the cooker used a double-glazed transparent plastic cover on all its sides, excluding its bottom (Mahavar et al., 2013). Thus, the box cooker was able to reduce heat loss and its maximum cooking container top surface temperature reached 142°C. its price evaluation showed that the solar cooker costs around INR 2500.

Many modifications have been conducted on the box type solar cookers to increase their cooking temperature and improve their slow cooking time. (Amer, 2003) was able to increase the cooking temperature up to 132°C by providing a thick insulation under the absorber plate and on the same research, by providing a double exposure at the bottom of the absorber plate, the cooking temperature was further increased to 155°C.

Box type solar cookers have the advantage of being simple, easy and low cost for manufacturing and use. But their low concentration ratio (mostly up to 10) results in a lower cooking temperature and slow cooking time (Sedighi et al., 2014).

Concentrating type solar cooker uses reflectors working on one or two axis tracking with a concentration ratio up to 50 and temperature up to 300°C, which is suitable for cooking (Sedighi et al., 2014). There are different types of concentrating solar cookers with the common ones being the panel cookers, parabolic cookers and non-imaging solar cookers.

The panel cooker operates at principle of solar box cooker. Its construction is slightly different. It does not have an insulated box but has large (often multi-faceted) reflective panels. Panels direct the sunlight on a cooking vessel. Panel cookers are the easiest in construction and least costly to make, requiring just four reflective panels and a cooking vessel, but they are unstable in high winds and do not retain as much heat when the sun is hidden behind clouds. The convection and radiative heat transfer losses are higher in this cooker compare to solar box cooker. But it can cook all items which can be cooked in solar box cookers (Rathore et al., 2015).

The parabolic cooker uses the principles of concentrating optics. These solar cookers primarily consist of a reflecting collector and a receiver at point of focus, Figure 2.3b. The incident solar radiation is directed by reflector on to the cooking pot located at the focus. Parabolic solar cooker uses large inexpensive reflective surfaces like anodized aluminum sheet or glass mirrors, which are usually less expensive. The smaller absorbing (receiving) surface is insulated from all sides except the side exposed to concentrated solar energy. The mild steel structure supports the reflectors sun tracking mechanism to keep the concentrating collector normal to sun rays. The tracking mechanism adds a significant cost to the construction of a concentrating collector system. This type of cookers attracted people immediately all over the world due to their outstanding performance. Solar parabolic cookers can reach extremely high temperatures in a very short time and unlike the panel cookers or box cookers, they do not need a special cooking vessel (Cuce et al., 2013).

The cost and size of reflector is determined by heating capacity desired. The parabolic solar cooker involves direct sunlight to function and thus concentrator must be frequently orientated towards the sun. Advantages include high cooking temperatures, virtually any type of food can be cooked and short heat-up times are possible. Thus, these cookers can be used for baking and frying. Rice cooking research on parabolic cooker (Karande et al., 2017) showed that by using a collector of $1.6m^2$ with 0.4m focal length and a thermal storage oil at the receiver, the solar cooker was able to cook a 0.5kg rice in 1liter of water in 3hrs. A research in Malaysia (Jebaraj et al., 2015) compared efficiencies of solar oven with and without parabolic collector. And it showed that both efficiencies increase with increase in time due to increase in trapped heat. After 150 min the oven with parabolic collector had an efficiency of 53.62% while the oven without parabolic collector gave an efficiency of 35.86%. Another research in Sudan (Akoy et al., 2015) compared the three types of direct solar cookers, box type, panel type and parabolic type. They were compared by their power output and efficiency using WBT. The parabolic cooker showed the highest power output of 51.9W while the box cooker and the panel cooker gave a power output of 21.13W and 12.94W respectively. But efficiency wise the box cooker was the most efficient of the three with 77.4% while the parabolic and panel cookers had an efficiency of 31.53% and 67.4% respectively. This was due to high temperature gradient loss with the ambient air. A research in Iran also tested the performance of this type of solar cookers for baking a thin Arabic traditional bread of Ǿ 45cm (Nazari et al., 2013). The researchers used a Ǿ 1.3m parabolic dish and a baking plate of Ǿ 48cm and thickness 6mm at the receiver. The parabolic solar cooker was able to bake 12 bread an hour for at least 6hrs a day and 8 months a year (each bread is made of 200g of dough). And its overall efficiency is around 50%.

Another type of solar concentrator cooker is the Scheffler collector, Figure 2.3a. It is a fixed focus solar radiation concentrator which has a capacity to increase the temperature of the receiver up to 200 °C (Kumar et al., 2017). It is used for different applications like, for power plant, drying purposes and cooking. But due to its relatively large sizes and automatic tracking systems, it is mostly used at institutional or large business level.

Generally, reflector cookers have the advantages of achieving high temperatures and consequently short cooking times with some of them able to be used for baking and frying, Table 2.4. Relatively inexpensive versions of these cookers are possible. Disadvantages of these cookers are their size, cost, the risk of fires and burns and the inconvenience to adjust the cooker as it requires frequent directional adjustment to track the sun. Most direct-focusing cookers are also unstable at wind speeds exceeding 10km/h. **(Sedighi et al., 2014).**

Table 2.4: Summary of the advantages and disadvantages of different solar cookers (Rathore et al., 2015).

Type of Cookers	Advantages	Disadvantages
Solar box cooker (Solar oven) T= 150°C	• Uses both direct & diffuse radiation. • Requires little intervention by the user. • Very easy &safe to use. (2-6 kg/day) • Easy to construct but • High acceptance angle.	• Slow but even cooking i.e.,1.5 to 2 hours. • Not used for frying.
Panel Cooker T = 200-250°C	• Better performance than box cooker	• Poor performance on cloudy conditions. • Relies more on reflected radiation.
Collector Cooker	• Uses both direct and diffuse radiation. • Simple, safe and Convenient to use.	• Complicated to build. • Expensive.
Concentrating (reflector) Cooker, η =50%	• Quite efficient. • Can achieve extremely high temperatures 300 -350°C. • Cooking is quicker. (1/2 to 1 hour)	• Complex design • Requires the user's attention. • Strong reliance on direct beam. • Low acceptance angle. • Relatively high cost. • Safety problems (burns or eye damage)

Non-imaging solar cookers or tube type direct solar cookers uses a parabolic trough reflector to concentrate solar radiation on to a cylindrical absorber (receiver) and the inside of the cylinder acts as an oven for cooking and baking purposes. Some of these cookers also have a vacuum tube chamber to reduce the heat loss, and are called vacuum tube direct solar cookers, Figure 2.2. The vacuum tube direct solar cooker thus can be regarded as a combination of the box type and the concentrating type solar cookers. It gives solution to most of the draw backs of direct solar cookers. It is an evacuated made of concentric cylinder glasses with the inner part used as oven for cooking and the outer part (the vacuum chamber) used as insulation. The outer part can also be filled with air since, trapped air has a good insulation property. Parabolic trough reflector is used to increase the tube type cooker’s solar heat gain. One end of the tube is left open to allow a slender cooking tray to be inserted. The tray has a handle attached to rubber seal which acts as the door for the oven. The opposite end is fitted with a fixed stopper or the tube is permanently sealed during the manufacturing process (Vijayakumar et al., 2019). Not many researches have been conducted on this type of cookers as the technology is new compared to other solar cookers. A research in India used an evacuated tube of length 1.5m, outer diameter of 47mm and inner diameter of 37mm which was made of borosilicate glass of 1.6-2.0mm thickness (Vijayakumar et al., 2019). The parabolic trough was made of aluminum sheet metal covered with aluminum foil which has reflectivity of around 90%. And it has a size of length 1.2m, Ǿ 600mm and a depth of 150mm. The maximum temperature attained was 302°C. And a water boiling test showed that it takes 220Sec to boil 50ml of water (until it reaches 100°C) at an ambient temperature of 36°C. Improvements in glass technology is allowing for larger diameter tubes to be fabricated, which will allow for the manufacturing of large vacuum tube solar cookers (Solar Cooking Wiki, 2019). Vacuum tubes prevent the heat loss of the cooker through conduction and convection. Thus, these cookers can hold and retain heat better than any other style of solar cookers; thus, it will heat up quite well even in less than optimum conditions. Its cooking temperature reaches more than 200°C in short time; good for baking and frying. And the chamber is so effective it often does not require a large reflector to capture sunlight and it does not also require a constant adjustment for solar tracking. Furthermore, they are small and portable (gosun, 2021d).

Design and Testing of a Vacuum Tube Solar Cooker conducted in Prince Mohammed Bin Fahd University in 2017 (Alabdulkader et al., 2017) used a Borosilicate glass evacuated tube with black internal absorbent surface and a dimension of 620mm long, 70mm outer diameter and 55mm inner diameter, Figure 2.2. A 2mm polished stainless steel coated with zinc was used for the reflector. The result showed a maximum temperature of 288°C which was attained in a short period of time. The researchers also mentioned in their conclusion that the cooker showed a better efficiency compared to other direct solar cookers.

But the main disadvantage of these cookers is their relatively high price and that evacuated tubes cannot be easily manufactured in the local market, especially in developing countries. Their price, for example for a 3Lits capacity, ranges between ETB 3,500 to ETB 7,500, from different manufacturers, without considering shipment and import taxes.

The other type of non-imaging solar cooker is the one that does not have a vacuum tube insulation chamber covering the oven. Because of this, the convection and radiation heat losses are high but their cost is low and their manufacturing is very simple. The Tolokatsin solar cookers are the famous type of this type of cookers, Figure 2.3d. Their concentrator has a reflectivity of 93% (Mejía et al., 2020; Mora et al., 2016). A research in Mexico conducted on a Tolokatsin solar oven, which is used for surgical equipment sterilization and having a receiver of length 0.4m and radius 0.2m, showed that at solar radiation of 756W/m² the oven reached a stagnation temperature of 160°C in a period of approximately 2hrs and its thermal efficiency is 38.87% (Mora et al., 2016). Recently conducted testes on these cookers has shown an improved output. A Tolokatsin V solar cooker that incorporate two 4L trays is tested to have a stagnation temperature of 170°C at a solar radiation of 700 W/m² and its overall efficiency is found to be 73%. Water boiling test by using 7Kg of water in the two trays resulted in an average water temperature of 94°C after 2hrs and 40min starting form 10:20AM at a solar radiation varying between 518-736W/m² (Mejía et al., 2020).

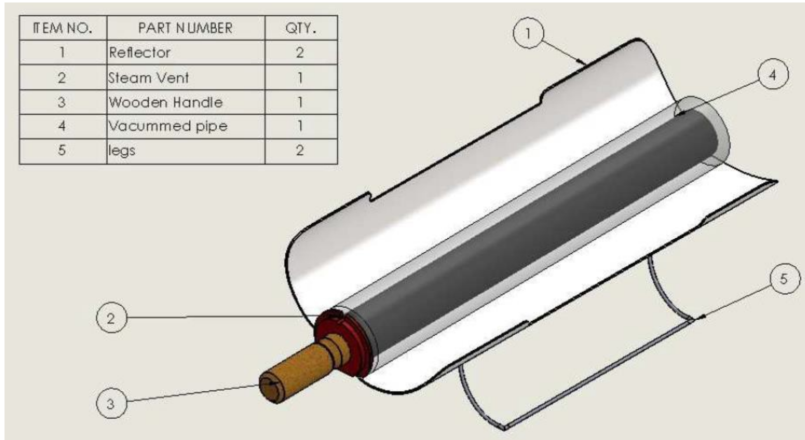

Figure 2.2: Vacuum tube solar cooker (Alabdulkader et al., 2017)

Figure 2.3: a) Scheffler Mirror, b) Parabolic cooker, c) Glazed Box Cooker, d)Tolokatsin

2.3. Simulation of Solar Cook Stoves

CFD is a powerful tool for predicting the outcome of an engineering experiment. Thus, with the development of different CFD software now a days, it has become a basic step in research and projects analysis before conducting an expensive experiment (Ali et al., 2014). But most solar cook stoves are inexpensive and can be setup in a short time. Therefore, CFD simulation of a solar cook stoves is rarely conducted in researches. In addition to simulating of an experiment in a less costly way, a CFD software can predict the outcome of an experiment by considering its may parameter inputs within a short period of time, which is very time consuming to be acquired in practical experiments (Versteeg et al., 2007). This could be the different weather conditions for different days of the year or other modeling parameters.

This section reviews researches conducted on solar cooking technologies using simulation software. Thus, the first topic is a review on a mathematical modeling of a box type solar cooker evaluated using software developed in C++ (Terres et al., 2013). The box type solar cooker has double glass covers, insulated body and a reflective interior lining of aluminum foil. The mathematical model has been solved by means of the fourth order Runge Kutta's method through the use of software developed in C++. Constant ambient temperature and solar radiation were considered for the mathematical model. Finally, the mathematical model output was compared with the physical experiment using water boiling test. The reflective temperature showed a maximum variation of 26.4% while the glass temperature showed a variation of 7.6% at starting of the test. And the researcher concludes that as the solution converges these errors will be minimal.

Another research in this section is a solar cooker with 1.5 m^2 aperture area of compound parabolic dish concentrator integrated with thermal storage media (1.5litter of oil and 0.74kg of rock) as an absorber (area of 0.4m^2) (Muluken, 2018). The absorber with thermal storage is simulated by COMSOL software to show temperature distribution. And it showed that the temperature of the TES could reach 365K after 6hours, where as in the experimental result, due to so many losses that were not considered in the CFD simulation, the energy reduced in some extent and it only reached 354K.

Thus, a good prediction of a CFD simulation depends on how good the experimental setup is defined by the user and the software, and on the different computational errors associated with the selected software (Versteeg et al., 2007).

2.4. Solar Cookers in Ethiopia

Due to the huge solar power resource in Ethiopia, there is a short-term and a long-term plan by governmental and non-governmental organizations to harness this energy. The short-term plan includes the distribution of 500 solar thermal systems and 3,600 solar cookers along with solar PV systems (Tiruye et al., 2021).

ET-Solar Tech is a small Ethiopian company that started the manufacture of different solar cookers in 2000 (Solar Cooking Wiki, 2017). The article mentions that at that time no one knew anything about solar cookers and it was like a magic for everyone to see food being cooked by solar energy. Bereket Dessie the proprietor reported that things are changing now, however. ET-Solar Tech's customers are NGOs such as Sol Solidari, World Vision Ethiopia, GIZ, and PISDA working with Solar Cooking Netherlands, Horn of Africa Regional Environment Centre and Network (HOAREC/n), DEA, and the Catholic Ministries working on the health and school programs. ET-Solar Tech also works with various small, local NGOs and other private people. By 2008 more than 5000 CooKits had been produced by ET-Solar Tech. In their shop Scheffler Reflectors are produced, which can be used to prepare *injera*, the local flatbread. Other cookers produced are the SK-14, box cookers, and CooKits.

In addition, different promotions and trainings have been conducted in Ethiopia to make solar cookers gain large acceptance in the society by NGOs and government organizations since around 1980 (Solar Cooking Wiki, 2020). But its acceptance is very slow due to two major facts (Appropedia, 2013). The first one is cultural resistance; people have used wood to cook since the inception of the domestic fire. Thus, acceptance of so radical a change as cooking with solar energy can only happen where there is real need. But with ever increasing desertification on one hand and population increases on the other in Ethiopia, the need is growing rapidly. And the second barrier to solar cooking's broad acceptance is the quality of the cookers which is mainly based on cooking capacity, speed, price, availability, simplicity, ease of maintenance, mobility and storage space requirement.

2.5. Testing of Solar Cookers

When it comes to solar cooking there are three major testing standards that are commonly employed in different parts of the world (Yahya, 2013). These are the American Society of

Agricultural Engineers Standard (ASAE), Bureau of Indian Standard Testing Method and European Committee on Solar Cooking Research Testing Standard. The procedures followed to evaluate the performance of solar cooker for all the tests consist of some the following basic methods.

The first is the cooking time for different food products. This test is similar to the controlled cooking test (CCT) method and can be extended to include the kitchen performance test (KPT) method in order to determine the acceptance of the solar cooker by the society. The CCT is a laboratory or a field test that evaluates the performance of the cooking stoves using a standardized local cooking task(s) (Kipruto, 2011). This method reveals behavior of the stove under the ideal cooking conditions in a locality/project area. Thus, this method evaluates the ideal/maximum performance of the cook stoves under the actual operating conditions in the households. Here, local cooks are mostly employed to carry out the cooking tasks in order to provide a realistic result. This shows that CCT is capable of providing reliable result as compared to the WBT with regard to predicting actual performance, quality of the stove and fuel consumption in the field. But this method cannot be used to compare the performance of different stoves as it involves uncertainties due to variation in the ingredients and judgment of the observer as to when exactly the food is completely cooked (Yahya, 2013). This test is critical for solar cookers as they depend highly on availability of high solar radiation during the day. And it determines how well the solar cookers can perform the required task at different hours of the day.

The other common basic test is the time required for a sensible heating of a known quantity of water up to the boiling point. This is the same as the water boiling test (WBT) method. WBT is a laboratory test or in some cases a field test that involves the investigation of the cooking stoves in a controlled environment in order to evaluate or reveal their technical performance. This method focuses on simulation of cooking practices by water boiling. For this the WBT involves 3 stage tests which are the cold-start test, the hot-start test and the low power simmering test. Thus, the WBT is a cheap and quick method for comparing the performance and overall efficiency of different stoves, since it is simple and easily applicable for almost all type of stoves. But it does not reveal the performance of the stoves during actual/real cooking. It only provides a rough approximation. The accuracy of the measured parameters are therefore not ascertained hence may give inaccurate results during application (Kipruto, 2011). But it can be used to compare the performance of a solar cooker with other solar cookers or any type of cookers such as biomass stoves, electric stoves or gas cookers.

The stagnation temperature and time taken to reach this temperature is another way of evaluating solar cookers performance. It is the maximum temperature of the oven or plate at no load. This method uses the stove use monitor (SUM) which is a temperature monitoring system that involves the installation of electronic temperature data loggers in the cookstoves (Kipruto, 2011). The temperature data loggers are commercially available and are small, rugged and low cost. The SUMs measure the temperature changes over a period of time and stores the data in the memory of the data logger. Thus, a temperature profile of the cook stove over a period of time can be obtained. This makes the SUM an important testing method for solar cooking stoves as they help in determining the stagnation temperature and the time required to reach this temperature for different hours of the day. This can be used to predict its performance for different food preparation.

The stagnation temperature is also used to determine the first and second figure of merit, F_1 and F_2 respectively. The first figure of merit (F_1) is defined as the ratio of optical efficiency (η_o) and the overall heat loss coefficient (U_L).

$$F1 = \eta_o / U_L \tag{2.1}$$

Experimentally,

$$F1 = (Tps - Tas)/Hs \tag{2.2}$$

Where *Tps, Tas* and *Hs* are stagnation plate temperature, average ambient temperature and intensity of solar radiation respectively. The second figure of merit (F2) is evaluated under full load condition a WBT. Finally, overall thermal efficiency of a solar cooker under load can be calculated as follows.

$$\eta_o = \frac{Mw\ Cw\ \Delta T}{I_{av}\ Ac\ \Delta t} \tag{2.3}$$

Where, η_o represents overall thermal efficiency of the solar cooker; *Mw,* mass of water (kg); *Cw*, Specific heat of water (J/kg/^{o}C); *ΔT,,* temperature difference between the maximum temperature of the cooking fluid and the ambient air temperature; Ac, the aperture area (m²) of the cooker; *Δt,* time required to achieve the maximum temperature of the cooking fluid; I_{av}, the average solar intensity (W/m²) during time interval, Δt (Adewole et al., 2015).

The Indian standard produce a characteristic curve which is good predictive tool, but the test protocol may be difficult to replicate in less developed areas. Thus, the international standard for solar cooker testing and performance report was developed by many people from different locations to make testing as simple as possible and to make tests repeatable for different areas of the world, thus, allowing us to compare different solar cookers at different locations. For this, the committee convened at Coimbatore on Jan 9, 1997 and agreed that the one figure best representing thermal performance is effective cooking power which accounts for both different cooking sizes and heat gain rate. And the uncontrolled variables which influence the test can be minimized by fixing a range of these conditions in which the test can be performed (FUNK, 1999).

2.6. Literature Review Summary

Table 2.5 is taken from a report conducted on testing of commonly used solar cookers by the Solar Kitchen of Tamera (The solar kitchen of Tamera, 2018). The report further evaluates these cookers through interviews of users and entails on their simpleness to use, weather resistance, suffice in capacity, fire hazardousness and food burning potential. Table 2.7 is the performance summary review of all solar cookers mentioned in this literature review with some additions.

Moreover, there are different type of vacuum tube solar cookers which are available in the market, Figure 2.4. One of the well-known brands is the GOSUN vacuum tube solar ovens. These ovens come in three sizes. A smaller size called the GO oven, Figure 2.5a, a medium size called the SPORT oven, Figure 2.5b and a larger size called the FUSION oven, Figure 2.5c. The vacuum tube's inner tube has an external coating of aluminum nitride to catch and absorb light, stainless steel to conduct heat and copper for trapping infrared radiation. In addition, all ovens are equipped with a GOSUN dial which uses a simple shadow technique to indicate proper alignment of oven with the sun ray. The FUSION vacuum tube solar cooker has a backup electric heater that is 144W and uses a 12V, 15Amp input. Some specification and performance values of these ovens are summarized in Table 2.6 (GOSUN, 2021a, 2021b, 2021c).

Figure 2.4: commercially available vacuum tube solar cookers

Figure 2.5: a) GOSUN GO, b) GOSUN SPORT, c) GOSUN FUSION

Table 2.5: Test results of different solar cookers at Solar Kitchen of Tamera (The solar kitchen of Tamera, 2018)

No.	Type of Solar Cookers Tested	Aperture Area	Estimated Power Output at G_s=900W/m²	Max. Temp.	Tracking	Cooking Volume	Price (€)
1	Scheffler Mirror	4.3m² - 6.4m²	2.2KW - 3.2KW	400ºC	Auto	Up to 40L	2000
2	Yaholnitzki's "The Parabola"	1.2m²	1KW	170ºC	15 - 20min	3x [30x7x 10]cm*	220
3	Tolokatsin	1.1m²	700W	150ºC	2hrs	9L	150
4	Funnel Cooker	0.5m²	300W	150ºC	1hr	3L	40
5	SK-14	1.5m²	600W	170ºC	15min	10L	450

Table 2.6: Specifications and performance of GOSUN ovens (GOSUN, 2021a, 2021b, 2021c)

No.	Parameter	FUSION	SPORT	GO
1	Cooking capacity	3L	1.4Kg	370ml
2	Maximum temperature	288ºC	371ºC	288ºC
3	Working temperature	93 - 232ºC	93 - 288ºC	93 - 232ºC
4	Meat cooking time at full sun	≈40min	55min	55min
5	Meat cooking time at medium sun	100min	1.5hrs	1.5hrs
6	Meat cooking time at low sun	-	2.5hrs	2.5hrs
7	Cost ($)	429	219	119

Table 2.7: Summary of Solar Cookers Performance based on Stagnation Temperature

	Research Title	Type of Solar Cooker	Ts (°C)	TTs	Research output F1	Research output η (%)	Ref.
1	Design and development of solar thermal Injera baking: steam based direct baking	Indirect solar thermal Injera baking with steam	170	45-60 (min)	-	-	(Tesfay et al., 2013)
2	A novel indirect parabolic solar cooker	Indirect parabolic solar cooker with Shell oil heat transfer medium	-	-	-	39	(Omotoyosi et al., 2017)
3	Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit	Novel indirect solar cooker	120	9hrs (started at 6AM)	-	-	(Hussein et al., 2008)
4	Design and manufacturing of thermal energy based Injera baking glass pan	Indirect solar thermal Injera baking using oil	191	45min	-	-	(Adem et al., 2017)
5	High-efficiency solar oven for tropical countries	Direct solar heating of oven with parabolic dish collector	60	150 min	-	53.6	(Jebaraj et al., 2015)
6	Solar cooking in Ethiopia: Experimental testing and performance evaluation of SK14 solar cooker	Direct solar cooker using parabolic dish collector	188	25 min	0.22	46.4	(Mekonnen et al., 2020)

7	A Direct Solar Fryer for Injera Baking Application	Direct solar frying for Injera baking continuous type model	120-130	30 min	-	37	(Hailu et al., 2017)
		Direct solar frying for Injera baking alternating type model	160-180	30 min			
8	Using a New Solar Sterilizer for Surgical Instruments as a Solar Oven for Cooking	Tolokatsin Solar Oven	160	2hrs		38.87	(Mora et al., 2016)
9	Design, Construction and Performance Evaluation of Solar Cookers	Box type solar cooker	127	3hr and 30min	-	77.4	(Akoy et al., 2015)
10	Thermal Performance of a Reflector Based Solar Box Cooker Implemented in Ile-Ife, Nigeria	Box type solar cooker with reflector	76	200 min	0.08	-	(Adewole et al., 2015)
11	AN EXPERIMENTAL STUDY ON BOX-TYPE SOLAR COOKER	Box type direct solar cooker	100	240 min	0.1061	-	(Sonali et al., 2015)
12	Comparative study of single and double exposure Box-type solar cooker	Box type solar cooker with double exposure	102	180 min	0.1131	-	(Saravanan et al., 2014)
13	Development and Performance Evaluation of a Solar Baking Oven	Box type solar cooker	121	150 min	0.1204	-	(Mekonnen et al., 2020)
14	Design and experimental testing of an innovative building-integrated box type solar cooker	Box type solar cooker with parabolic trough as booster reflector	128 and 165	180 min	0.152	-	(Harmim et al., 2013)

Where Ts is stagnation temperature and TTs is time to reach stagnation temperature.

Furthermore, a comparison made by the GOSUN solar stove manufacturers show that the commercially available vacuum tube solar cooker has more advantage over the other types of solar cookers, Figure 2.6.

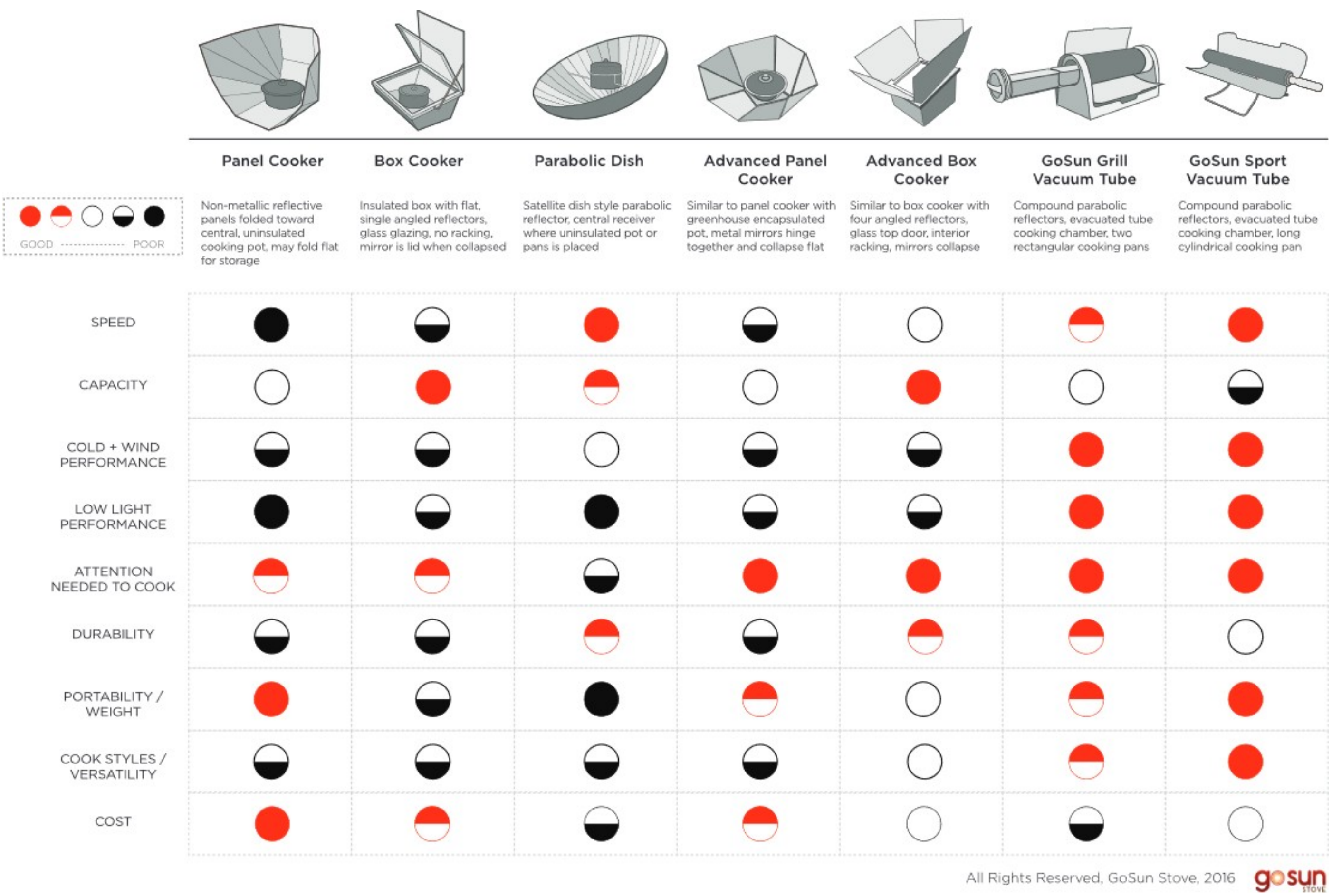

Figure 2.6: Stove cookers compared by GOSUN Stove, 2016

This brings us to the main topic of this research, which suggests a low-cost tube type direct solar oven for the rural and urban parts of Ethiopia. As mentioned earlier in this topic, tube type direct solar cookers have the advantage of being small while producing high cooking temperature which is sufficient enough for baking and frying. Their portability and small cooking time also give them the potential to be widely accepted by the society, especially for small scale urban businesses. Their drawbacks for being expensive and their difficulties to be manufactured locally is eliminated on this research by changing the shape of the outer cover of the transparent tube from cylindrical to a rectangular prism and by replacing the inner coated glass tube that has an external coating of aluminum nitride, stainless steel and copper with an aluminum sheet metal painted black. Additionally, replacing of the coated inner glass tube is expected to minimize the optical refraction losses on the glass, thus resulting in more solar energy to be absorbed by the receiver.

These tubes can have an air tight chamber or a vacuum chamber around the oven tube for good insulation. But vacuum chambers require evacuated tubes which currently are not being produced in Ethiopia and which are expensive to import, especially for custom designs like the solar cookers. And vacuum tubes need extra care, as they are highly fragile and not easily repairable compared to the air tight tube solar cooker. Therefore, the focus of this research is to design and manufacture a low-cost tube type direct solar oven with air tight chamber that can be easily produced in Ethiopian local markets and that can have the potential to gain a wide acceptance by the society by making the above changes to the vacuum tube direct solar oven.

CHAPTER THREE:
MATERIALS AND METHODS

3.1. Method of the research and system description

The literature review shows the many researches conducted on solar thermal cookers and try to assess their potential for being a reliable and acceptable technology in both the rural and urban parts of Ethiopia. Thus, based on the review, the tube type direct solar cooker has a good potential compared to the other solar thermal technologies. As mentioned in the review it is small, portable, well insulated and reaches high temperature within a short time.

Therefore, this research aims to design, manufacture, simulate and test a low-cost tube type direct solar cooker, which is made of locally manufactured square air-tight prism. As the technology is intended for both the rural and urban parts of the country, the research takes Addis Ababa as its initial reference site (location of application). Furthermore, design of the solar oven is initialized by analyzing the size of the solar oven required to bake 10pcs of Sheger breads in 30mins, as Sheger bread is a well-known bread in Ethiopia. Thus, relating the capacity of the oven with Sheger bread will give a clear understanding of what to expect from the oven. Also, the maximum amount of Sheger bread that one can buy at a time is 10pices. It should be noted that, the initial parameters might change depending on the output of the analysis. The analytical analysis is done using MATLAB software, in order to solve the problems that need iteration easily and in order to simplify solving of the problem for different parameter changes other than the initial parameter. Graphs are also developed using MATLAB code from the analytical design for further analysis. The simulation part of the research is done using COMSOL software. It is used to simulate the solar ray trajectory at the solar oven and of the reflector and to analyze the heat transfer inside the oven to verify the design output. Finally, the optimum model from the analysis is chosen for practical experiment and manufacturing is conducted in Addis Ababa Institute of Technology, AAIT, mechanical workshop. The test on the prototype is conducted according to standards of solar oven testing. The overall research methodology step is shown by the block diagram in Figure 3.1.

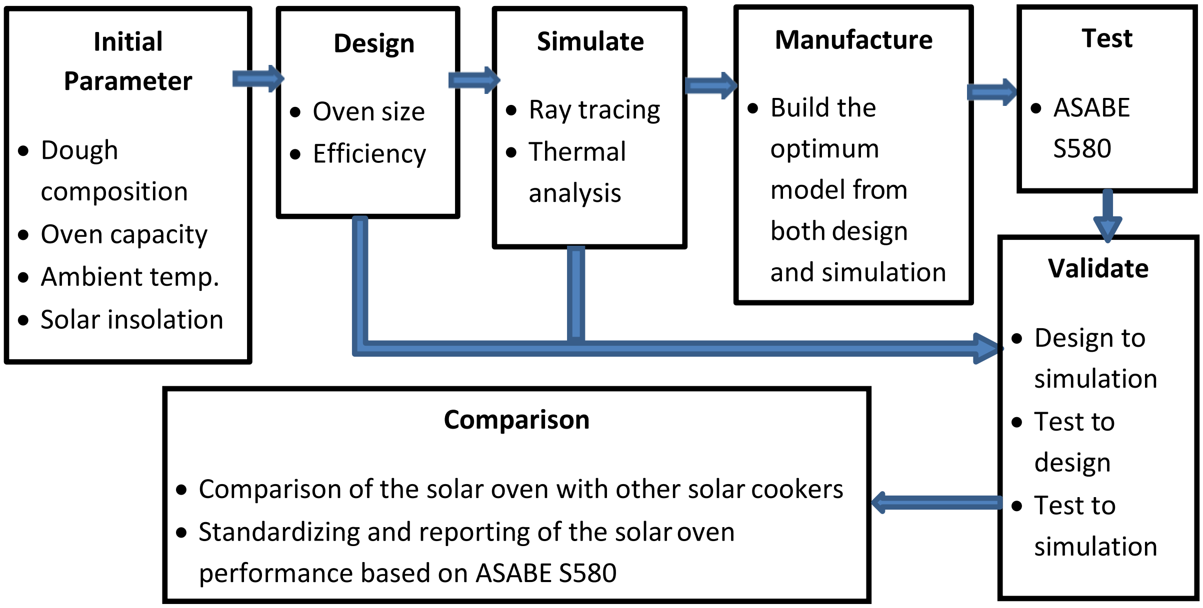

Figure 3.1: Research methodology flow diagram

The working principle of the tube type direct solar oven is very simple as shown in Figure 3.2. The baking oven is placed inside an air tight chamber made of a transparent material, just like an evacuated tube, so that solar rays reflected from the parabolic trough concentrator can freely reach the oven while good insulation is maintained for the oven by the air tight chamber.

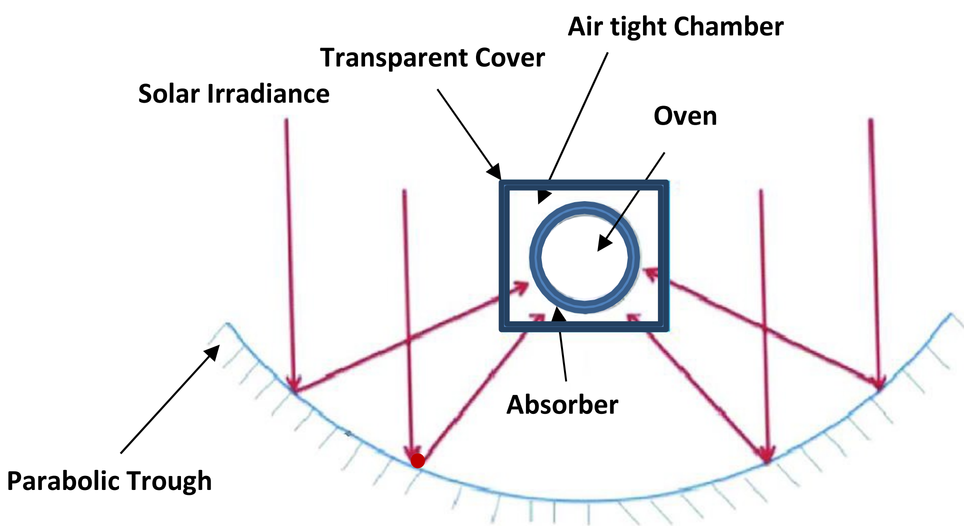

Figure 3.2: Working principle

Thus, the solar cooker has three main parts; the air tight tube, the oven and the parabolic trough reflector. The air tight tube is a square prism on the outside which is made of a transparent plastic material (acrylic plate) and an inner black painted aluminum cylinder. Because acrylic plates have a high transparency and a low thermal conductivity than glass, with a light transmittance of more than 92%. Additionally, they are light, flexible and impact resistant for use compared to glass. The maximum continues working temperature of these plates without deflection is 71ºC, which is more than the maximum temperature expected at the transparent cover of the solar oven. And for the oven, aluminum has a high thermal conductivity and is cheaper than copper. The high reflectivity of aluminum is cancelled by painting its surface black, thus making it a good absorber for our solar cooker. The air is sealed between the transparent cover and the absorber tube. The square transparent prism is made by cutting 4 pieces of rectangular acrylic plates and attaching them using general purpose semi- transparent silicon.

The oven has two parts that are attached together, the oven door and the sliding tray. The sliding tray is made of food grade aluminum material while the door is made of high temperature rubber attached to a sheet metal for strength. The rubber acts as a good insulation and gives the oven an air tight seal. The rubber has a small vent hole to reduce the pressure developed inside the oven during cooking. A sheet metal handle attached by a rivet to the oven door is used for pulling and pushing the tray assembly in and out of the oven.

Finally, we have the parabolic trough made of aluminum sheet metal, since aluminum surface has a high reflective capacity. And the whole oven is placed on an adjustable supporting stand, for easily adjusting the solar oven in the direction of the sun.

3.2. Testing methods

A no-load test, a bread baking test and a water boiling test are used to test the performance of the solar oven. The no-load test is conducted to find the stagnation temperature and pre-heat time of the solar oven. And the bread baking test is conducted to find the actual bread baking performance of the oven and its utilization efficiency. Whereas, the water boiling test is conducted to find the prototype's overall thermal efficiency. The bread baking test and the WBT were each taken three times at three different days. The bread baking test is conducted. And during the test, the bread core temperature, the oven temperature and the ambient temperature are continually recorded with in a maximum of 5mins interval. For the water boiling test, test standards specify that cookers shall be tested using 7,000 grams potable water per square meter intercept area. Electronic weighing device is used for accuracy in weighing the samples for the tests. Thermocouples are used for temperature sensing inside the oven by passing the leads through the door of the oven and sealing the entrance with silicon to avoid vapor and heat loss. Test data for water boiling test is recorded while cooking vessel content (water) is at a temperature between 5°C above ambient and 5°C below local boiling temperature.

Thus, using equation 2.2, 2.3, 4.1 and 4.2 and the MATLAB code on appendix 1 and appendix 2, the first figure of merit, the second figure of merit, the standard cooking power, the utilization efficiency and the overall thermal efficiency of the tube type direct solar oven can be determined.

3.3. Cost analysis

The cost analysis is conducted using simple payback period and comparing the result with other cookers. Payback period refers to the period of time required for the return on an investment to "repay" the sum of the original investment. Payback period is usually expressed in years but since our solar baking oven has a low price which can be repaid in a few months, we will express the payback period in days. Thus, we start by calculating the Net Cash Flow for each day:

Net Cash Flow Day 1 = Cash Inflow Day 1 – Cash Outflow Day 1

Then, Cumulative Cash Flow = (Net Cash Flow Day 1 + Net Cash Flow Day 2 + Net Cash Flow Day 3… etc.) Accumulate by days until Cumulative Cash Flow is a positive number: then that day is the payback day. It can also be expressed as initial investment divided by estimated daily net cash inflow for a constant daily income.

Payback Period = Amount to be initially invested / Estimated Daily Net Cash Inflow

But for our research, since the daily cash inflow depends on the amount of solar radiation for that day, we will use the first expression for our analysis.

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CHAPTER FOUR:
DESIGN AND SIMULATION

4.1. Energy required to bake a wheat bread

Small bread in Ethiopia ranges from 50g to 100g, but the bread that is going to be considered for the analytical analysis will be a 75g bread based on the widely distributed bread in Addis Ababa, which is Sheger Bread. A bread is considered 'baked' when its core temperature reaches 92°C - 95°C (Cauvain et al., 2007). And crust formation starts at 100ºC when moisture content at the surface starts to evaporate. The evaporation temperature differs with altitude and at an altitude of 2,355m, which is the altitude of Addis Ababa, the evaporation temperature reduces to 92°C. Colorization of the crust (browning of the crust) takes place around 115ºC (Cauvain et al., 2007). Thus, at the end of the baking process the surface temperature of the bread will be close to 120ºC (Vanin et al., 2009). Approximately, 50% of water added to 100% of flour results in a fine textured light bread (Mondal et al., 2007). For a typical loaf with finished weight of 800g, there would be a loss of 50 - 55g during the baking process which is mostly due to evaporation (Cauvain et al., 2007). Thus, the energy required for bread baking is the sum of the energy used to raise the temperature of the bread/dough to the required value and energy used to evaporate the moisture content at the surface of the bread/dough, which is around 6% of the dough weight.

Therefore, to get a 75g bread output we need to prepare a dough that will weighs around 80g, where 5g of the moisture content will be lost due to evaporation. And considering a 50% water for a 100% flour, we will need a 53g flour and 27g water, neglecting the weight of yeast and salt. According to research, the average treated wheat flour density is 593kg/m^3 (Kang et al., 2012). The density of the dough before proving will depend on the type of flour used. The gas-free density of the dough made from weak flour was larger than that of the strong flour, an average of 1.2720 g cm^{-3} compared with 1.2560 g cm^{-3}, despite the same water levels in the two doughs (Campbell et al., 2001). During fermentation, the production of CO_2 due to yeast's metabolic activities causes the bubbles to increase in size. This increases the volume of the dough and reduces its density. The density of the dough after proving depend on the time of fermentation. According to research, a bread dough will have a density of around 650kg/m^3 after 90mins of fermentation in a free expansion proving process (Elmehdi et al., 2007). This figure will be later used to calculate the oven space required. The specific heat capacity of bread/dough varies with temperature according to equation (4.1) (Adamic, 2012).

$$C_p = 0.077T^2 - 68.94T + 16646 \tag{4.1}$$

The unit for C_p is in J/kg_K and the temperature is in K. The mass for calculating the energy required to raise dough temperature was considered constant since, this would give as a more affirmed value for energy requirement. Thus, our final equation will be as follows;

$$Q_E = \mathrm{m}C_p\Delta\mathrm{T} + Q_w \tag{4.2}$$

Where,

QE = useful energy required

m = mass of bread/dough

Cp = specific heat of bread/dough

ΔT = baking temperature minus initial temperature

And Q_W = energy required to evaporate water

Since, the specific heat of bread/dough change with change in temperature, we will use a MATLAB code (Appendix 1), to form a loop that will calculate the heat required to raise the temperature of the dough by 1ºC. The loop will continue to sum the calculated heat energy starting from the initial dough temperature, until it breaks at the given final bread temperature. And each time the temperature is increased in the loop by 1ºC, the specific heat will also change with the new temperature. Finally, the total amount of energy required to evaporate the water, $Q_{W},$ will be added to the total amount of energy from the loop. Thus, taking the latent heat of vaporization of water to be 2260kJ/kg, and the initial and final temperature of the bread/dough core to be 25ºC and 95ºC, respectively, we will find the energy required to bake 75g of bread to be 22.2kJ. It should be noted that this energy is only the heat energy required to turn the dough in to bread. It does not include any losses associated with the baking process.

4.2. Volume of oven

The volume of the oven will depend on the maximum amount of bread that it can bake at a time. Thus, considering that almost all Sheger shops are allowed to sell a maximum of 10pcs of 75g bread for one individual, the thesis initial interest would be to design a solar oven that bakes bread which has a mass equivalent to 10pcs of Sheger bread.

The density of Sheger bread is found experimentally to be around 200kg/m³. The experiment was done by wrapping one Sheger bread in a tight plastic and immersing it in a jar filled with water to find the amount of water displaced. The volume of water displaced is the same as the volume of the bread, which is 375cm³ (i.e., 0.375×10^{-3} m³). Thus, 10pcs of Sheger bread will have a volume of 3.75×10^{-3} m³. Therefore, considering a maximum oven filling capacity of two-third, we get a total oven volume of 5.625×10^{-3} m³.

Thus, basing our design on Sheger bread size, we will consider two type of oven sizes; one with Ø0.080m and length 1.12m and the other with Ø0.075m and length 1.27m. And the choice from the two will be based on their thermal analysis. The rectangular transparent prism for vacuum chamber or trapped air insulation will be first taken as a square of size 0.12m and length the same as the oven. But other transparent cover sizes will also be considered on the thermal analysis.

4.3. Thermal analysis of the oven

The oven power output depends on the solar radiation collected by the concentrator and reflected to the receiver, and all the overall thermal loss of the oven. Thus, Addis Ababa's solar insolation data is required for the design. This data is collected from Ethiopian National Meteorology Agency.

Then to find the amount of solar radiation that is reflected by the concentrator and absorbed by the receiver, we use the following equation (Duffie et al., 2013).

$$S = I_b \rho (\gamma \tau \alpha)_n k_{\gamma \tau \alpha} \qquad (4.3)$$

Where;

I_b = incident beam radiation

ρ = the specular reflectance of the surface and

$k_{\gamma\tau\alpha}$ = the incidence angle modifier

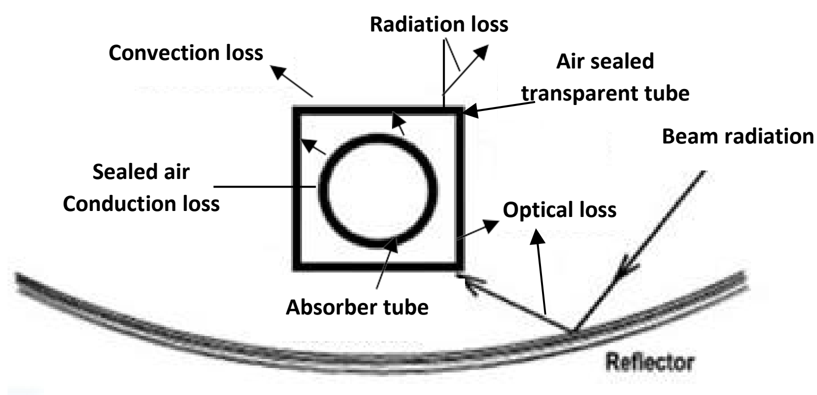


Figure 4.1: Thermal losses of the tube type direct solar oven

The analysis is started by determining the useful heat gain we want from our oven, and this will be based on the energy required to bake 10pcs of Sheger bread, as it is mentioned in the previous discussions. Thus, for 10 breads 800g of dough is required of which, 270g is water and 530 is flour. And the energy required to bake it will be;

$$Q_E\text{=22.2KJ x 10 = 222KJ}$$

Thus, to bake 10 pieces of Sheger bread in 30mins we will need a useful heat transfer of Q_u.

$$Q_u\text{=222KJ / 30mins = 123W}$$

As illustrated in figure 4.1, the tube type direct solar oven has an optical loss due to the reflectivity of the parabolic surface and transmittance of the transparent cover, which is affected by material property, surface finish, foreign particles and manufacturing defects. But this loss is very small compared to the heat transfer losses from the oven (Duffie et al., 2013). Thus, neglecting optical losses, we have a radiation and convection loss at the outside surface of the transparent cover which is equal to a radiation and conduction loss from the oven outer surface to the transparent cover (Duffie et al., 2013). There is no convection loss between the transparent tube and the oven outer surface, since this chamber is sealed at both ends and the air between them is still air. Still air has low thermal conductivity and thus acts as a good thermal insulation for the oven. But the radiation and conduction loss increase as the temperature of the oven increases. And this is affected by the evaporation of moisture from the bread. During evaporation the heat transfer of the oven will reduce and more heat will be transferred to heat the air inside the oven and to increase the temperature of the oven wall.

The coefficient for the losses can be calculated based on the equations provided on (Duffie et al., 2013). According to the book we start our iteration by guessing the temperature of the transparent cover, T_g. Then by taking the average temperature between the cover and the ambient air, T_{Av}, we will determine the density, ρ, the thermal conductivity, k, and dynamic viscosity of air, μ, at the transparent cover from air property table. And for ease of calculation, we will determine the equivalent diameter for our square tube with the following equation.

$$D_e = 1.3(axb)^{0.625}/(a+b)^{0.25}$$

Next, we can find the Reynolds No. and Nusselt No. by using the following formulas.

$$Re = \rho VD/\mu \quad (4.4)$$

And

$$Nu = 0.3Re^{0.6} \quad (4.5)$$

This is the equation recommended by McAdam for flow of air across a single tube in an outdoor environment, for $1000 < Re < 50{,}000$. Here, V and D are air velocity and cover nominal diameter, respectively. For Re to be greater than 50,000, at the surface of the outer transparent cover, the wind speed should be more than 10m/s. This is considered as a strong breeze and is a very rare weather in Addis Ababa. After this, the convection and radiation heat loss coefficient at the transparent cover can be determined by the following equations.

$$h_{c,g-a} = Nu.\ k/D \quad (4.6)$$

And

$$h_{r,g-a} = E_g.\sigma.4T_{Av}^3 \quad (4.7)$$

Where,

$h_{c,g-a}$= convection heat loss coefficient by wind

$h_{r,g-a}$= radiation heat loss coefficient from cover to ambient

E_g= emissivity of acrylic cover, 0.88

And σ= Boltzmann constant, 5.67x10^{-8}

Since, the space between the oven cover and the acrylic cover is sealed air, there is no convection loss, only radiation and conduction loss through the trapped air. And the equation for radiation loss between two concentric surfaces is shown in equation (4.8) and that for conduction is shown in equation (4.9).

$$h_{r,o-g}=\frac{\sigma\left({T_o}^2+{T_g}^2\right)(T_o+T_g)}{\frac{1-E_o}{E_o}+\frac{1}{F_{12}}+\frac{(1-E_g)A_o}{E_gA_g}} \tag{4.8}$$

Where,

$h_{r,o-g}$= coefficient of radiation from oven to transparent cover

T_o= oven cover temperature in K

T_g= Acrylic cover temperature in K

E_o= oven cover emissivity

F_{12}= view factor between the two covers

And A_o and A_g are the oven and transparent cover areas, respectively.

$$h_{cd,o-g}= \mathrm{K/x} \tag{4.9}$$

Where,

$h_{cd,o-g}$= coefficient of conduction from oven to transparent cover

K = air conductivity at an average temperature of oven and cover form property table

x = distance between oven and transparent cover

Thus, we will get a total loss coefficient, U_L , of;

$$U_L = \left[\frac{1}{A_g\left(h_{c,g-a}+h_{r,g-a}\right)} + \frac{1}{A_o\ \left(h_{r,o-g}+h_{cd,o-g}\right)}\right]^{-1} \tag{4.10}$$

Now, we can determine the acrylic cover temperature by equalizing the loss from the oven with the loss form the acrylic cover. And this will yield as the equation (4.11) (Duffie et al., 2013). From this, we can compare our initial guess of T_g.

$$T_g = \frac{T_o.A_o\left(h_{r,o-g}+h_{cd,o-g}\right)+T_a.A_g\left(h_{c,g-a}+h_{r,g-a}\right)}{A_o\left(h_{r,o-g}+h_{cd,o-g}\right)+A_g\left(h_{c,g-a}+h_{r,g-a}\right)} \tag{4.11}$$

Here, the temperatures are in degree Celsius. If the cover temperature is not similar with the initial guess, we will repeat the process by substituting the acrylic cover temperature with new calculated value. And we will stop the iteration when the initial guessed acrylic cover temperature is close to the final calculated value. A MATLAB code (Appendix 2) is used to perform the iteration up to a given error.

The useful energy gain per unit of collector length, q'_u, expressed in terms of the local receiver temperature, T_r, and the absorbed solar radiation per unit of aperture area S is given by equation (4.12).

$$q'_u = \frac{A_a S}{L} - \frac{A_r U_L}{L}\left(T_r - T_a\right) \tag{4.12}$$

Where;

A_a = unshaded Aperture area (m^2)

A_r = Receiver area (m^2)

T_a = Ambient air temperature

The term, $\frac{A_r U_L}{L}\left(T_r - T_a\right)$, is the thermal loss of the solar oven to the surrounding air through the transparent cover. As mentioned above, this loss increases with increase in receiver temperature. Thus, the loss of the solar oven for an average wind speed of around 3.5m/s (based on the five years wind data of Addis Ababa, Appendix 4) and an average ambient air temperature of 25ºC can be represented graphically against receiver temperature using the

MATLAB code on appendix 2 as shown in figure 4.2 and 4.3.

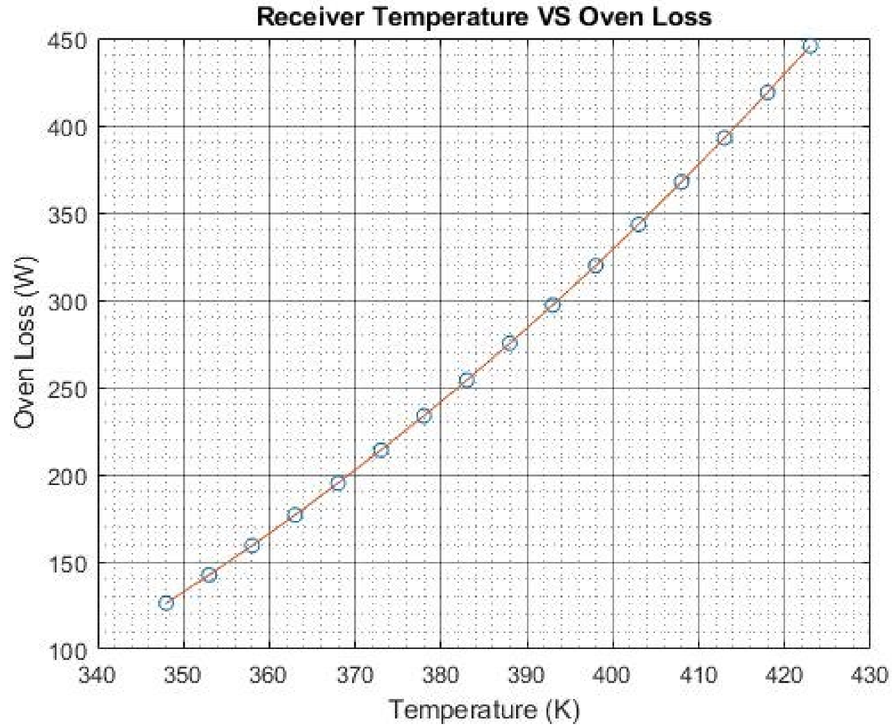


Figure 4.2: Oven loss for dia. 75mm and length 1270mm receiver

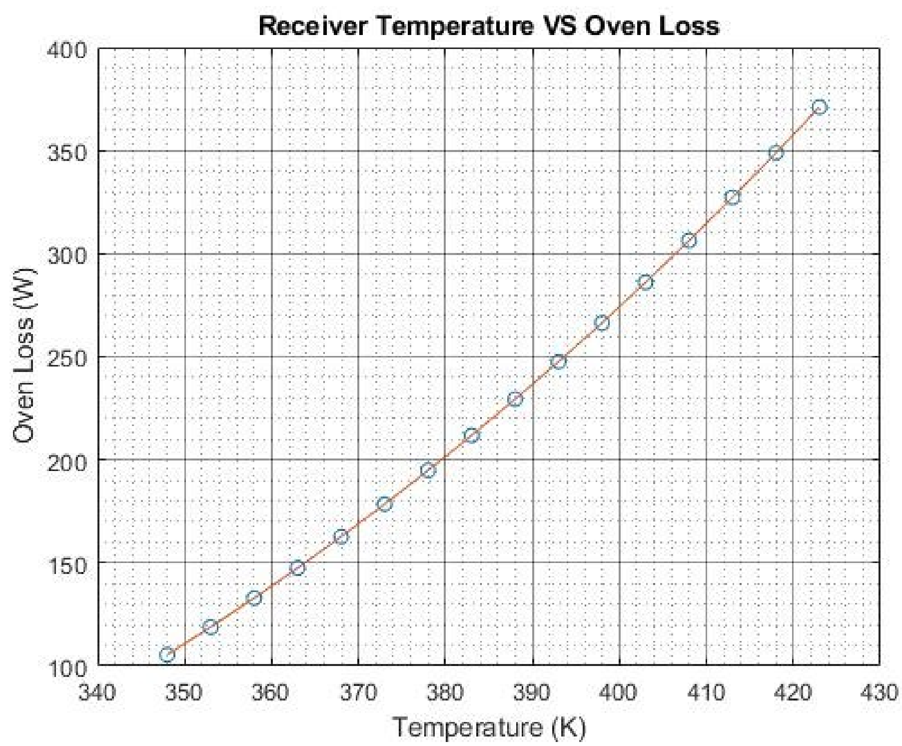


Figure 4.3: Oven loss for dia. 80mm and length 1120mm receiver

The graphs on figure 4.2 and 4.3 analyze the oven loss starting from an oven temperature of 348K, which is the minimum temperature required to bake a bread (Cauvain et al., 2007).

The useful energy gain per unit of collector length, q'_u, will be transferred to the bread dough and air inside the oven. And the remaining heat will increase the temperature of the receiver (the oven wall). This, will give us equation (4.13) which is;

$$q'_u = Q_{bread} + Q_{air} + m_r C_{pr} \frac{\partial T_r}{\partial t} \tag{4.13}$$

Where;

h= Heat transfer coefficient of oven to oven space (W/m^2.K)

A = Oven internal surface area (m^2)

m_r = Mass of receiver (Kg)

C_{pr} = Specific heat of receiver material (J/Kg.K)

Since, there is no forced air convection inside the oven, most of the heat is transferred from the oven wall to the bread through radiation and conduction. The air inside the oven is heated through natural convection from the oven wall. But as the oven space temperature comes close to the oven wall temperature, most of the heat from the oven wall will be transferred to the bread. Considering a steady state heat transfer, $m_r C_{pr} \frac{\partial T_r}{\partial t} = 0$. Thus, simplifying our equation by assuming all the useful energy that remains after the loss goes directly in to the bread dough, the required aperture area will be as follows, based on equation (4.12).

$$A_a = (Q_{bread} + Oven\ Loss)\ \frac{L}{S}$$

A 3D graph and a 2D color graph is plotted in figure 4.4 and 4.5, using the MATLAB code on appendix 3, to show the relationship between the aperture area, receiver temperature and solar radiation absorbed per unit of aperture area, for the two sizes of oven proposed.

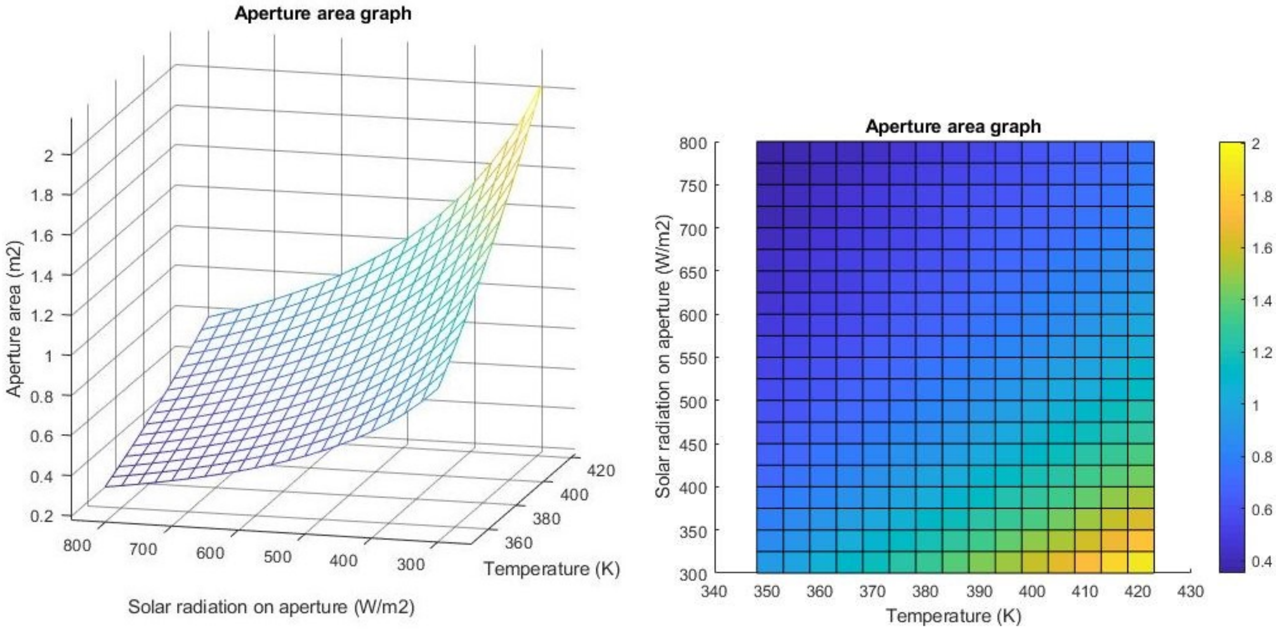


Figure 4.4: Aperture area required for dia. 75mm and length 1270mm receiver

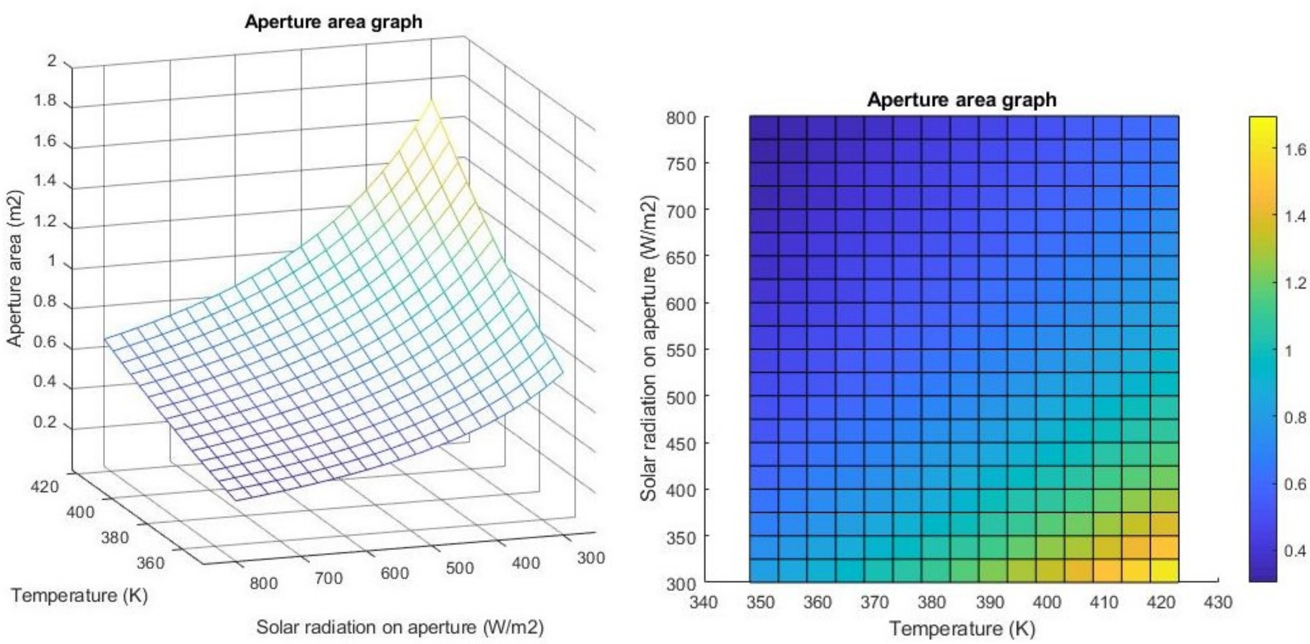


Figure 4.5: Aperture area required for dia. 80mm and length 1120mm receiver

From figure 4.4 and 4.5 we see that increasing the size of the oven diameter for and reducing its length, for the same oven volume and energy output, reduces the aperture area required.

The next step would be to find the monthly average solar radiation of Addis Ababa in order to determine the appropriate size and capacity of the tube type direct solar oven. The analysis will be based on the last five years solar radiation data recorded in Addis Ababa. The data is collected from National Meteorology Agency (NMA), Ethiopian. Table 4.1 shows the average monthly solar radiation of Addis Ababa taken at the sunshine hours from 8:00AM to 5:00PM, based on the representative day of the months.

Table 4.1: Monthly average solar radiation data of Addis Ababa (W/m^2)

Month	2016	2017	2018	2019	2020
Jan	228	547	493	553	474
Feb	555	518	553	490	532
Mar	573	572	324	555	NA
Apr	402	520	349	270	NA
May	522	493	488	333	NA
Jun	330	359	373	324	390
Jul	461	302	456	237	279
Aug	527	483	206	365	337
Sep	NA	378	437	339	382
Oct	NA	394	351	569	408
Nov	NA	547	526	389	521
Dec	535	449	459	290	496
Yearly Avg.	**459**	**464**	**418**	**393**	**424**

The minimum solar radiation based on monthly average solar data from the past five years is 206W/m^2. But baking is a process that is performed for a few hours in a day for households and small-scale commercial bakeries. Thus, the analysis will be based on minimum yearly average solar radiation of Addis Ababa, which is 393W/m^2. For analyzing the payback period of the solar oven for small-scale commercial bakeries, a more detail solar radiation data analysis method is used in the cost analysis topic.

The absorbed solar radiation per unit of aperture area can be found using equation (4.3). The specular reflectance of aluminum is more than 0.9 (Quazi et al., 2015) and the incident angle modifier is used to account for deviations from the normal of the angle of incidence of the radiation on the aperture. Thus, taking the specular reflectance of the aluminum receiver to be 0.9, and assuming a unity incidence angle modifier, the solar radiation absorbed by the aperture area will be around 350W/m^2.

Therefore, by taking the minimum yearly average solar radiation, thermal loss of the solar oven and its manufacturing process in to consideration, the initial parameters of the tube type direct solar oven are changed as follows. The internal oven diameter is changed to 0.1m and its length to 1m. This, will have a capacity to bake 1kg bread dough considering an oven loading of two-third. Thus, the maximum oven baking capacity is changed to 1kg bread dough. Using the MATLAB code on appendix 1, the energy required to bake one kg of bread dough is 296KJ. Thus, to bake 1kg of bread dough in 30mins we will require a power of 164W. Increasing the size of the transparent cover will reduce the thermal loss but the size will be limited by the focal length, which is the distance of the receiver form the bottom of the parabolic trough. Therefore, by trial and error, the maximum size of the transparent cover for the specified oven capacity and size will be a 0.14m by 0.14m square cover. The thermal loss and the aperture area required graph based on these parameters are shown in figure 4.6 and 4.7, respectively.

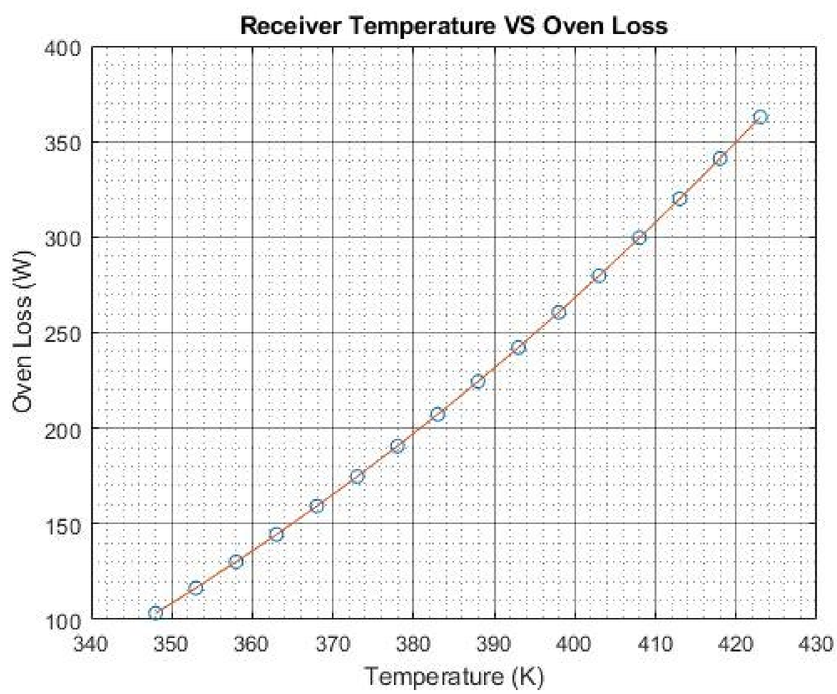
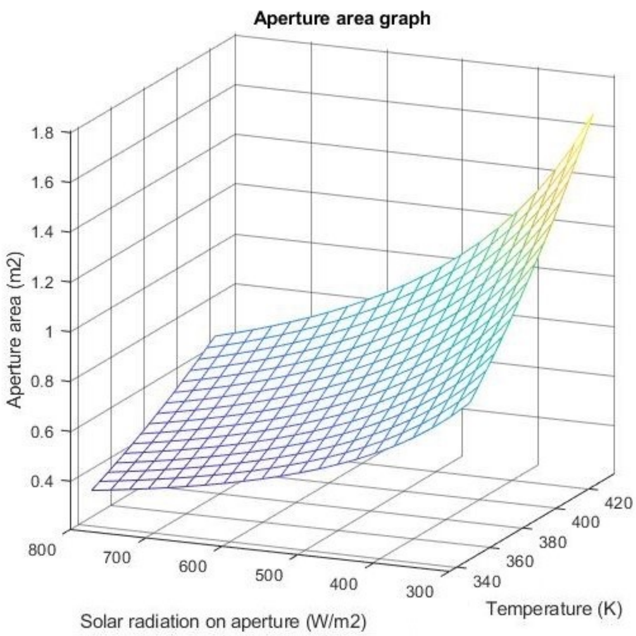


Figure 4.6: Oven loss for dia. 100mm and length 1000mm receiver



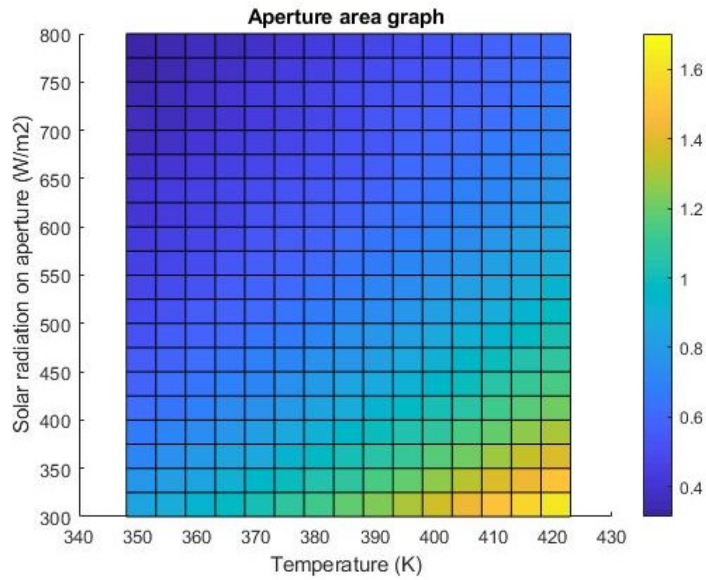


Figure 4.7: Aperture area required for dia. 100mm and length 1000mm receiver

As mentioned previously, bread can be baked at different oven temperature. And the final bread quality will depend on this temperature. This research aims to have a finished bread output from the solar oven with a quality similar to Sheger bread. A Sheger bread has a soft crust which is at its initial stage of browning. This stage comes around 15ºC above evaporation temperature (Cauvain et al., 2007). Thus, based on the minimum yearly average solar data, we can select a minimum unshaded aperture area of $0.8m^2$ for the solar oven. Taking the reflector length to be the same as the receiver length, the aperture area unshaded width will be 0.8m.

From these values, the shape of the parabolic trough reflector can be determined using the following sets of equations (Macedo-Valencia et al., 2014).

$$C = A_a/A_r = 7.8 \tag{4.14}$$

Where, C is the concentration ratio.

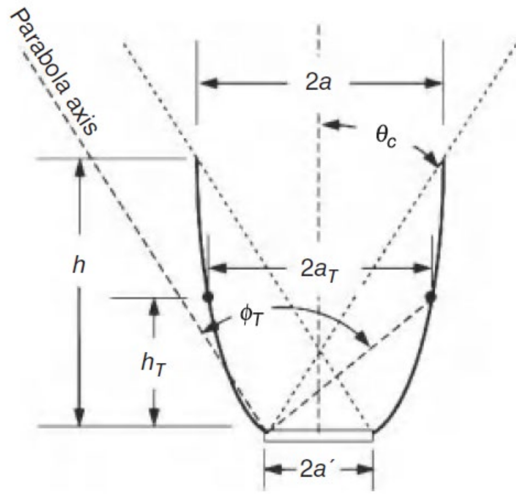


Figure 4.8: Parabolic trough design (Duffie et al., 2013)

Thus, the acceptance half angle can be determined using equation (4.18).

$$\Theta_c = \sin^{-1}(\frac{1}{C}) = 7.4^o \quad (4.18)$$

And, the focus will be;

$$f = Ar*(1 + \sin\Theta_c) = 0.117m \quad (4.19)$$

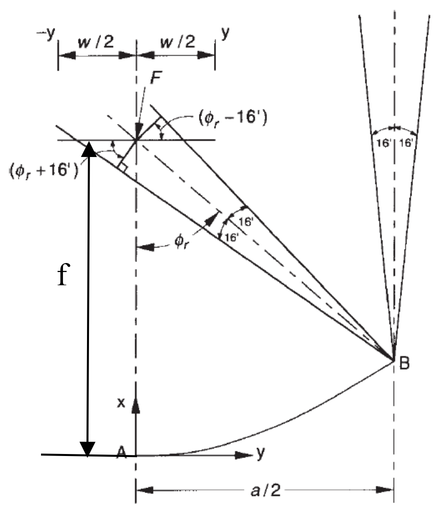


Figure 4.9: Design of CPC (Duffie et al., 2013)

Thus, combining figure 4.8 and 4.9, we have;

$$h = a^2/16*f = 0.35m \quad (4.20)$$

And, our parabolic equation will be;

$$Y = X^2/4f \quad (4.21)$$

For,

0.40m < X < -0.40m and 0 < Y < 0.35m

The final summary of selected materials and dimensions are shown on Table 4.2.

Table 4.2: Summary of selected materials

No.	Part name	Material	Dimension
1	Receiver (Oven)	Aluminum sheet metal painted black	Φ 0.1m x 1mx 1mm
2	Transparent tube	Acrylic plate	140 x 140 x 4mm
3	Parabolic reflector	Aluminum sheet metal	1.15m x 1m x 1mm
4	Front seals	Plywood	140 x 140 x 20mm
5	End seals	Plywood	140 x 140 x 20mm
6	Oven Door	High temperature rubber	Φ 0.1m x 13mm
7	Adjustable Stand	RHS (rectangular hallow steel)	25 x 25 x 2mm

Next, software simulations are used to validate the calculated results. COMSOL software is used to visualize the solar ray characteristics at the solar oven and identify the ray path and characteristics at the reflector and receiver. It is also used to analyze the heat transfer inside the oven.

Ray tracing and thermal analysis using COMSOL

4.4.1. Ray tracing

Next, software simulations are used to validate the calculated results. COMSOL software is used to visualize the solar ray characteristics at the solar oven and identify the ray path and characteristics at the reflector and receiver. It is also used to analyze the heat transfer inside the oven.

COMSOL Multiphysics is a cross-platform finite element analysis, solver and multi-physics simulation software. It allows conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs). COMSOL provides an IDE and unified workflow for electrical, mechanical, fluid, acoustics, and chemical applications (Wikipedia, 2015). Thus, it will be a helpful tool for simulation and validation of the project.

The ray tracing simulation is performed using a 2D model wizard on COMSOL. Geometrical optics physics is used for the analysis. The geometry is made of four objects; the parabolic reflector, the transparent cover, the receiver and a ray emitting boundary, as shown in figure 4.10. The size is taken from the final parameters of the design. Equation (4.21) is used to construct the parabolic reflector.

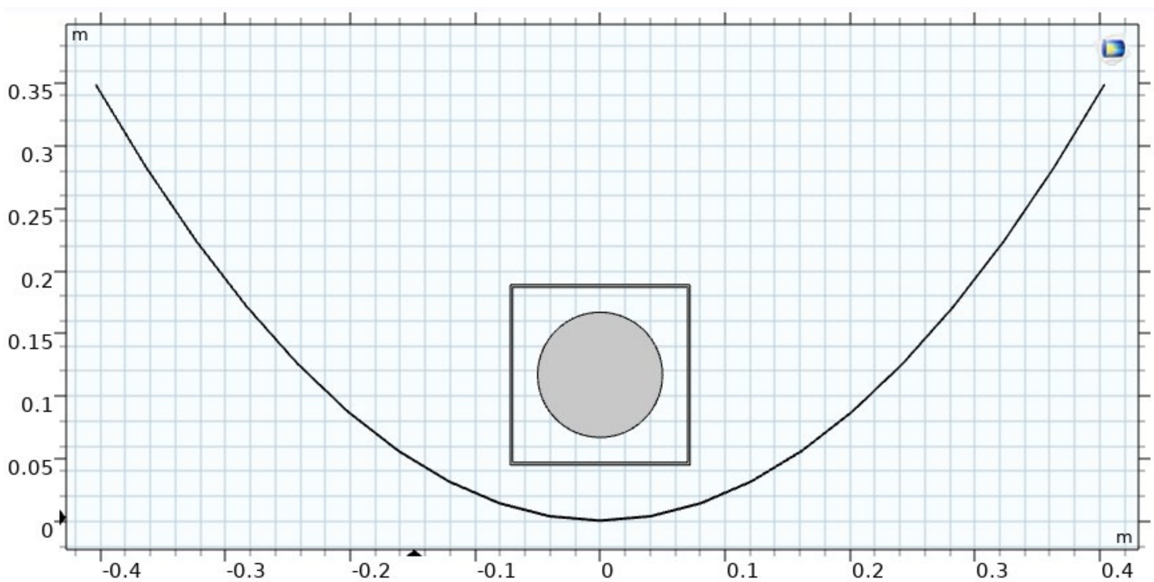


Figure 4.10: Reflector and receiver geometry on COMSOL

Aluminum material is assigned for the parabolic reflector form the COMSOL material library. Transparent acrylic sheet is assigned for the square cover from library. An illuminated surface releasing 100 rays is assigned for the boundary above the solar oven which emits its rays downwards on to the solar oven. Finally, the ray path is computed from 0 to 1 nanosecond with an interval of 0.01 nanosecond. The result of the ray trajectories is shown in figure 4.11.

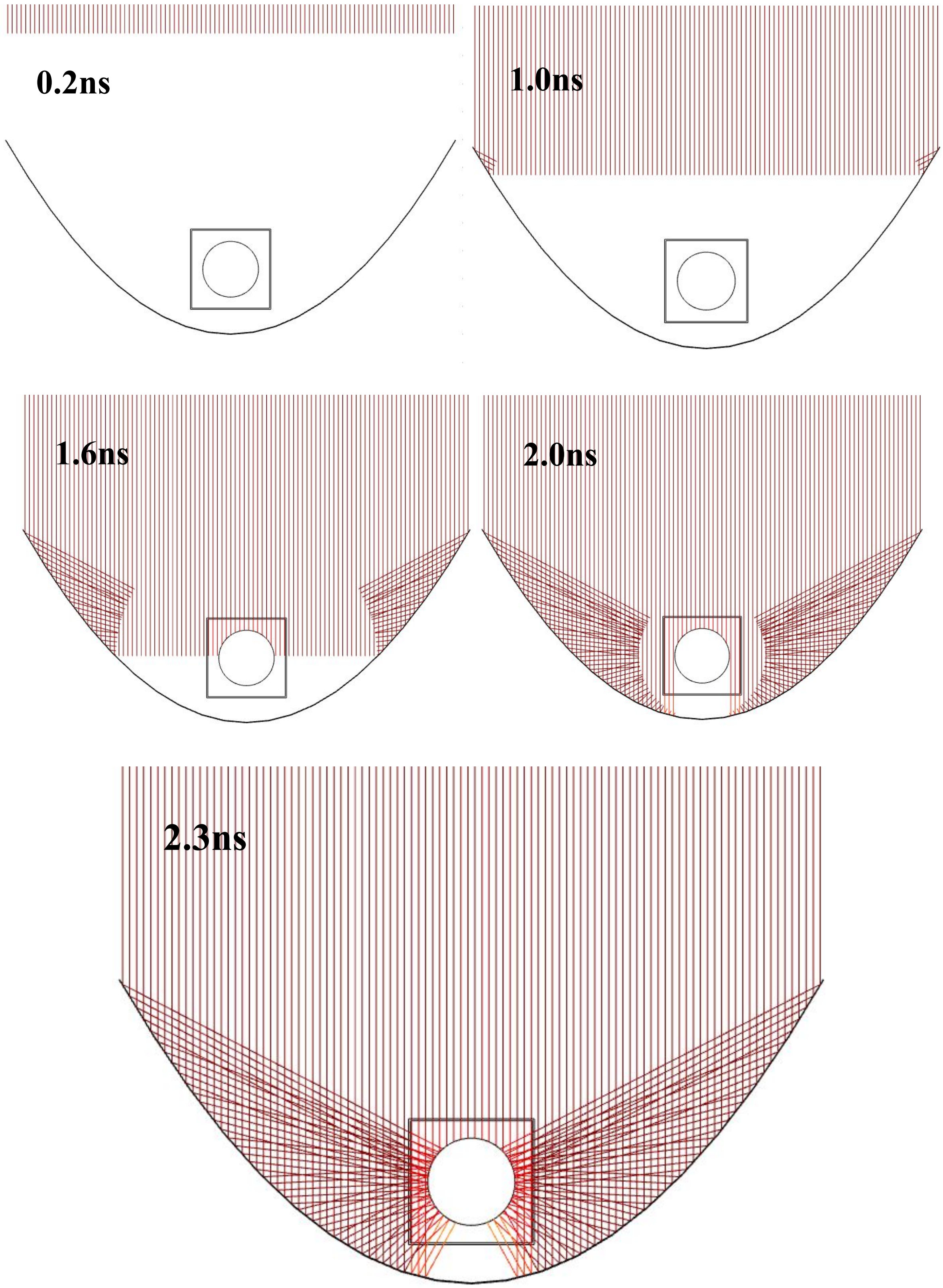


Figure 4.11: Solar oven ray trajectory simulation on COMSOL

Examining the ray trajectory at different fraction of seconds, as shown in figure 4.11, show us how the solar ray will reflect on the parabolic trough and reach the receiver for an incidence angle of 0º. Here, all the rays will reach the receiver surface and this validates the design but in practical, surface roughness losses, transparent cover optical losses and some impurities like dust and foreign particles on the solar oven will affect this result.

4.4.2. Thermal analysis

The thermal analysis at the receiver (oven) of the tube type direct solar oven is simulated on COMSOL using the 2D model wizard. The physics used for the analysis is a transient heat transfer in solids and fluids. The 2D representation of the solar oven for the geometry is taken by considering a sectional view at the middle of the oven, as shown in figure 4.12.

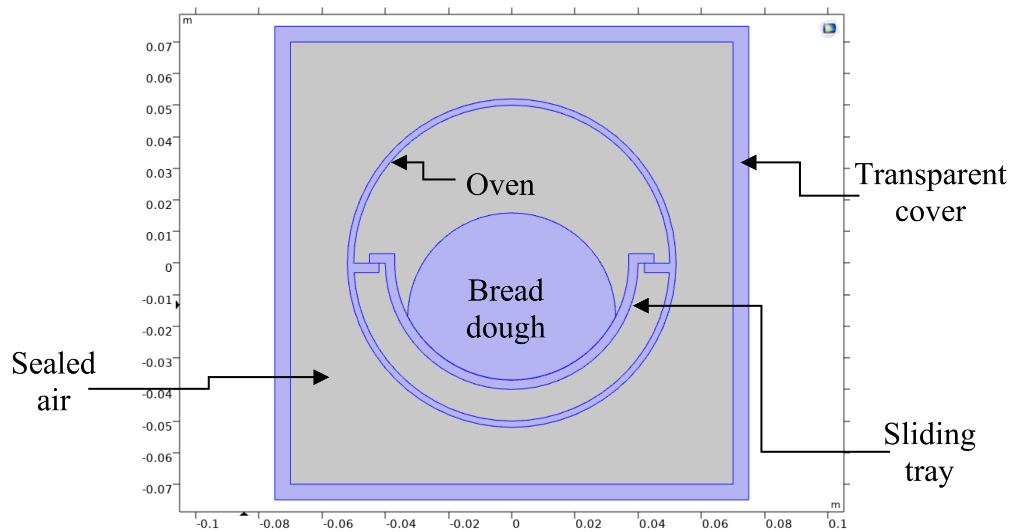


Figure 4.12: 2D geometry in COMSOL

Materials are assigned for the respective parts from COMSOL material library, except for the bread dough since it is not available in the software. Thus, a blank material is chosen for the bread dough and the properties in table 4.3 is assigned for the material. These properties are the same as the ones considered in the design.

Table 4.3: Parameters for COMSOL analysis

Parameters	Value
Area of bread	2.54 x 10^{-3}m² (1kg of dough, considering a unit depth)
Specific heat capacity of dough/bread	$C_p = 0.077T^2 - 68.94T + 16646$ (Adamic, 2012)
Density of dough/bread	$\rho = -0.647T + 587$ (Adamic, 2012)
Thermal Conductivity of dough/bread	$\kappa = 0.00001T^2 - 0.00634T + 1.47$ (Adamic, 2012)

After this, boundary conditions are assigned for the oven. There is a convective heat transfer at the outer surface of the transparent cover with a wind speed of 3.5m/s and average ambient temperature of 25ºC. And a temperature is assigned for the oven outer cover which is changed to analyze the heat transfer inside the oven at different temperature. The initial temperature of the oven, the bread dough and the surrounding air is considered to be 25ºC. Next, we proceed to the mesh.

The mesh/grid quality plays a significant role in the accuracy and stability of a CFD numerical computation. For a 2D geometry the mesh generator partitions the sub-domains into triangular or quadrilateral mesh elements which contain nodes. If the boundary is curved, these elements represent only an approximation of the original geometry. Each of the element nodes has specific thermal properties of apparent density, thermal conductivity, specific heat capacity, etc. (Monda et al., 2010). A dense unstructured mesh with triangular elements of appropriate size was generated in COMSOL Multiphysics 5.5. The mesh is finer near the edges where maximum heat transfer takes place. It was done by choosing a normal predefined mesh in COMSOL. Maximum mesh element size is 0.01m at the outer boundaries. In this problem, the meshed domain contains a total of 31082 triangular elements. There are no quadrilateral elements. The average mesh element quality is 0.9307 with a minimum mesh element quality of 0.3299. A mesh element quality >0.3, indicates that the mesh quality will not affect solution quality. The meshed dough is shown in figure 4.13.

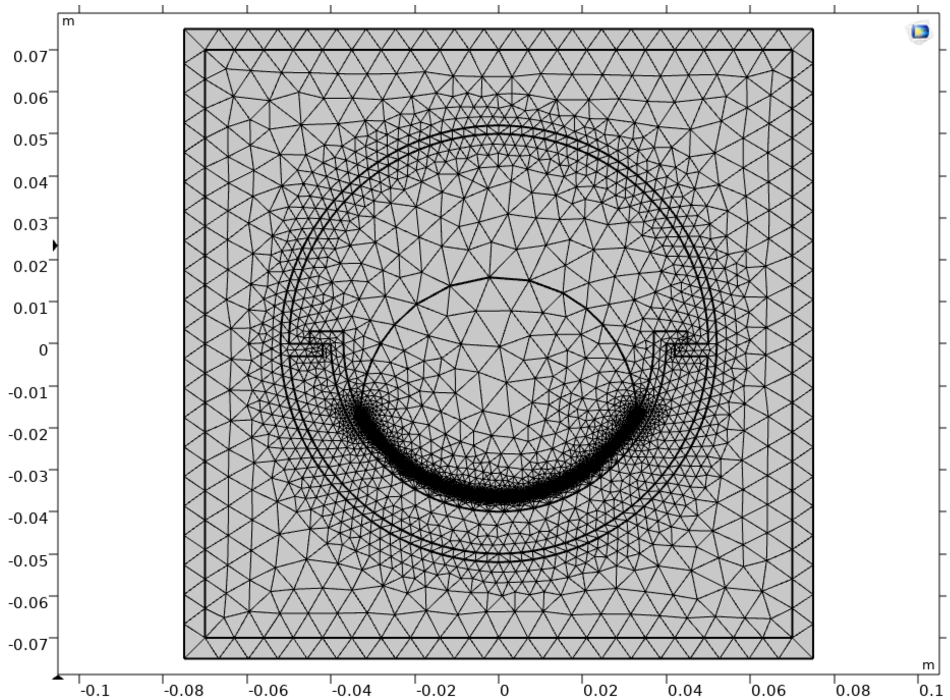


Figure 4.13: Meshed View

Finally, the transient heat transfer analysis is computed from 0 to 80mins with an interval of 5mins for different oven surface temperature. The 5mins interval is the maximum interval in for data collection in a solar cooker test. As mentioned in the previous topics, a bread is considered baked when the bread core temperature reaches 92-95ºC. Thus, for different oven temperatures, the time for the bread core to reach the baked temperature was analyzed using COMSOL and the result is shown in figure 4.14.

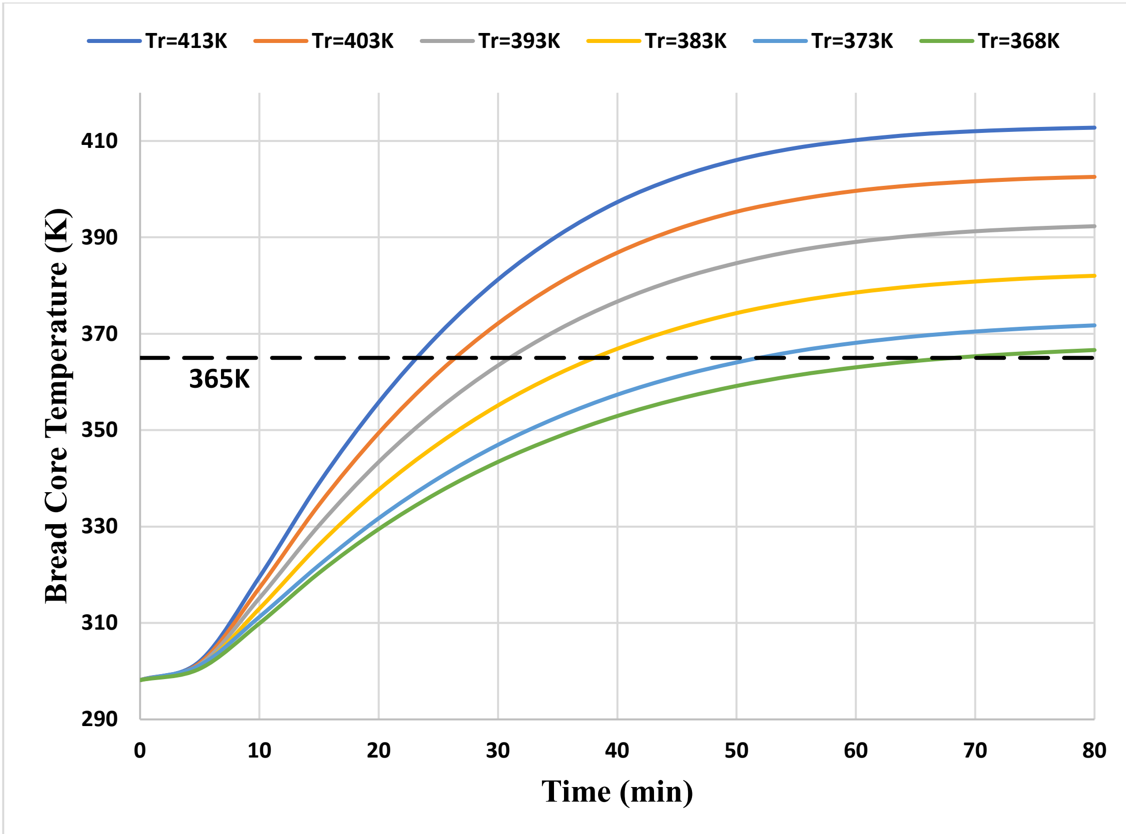


Figure 4.14: graph of bread core temperature at different oven temperature (Tr)

The baked bread temperature, 365K, is marked on the graph with a hidden line. Thus, for different oven surface temperatures, we can determine the baking time of the solar oven from the graph. Thus, for an average oven surface temperature of 100ºC, the solar oven will take 50mins to bake 1kg of bread dough. On the design section, based on the minimum yearly average solar radiation from the past 5 years, the surface temperature of the solar oven was calculated to be around 110ºC for the selected aperture area (refer figure 4.7). The COMSOL graph in figure 4.14 shows that for an average oven surface temperature of 110ºC, the solar oven takes around 35mins to bake 1kg bread dough. The result indicates a 5mins difference between the design and the simulation analysis.

The next analysis on the COMSOL result is the temperature variation of different points of the solar oven with time. This was also evaluated for different oven surface temperatures and the result is present graphically on the 2D geometry as shown in figure 4.15. It is used to predict the actual performance of the solar oven and the expected heat loss for a given oven surface temperature.

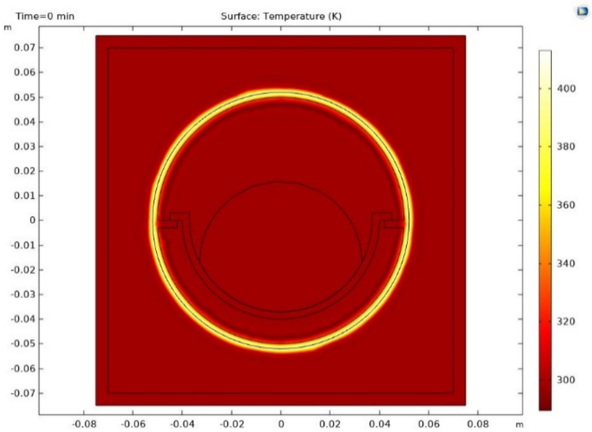


Figure 4.15a: 0min

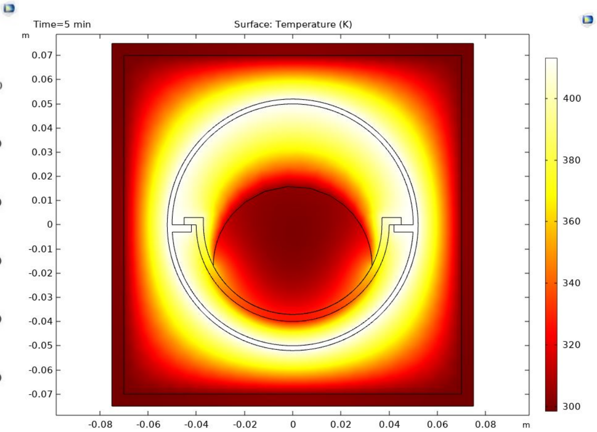


Figure 4.15b: 5min

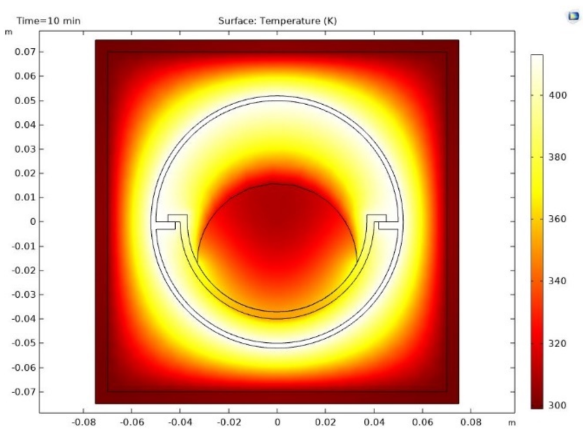


Figure 4.15c: 10min

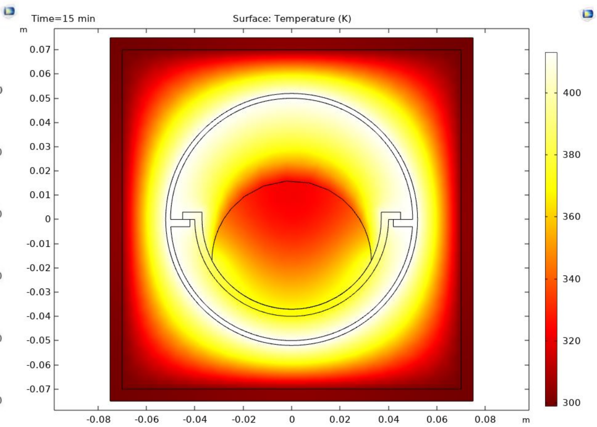


Figure 4.15d: 15min

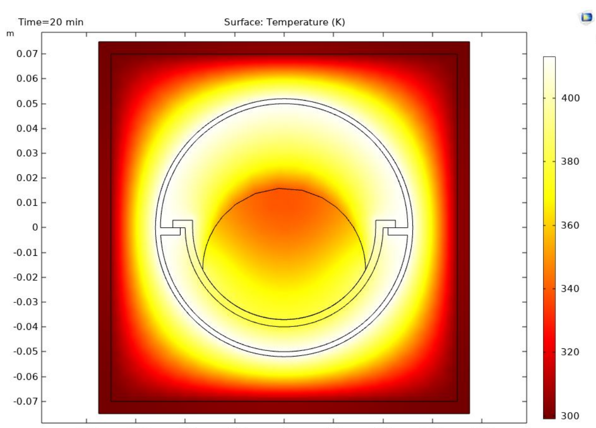


Figure 4.15e: 20min

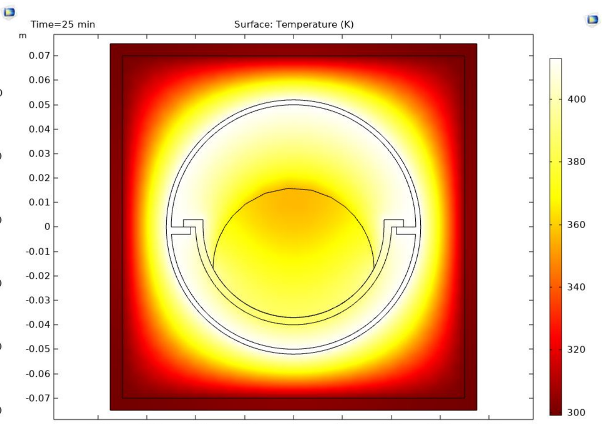


Figure 4.15f: 25min

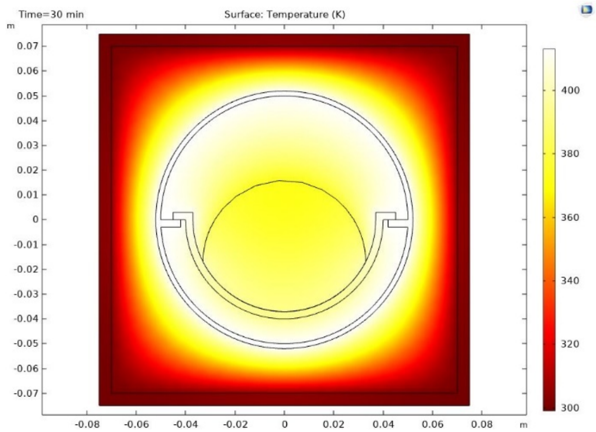


Figure 4.15g: 30min

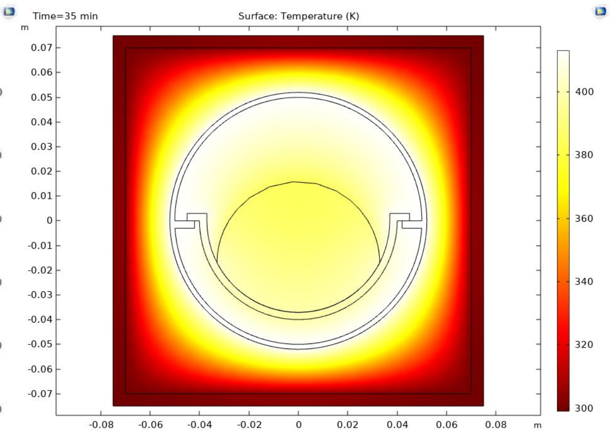


Figure 4.15h: 35min

Figure 4.15: heat transfer analysis in COMSOL

The graphical representation of the heat transfer and temperature distribution shown in figure 4.15 can also be presented in graph form, as shown in figure 4.16, for a more accurate reading of the temperatures with time. These graphs will later be used for comparing with the data collected during the actual experimental.

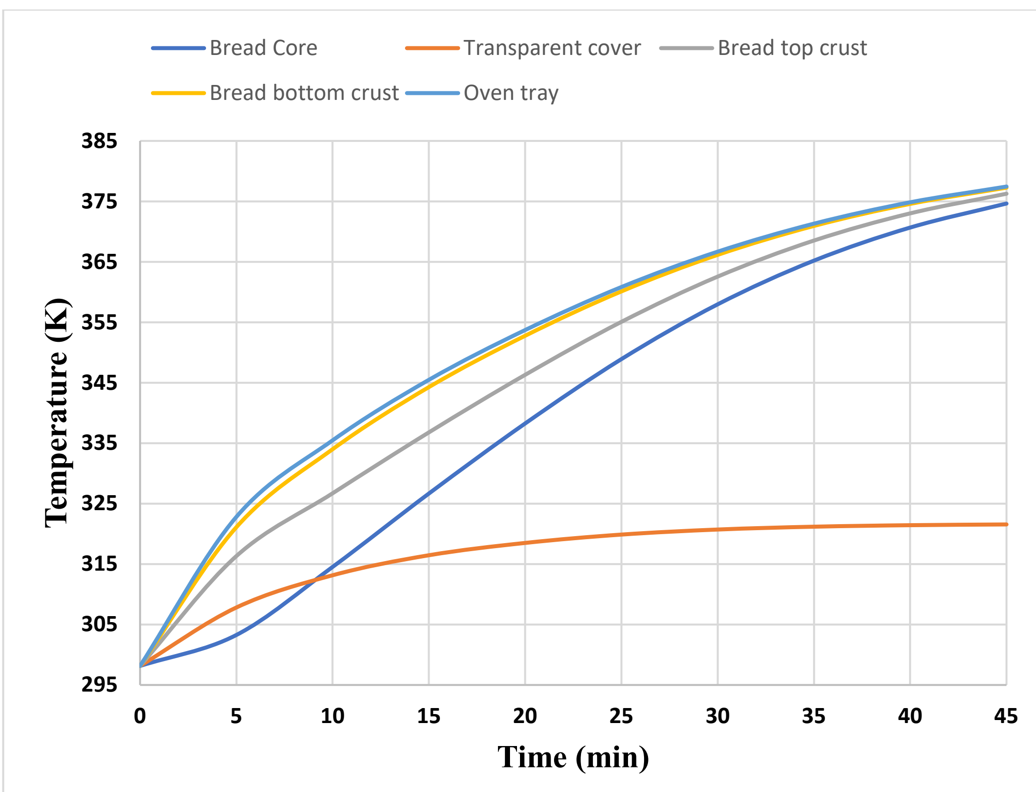


Figure 4.16: COMSOL result of temperature variation inside the solar oven with time

Figure 4.15 and 4.16 shows the heat transfer analysis result for the average oven surface temperature of 110ºC. The graphs show that the rate of the temperature rise of the oven body and the bread crust is higher for the first 5mins and decreases as the baking time proceeds. But for the bread core, it has a low rate of temperature rise in the first 5mins but this rate will gradually increase for the next ten to fifteen minutes. After this, the temperature rising rate will reduce and have a similar rate with the crust for the remining baking time. This is because the bread dough has a low thermal conductivity which increase with temperature as shown in table 4.3.

CHAPTER FIVE:
MANUFACTURING AND TESTING

5.1. Manufacturing

Manufacturing of the low-cost direct solar cooker will be based on the dimension obtained from analytical analysis. Thus, a workshop drawing of all parts of the prototype is prepared first based on the design analysis, appendix 3. This step is performed by using SOLIDWORKS software, as it is a powerful tool for drawing 3D and 2D geometry of parts and simulate their assembly. The material type of each part can also be clearly represented on the software. This step helps in preparing a time and resource schedule for the manufacturing process.

Manufacturing of the prototype can be divided in to four parts; manufacturing of the receiver, the parabolic trough, the tray and the stand. Manufacturing of the receiver requires four parts; the oven cover, the acrylic (transparent plastic) cover, the end seal and the front seal.

As mentioned in the previous chapters, the oven is made of aluminum sheet metal rolled through a sheet metal roller to its designed diameter and connected end to end with rivets. High temperature gasket maker is used at the rivet connections for air-tight sealing. Finally, the outer part of the oven is painted black to increase its absorptivity. The transparent cover is made of four transparent acrylic plates glued together and sealed air tight edge to edge with semi-transparent silicon sealant to form a rectangular prism. The front and end seals are carved from a wood plate according to dimensions mentioned on the attached drawing. Milling machine and a hole saw cutter is used for this work. Figure 5.1 to 5.3 shows the workshop drawings on SOLIDWORKS and the manufactured parts of the oven cover, the front seal and the end seal respectively.

Figure 5.1: Oven drawing and manufactured part

Figure 5.2: Front seal drawing and manufactured part

Figure 5.3: End seal drawing and manufactured part

The front and end seal are connected to the acrylic plates using screws and high temperature silicon sealant, while the oven connection is made by epoxy and high temperature silicon sealant. The manufacturing and assembly steps of the solar oven receiver in SOLIDWORKS and in practical are shown in figure 5.4 and 5.5, respectively.

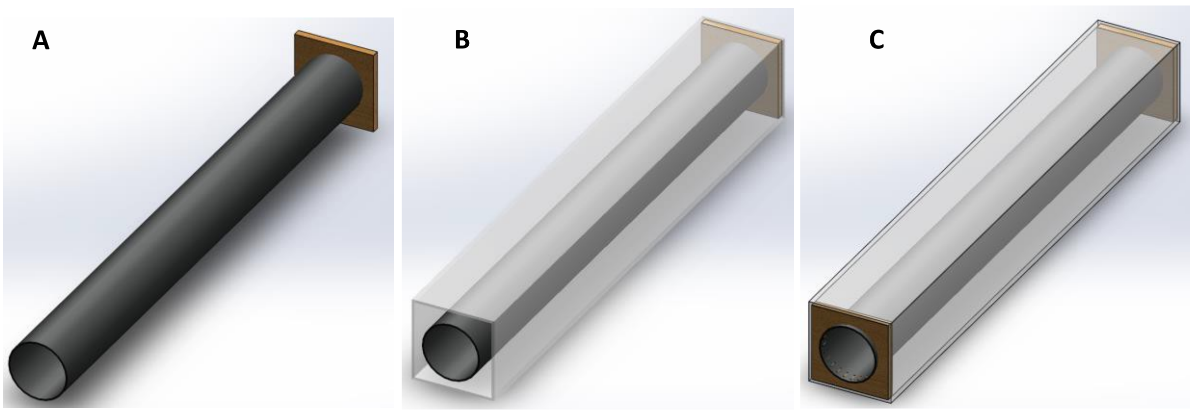


Figure 5.4: SOLIDWORKS receiver assembly steps

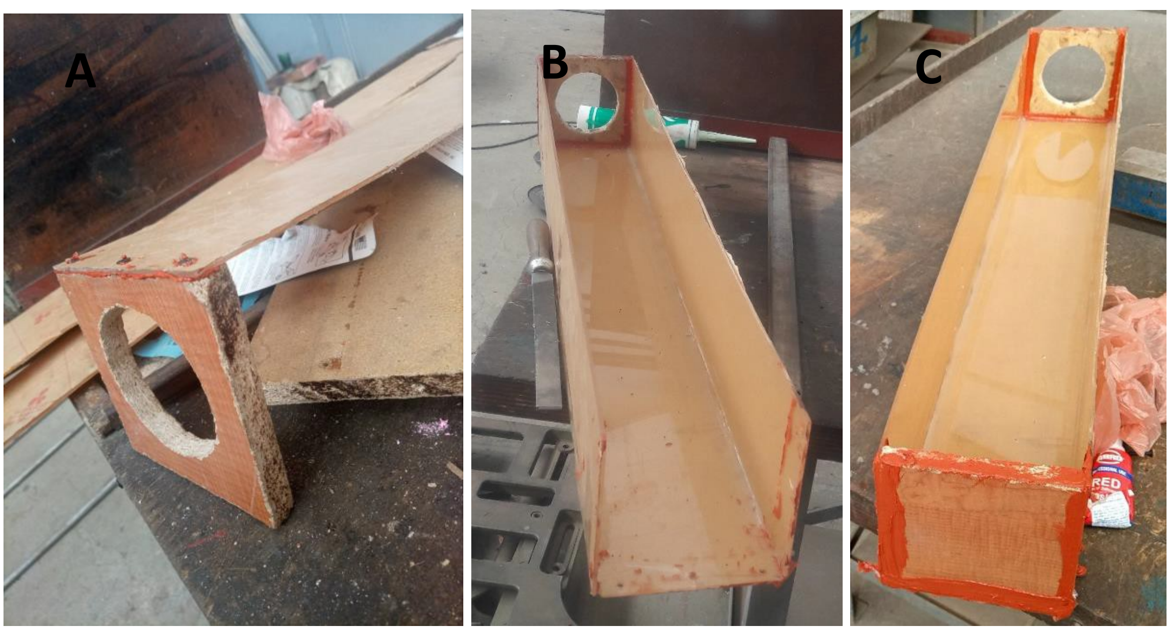


Figure 5.5: Practical receiver assembly steps

The parabolic trough assembly is manufactured by using two wooden plates and an aluminum sheet metal. First a one-to-one scale of the parabolic curve is drawn on the wooden plates, and using a small electrical hand jigsaw, the parabolic curve is carved on the wooden plates. Then the sheet metal is screwed on the plates after placing them one meter apart from each other. Figure 5.6 and 5.7 show The SOLIDWORKS and the practical manufacturing and assembly steps, respectively.

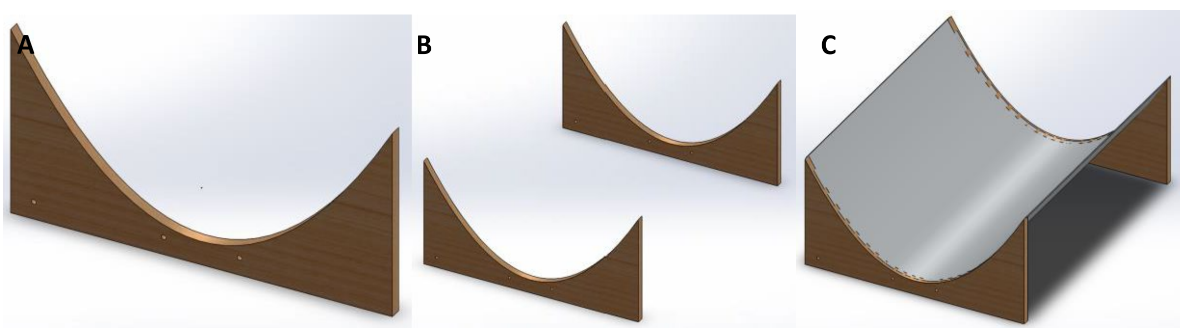


Figure 5.6: SOLIDWORKS assembly of the Parabolic trough

Figure 5.7: Practical assembly of the Parabolic trough

The tray assembly is made of two parts. And these are the sliding tray and the oven door. The sliding tray is made of food grade aluminum sheet metal. It is made by rolling, cutting and bending the sheet metal to the designed size. The door is made of rubber with sheet metal support on the outside and a handle riveted to the sheet metal. Figure 5.8 and 5.9 shows the sliding tray and the oven door in SOLIDWORKS and in practical, respectively.

Figure 5.8: Sliding tray SOLIDWORKS and manufactured prototype

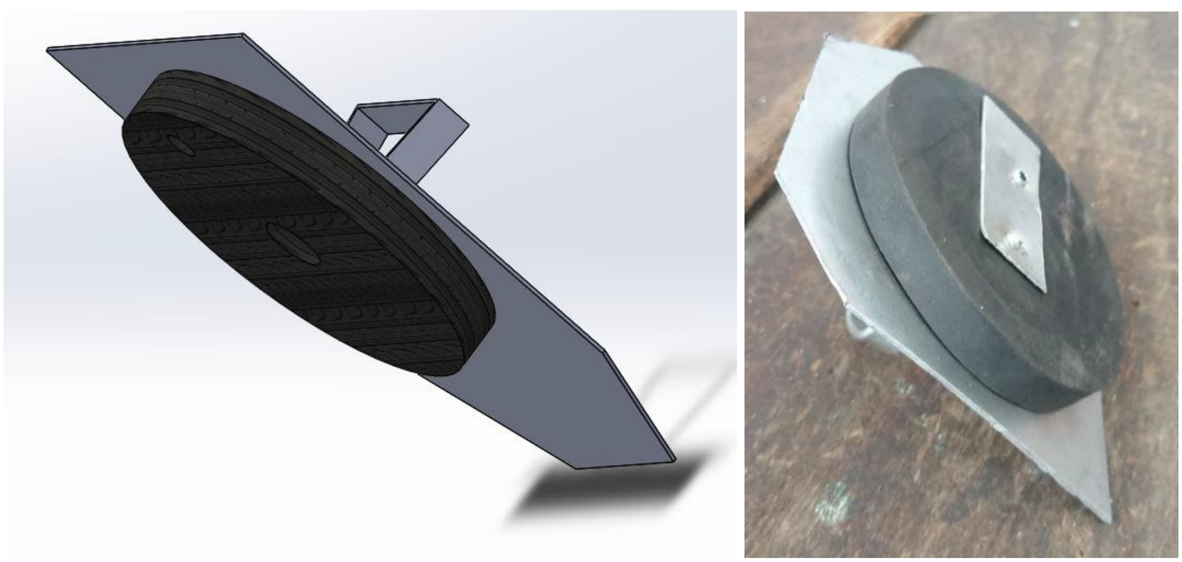


Figure 5.9: Oven door SOLIDWORKS and manufactured prototype

Finally, the stand is fabricated using RHS bar in a way that the whole solar oven assembly can be tilted and adjusted sideways. Thus, the final assembly of the tube type direct solar oven in SOLIDWORKS and in practical is shown in figure 5.10.

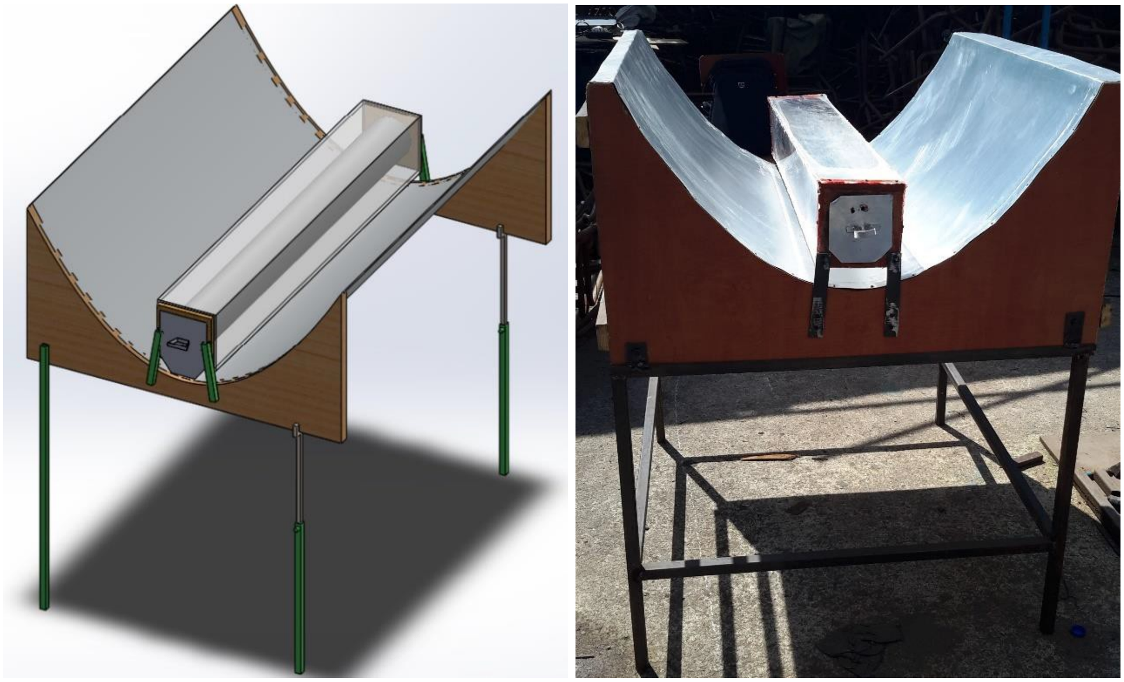


Figure 5.10: Final assembly in SOLIDWORKS and in practical

5.2. Testing of the Prototype

For testing the tube type direct solar oven prototype, a no-load test, a bread baking test and a water boiling test were used. The no-load test is conducted to find the stagnation temperature, the pre-heat time and thus, the first figure of merit of the solar oven. The water boiling test is conducted to find the performance index of the solar oven based on ASABE S580 test standard and its thermal efficiency. And the bread baking test is conducted to find the actual bread baking performance of the oven and its utilization efficiency. The tests were conducted in Addis Ababa Institute of Technology campus, where the latitude is 9.039^o and the longitude is 38.763^o. The elevation of the test location is 2,465m above sea level.

A National Instrument data logger, NI DAQ-9211, thermocouple and data logger are used to record the water temperature and the oven temperature at different time. Thus, a hole is drilled on the oven door and the thermocouples are passed through this hole and placed inside the oven. One thermocouple is placed 10mm above the bottom of the tray using high temperature adhesive tape and the other is placed around the center of the oven. The thermocouples are connected to the NI DAQ-9211 data logger which is connected to a PC. Thus, all readings are recorded on the computer using LAB-VIEW software which is compatible with the NI data logger.

Figure 5.11: Thermocouples passed through oven door and placed inside oven

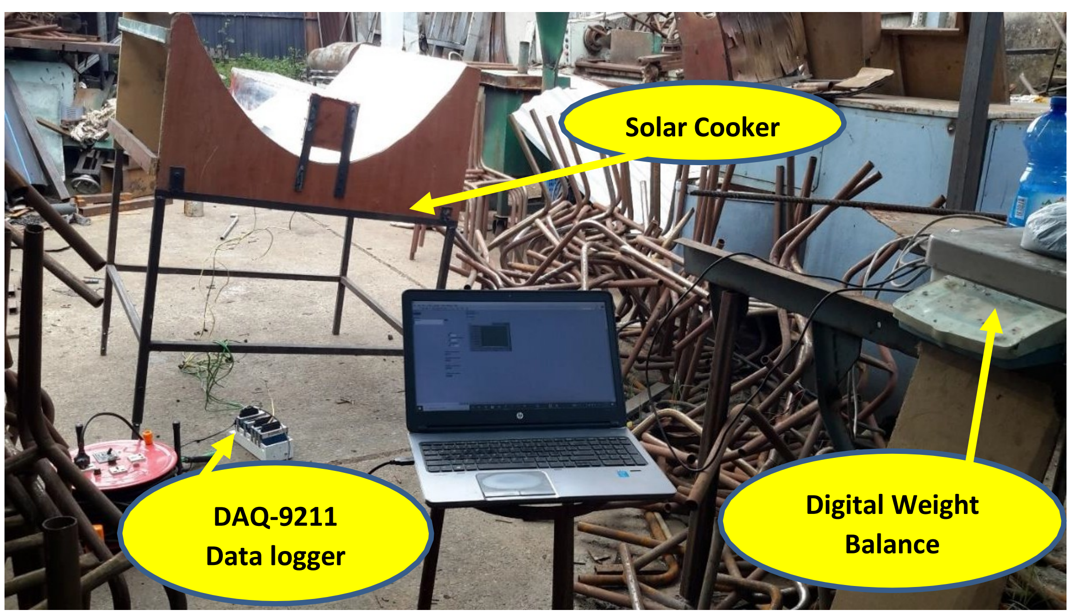


Figure 5.12: Testing arrangement of the tube type direct solar oven

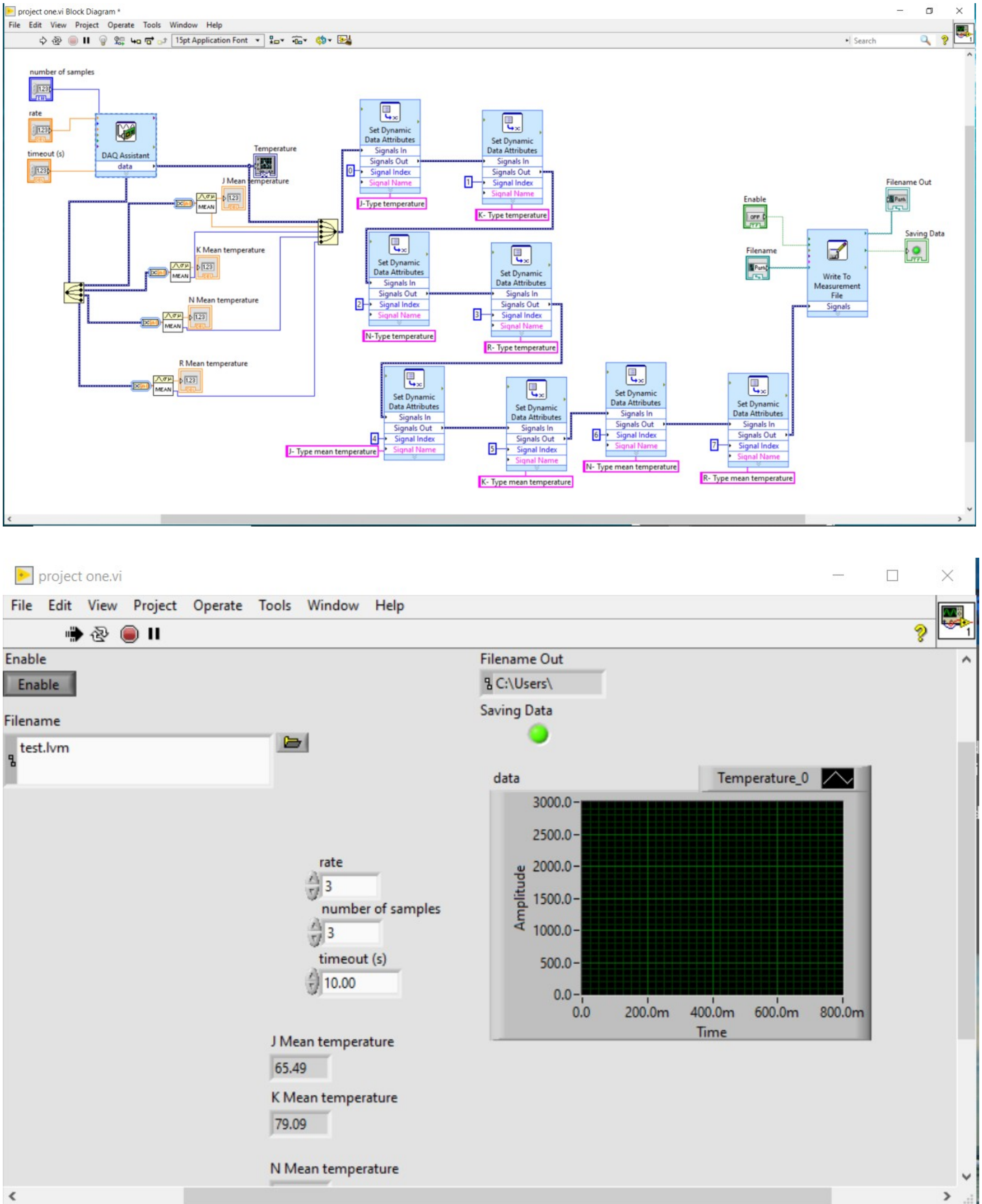


Figure 5.13: Data logger software setup and display

The tests were conducted during different days. The wind speed, the ambient temperature and the solar radiation from Ethiopian meteorology was recorded for the test time. The tests starting and stopping time was also recorded. During the test, both the oven temperature and the water/bread dough temperature were recorded in an interval of less than 5mins. The tilt angle for the solar oven during the test hour was determined by first determining the incidence angle through the following steps.

The declination angle, δ, is determined by using equation (5.1);

$$\delta = 23.45\sin(\frac{360}{365}(n + 284) \qquad (5.1)$$

Where n is the day of the test.

The hour angle, ω, at the time of test can be found by determining the day light hour of the day (sun rise to sun set). And for this we need the sunset angle at the date of the test.

$$\cos \omega_{sunset} = -\tan \delta \tan \phi \qquad (5.2)$$

$$\text{Day light hour} = \frac{2}{15}(\omega_{sunset}) \qquad (5.3)$$

Then, through ratio method the standard solar test time, ST, can be found using equation (5.4).

$$\omega = (ST - 12) \times 15 \qquad (5.4)$$

The zenith angle, θz, at the time of test was found by using equation (5.5);

$$\cos \theta z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \qquad (5.5)$$

The solar incidence angle, θ, is the angle between the sun's rays and the normal on a surface. For a horizontal plane, the incidence angle, θ, and the zenith angle, θz, are the same.

The “tilt angle” or “elevation angle” describes the vertical angle of the solar oven parabolic trough in relation to a horizontal surface on the ground as shown in figure 5.14.

Figure 5.14: Tilt angle of the tube type direct solar oven

The parabolic Trough of the collector is oriented as east-west position and to obtain the best performance parameters of the collector, the optimal position of trough to the sunlight is maintained by adjusting the tilt angle, ß, for the specific day and corresponding time of a day using equation (5.6).

$$ß = \phi \pm 15^{o} \quad (5.6)$$

The optimum tilt angle is calculated by adding 15 degrees to the latitude during winter, and subtracting 15 degrees from the latitude during summer.

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CHAPTER SIX:
DATA ANALYSIS AND DISCUSSION

6.1. No-load test analysis

The no-load test was conducted on Oct 15, 2021 at 09:50 AM local time, where the weather condition was sunny and the data collected from Ethiopian meteorology show that the average solar radiation during the test was 651W/m^2. The test was conducted from 09:50AM up to 11:00AM, where the average ambient temperature was 25 ºC. During the test, both the oven wall and oven space temperatures were recorded. The result showed that within 67mins the oven space temperature raised from 24 ºC up to 114.76 ºC and the oven wall temperature raised from 24 ºC up to 126.71 ºC, Figure 6.1.

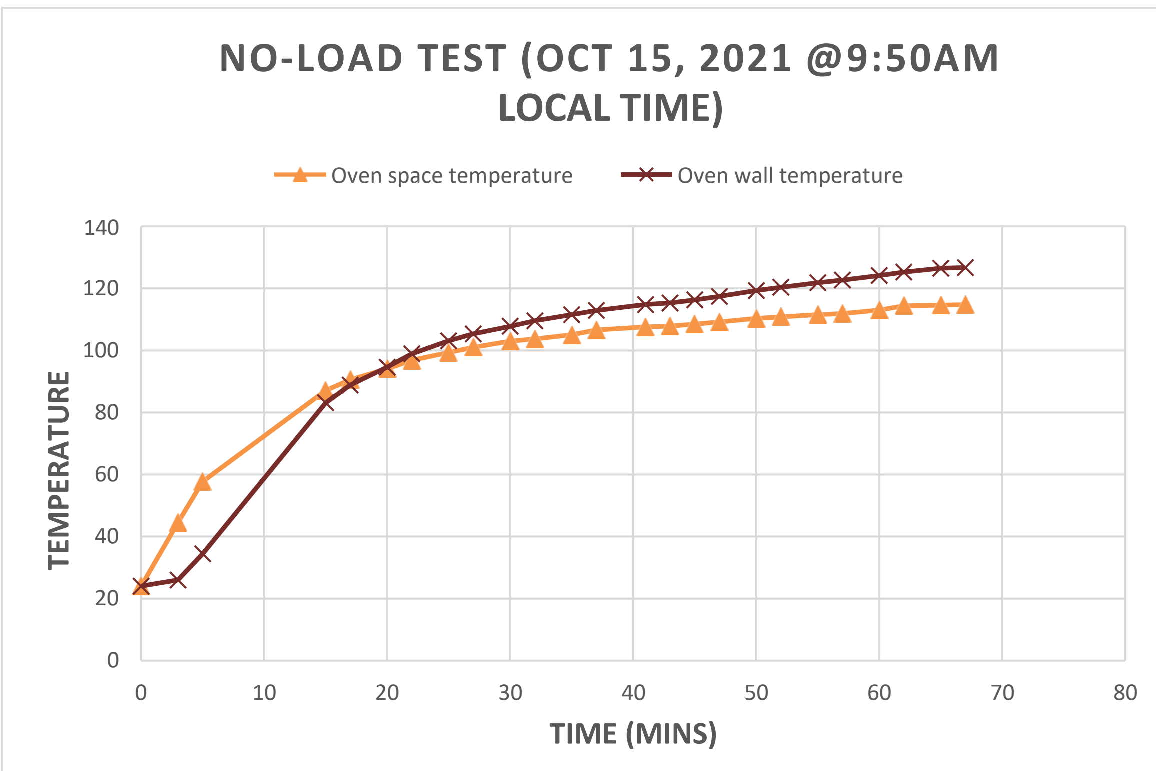

Figure 6.1: No-Load test result

From the test both the oven space and oven wall temperature reach above 90ºC within 20mins. This is the pre-heat time. The stagnation temperature depends on the solar insolation and for an average solar insolation of 651W/m^2, it takes 67 mins to reach a stagnation temperature of 127ºC.

6.2. Water boiling test analysis

The WBT test was conducted on Oct 15, 2021 at 11:10 AM. According to test standards, solar water boiling tests shall be conducted with a load of 7,000g potable water per square meter of intercept area. Thus, since the prototype has an intercept area of $0.1m^2$, the test was conducted with 700g of water using an electronic balance. The average solar insolation during the WBT was 692.5 W/m^2 according to Ethiopian Meteorology solar data. The test was conducted from 11:10AM to 11:40AM for 30mins. During this time, the average ambient temperature was 25 ºC and the water raised from 24.82 ºC up to 84.20 ºC, as shown in figure 6.2.

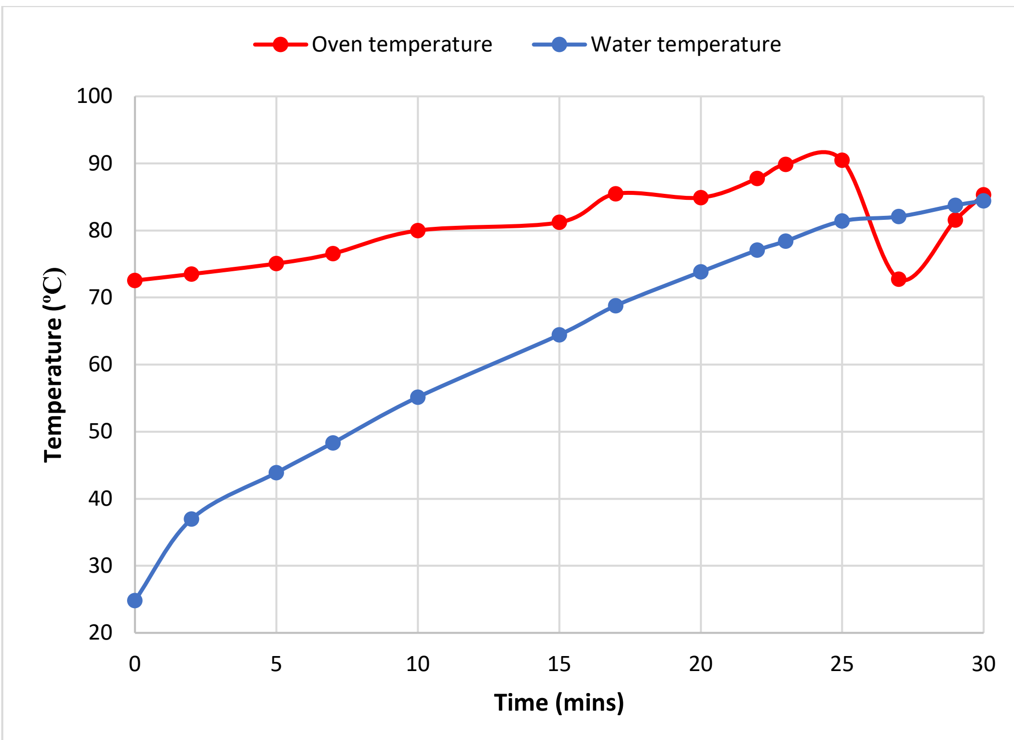

Figure 6.2: Water boiling test result

6.3. Performance indicator

First figure of merit (F1)

The no-load test helps to determine the first figure of merit of the solar oven. The first figure of merit (F_1) is defined as the ratio of optical efficiency, (η_o), and the overall heat loss coefficient, (U_L). A quasi-steady state (stagnation test condition) is achieved when the stagnation temperature is attained. High optical efficiency and low heat loss are desirable for efficient cooker performance. Thus, the ratio 'η_o / U_L' which is a unique cooker parameter can serve as a performance criterion. Higher values of F_1 would indicate better cooker performance

(Folaranmi, 2013).

$$F_1 = \eta_o / U_L = (T_{ps} - T_{as}) / I_s \quad (6.1)$$

Where, F_1 is first figure of merit (Km^2w^{-1}), η_o is optical efficiency (%), U_L is overall heat loss factor ($Wk^{-1}\ m^{-2}$), T_{ps} is absorber plate temperature (°C), T_{as} is ambient temperature (°C), and I_s is insolation on a horizontal surface (Wm^{-2}). Thus, using equation 6.1, the first figure of merit for the solar oven is, $F_1 = 0.158$.

Second figure of merit (F_2)

It quantifies the amount of heat that can be transferred from the oven to the load it contains. It could be called a sensible heating because during this test, heat is transferred from the oven to the water (load) without phase change. Mathematically, it is expressed using Equation (6.2).

$$F_2 = \frac{F_1 M_w C_w}{A_a \Delta t} \ln \left[\frac{\left(1 - (T_{wi} - T_{av}) / (F_1 . I_s)\right)}{\left(1 - (T_{wf} - T_{av}) / (F_1 . I_s)\right)} \right] \quad (6.2)$$

Where;

M_w = Mass of water

C_w = Specific heat capacity of water

T_{wi} = Initial temperature of water

T_{wf} = Final temperature of water

Δt = time taken to reach from initial to final temperature of water

A_a = Area of aperture

T_{av} = Average ambient air temperature during the test

I_s= Average solar radiation on a horizontal surface

From the water boiling test, the value of F_2 will be 0.23. This value is used to quantify the amount of heat absorbed by the load during the sensible test. Thus, 0.23W of heat is absorbed from the oven per m^2 for every degree rise in the oven temperature. Hence, considering the area of the aperture, which is 0.8 m^2, this means that 0.184J of heat is absorbed by the load (700g of water) for every degree rise in the oven temperature in a second.

Cooking power (P)

This parameter indicates the sensible heat gain of the oven, and it is the measure of the oven's ability to effectively heat food. This parameter is of great importance to the end users of the product. It is expressed mathematically by using equation (6.3):

$$P = \frac{Heat\ gained\ by\ load}{Heating\ time} = \frac{M_w C_w \Delta T}{\Delta t} \quad (6.3)$$

Where, ΔT is the difference between the final and initial temperature of water. Thus, P for the water boiling test is 97W. Next, the cooking power will be standardized using equation (6.4). This will enable comparison of results from different locations and data taken following test standards. The standard cooking power, P_{std} is a suitable parameter to for comparing concentrated solar cookers. Thus, equation (6.3) was standardized by correcting it to a standard insolation of 700 W/m^2 as shown in equation (6.4).

$$P_{std} = \frac{P\ x\ 700}{I_s} \quad (6.4)$$

Therefore, the standard cooking power of the tube type direct solar oven is 98W.

Thermal efficiency (η)

The thermal efficiency indicates how much percent of the available solar radiation on the aperture area does the oven convert to useful energy. And the general formula for this is shown in equation (6.5).

$$\eta = \frac{Output}{Input} = \frac{M_w C_w \Delta T}{I_s A_a \Delta t}$$

Thus, the thermal efficiency of the tube type direct solar oven is 17.3%.

6.4. Bread baking test analysis

The first bread baking test was conducted on Oct 25, 2021 at 10:12AM local time, where the weather condition was partially cloudy. The Ethiopian meteorology data showed that the solar insolation of the location at the time of test was 697.5 W/m^2 and the average ambient temperature during the testing hour was 24 ºC. The test was conducted from 10:12AM up to 11:03AM for 51mins, during which both the oven space temperature and the bread core temperature were recorded at different time intervals. And as shown in figure 6.3, it took

51mins to raise the bread core temperature from 25.09 ºC up to 88.60 ºC.

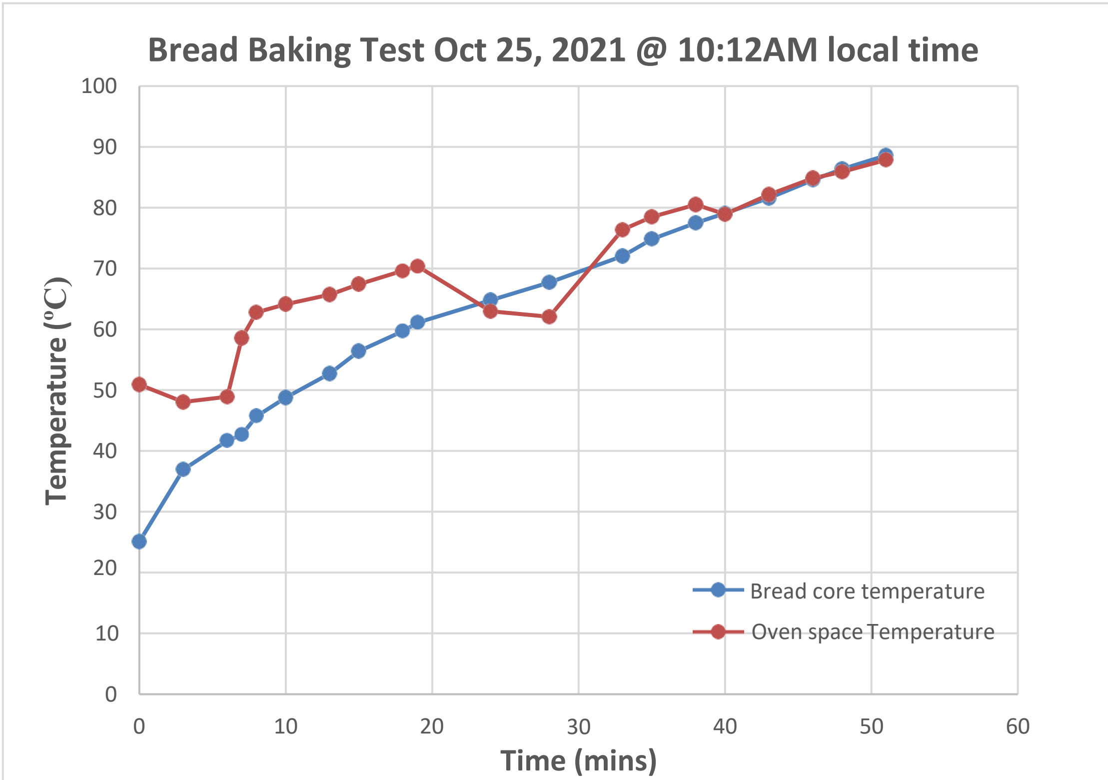

Figure 6.3: The first bread baking test result

The second bread baking test was conducted on Dec 11, 2021 at 12:03PM local time, where the weather condition was sunny. The Ethiopian meteorology data showed that the solar insolation of the location at the time of test was 691 W/m^2 and the average ambient temperature during the testing hour was 22 ºC. The test was conducted from 12:03PM up to 12:43PM for 40mins, during which both the oven space temperature, the bread core temperature and the ambient temperature were recorded at different time intervals. And as shown in figure 6.4, it took 40mins to raise the bread core temperature from 26.97 ºC up to 92.80 ºC.

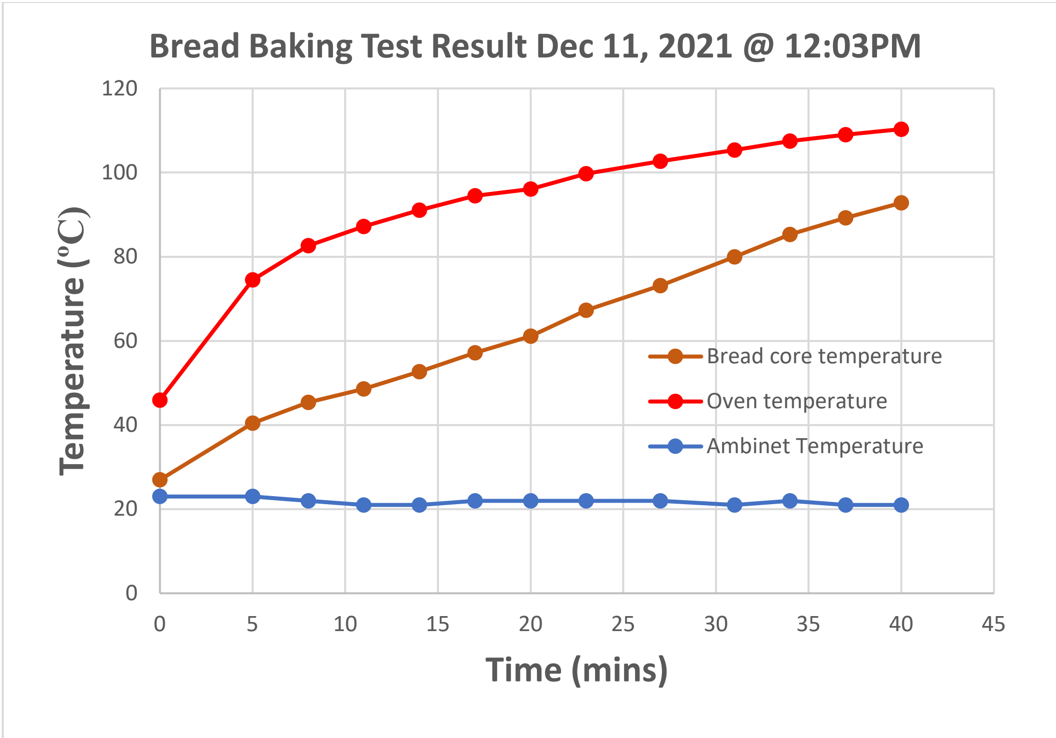

Figure 6.4: The second bread baking test result

The final bread baking test was conducted on Dec 18, 2021 at 12:45PM local time, where the weather condition was sunny. The Ethiopian meteorology data showed that the solar insolation of the location at the time of the test was 641.3 W/m^2 and the average ambient temperature during the testing hour was 24 ºC. The test was conducted from 12:45PM up to 01:25PM for 40mins, during which both the oven space temperature, the bread core temperature and the ambient temperature were recorded at different time intervals. And as shown in figure 6.5, it took 40mins to raise the bread core temperature from 26.11 ºC up to 95.47 ºC.

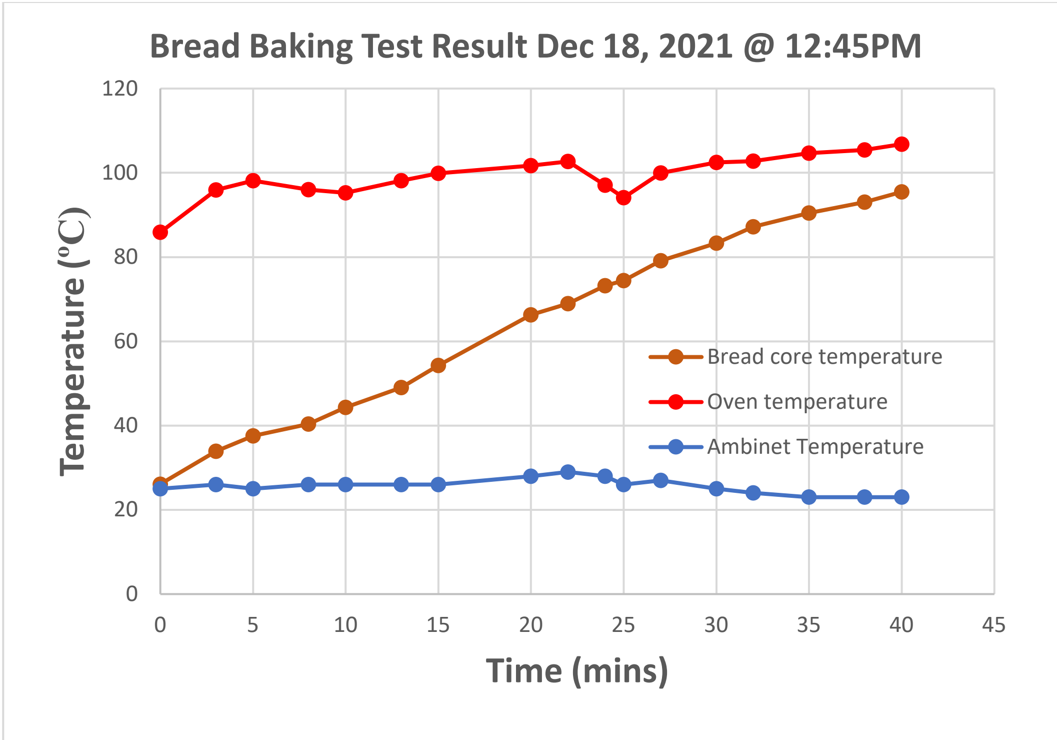

Figure 6.5: The third bread baking test result

The bread baking test was conducted to find the actual bread baking performance of the solar oven and its utilization efficiency. The output product quality is also compared with Sheger bread.

Utilization efficiency

To find the utilization efficiency of the prototype we use equation 4.1 and 4.2 together with the experimental data collected. Thus, for the first bread baking test, the test showed that for a solar insolation of 697.5 W/m², the tube type direct solar cooker raised the temperature of one kilogram of bread/dough from 25.1 ºC to 88.6 ºC in 51 min. Inserting the temperatures and mass of the bread dough in to equation 4.1 and 4.2 and using the MATLAB code on appendix 1, it shows that the useful energy transferred to the bread dough is 282 kJ. Therefore, the total power gained by the bread will be 92W. For an aperture area of 0.80m², the effective incident radiation measured on the plane of aperture will be 558W. Thus, the utilization efficiency of the tube type direct solar cooker for the first bread baking test is 16.5%.

$$P_{useful} = 282\text{KJ} / 51\text{mins} = 92\text{W}$$

And the power available to the solar cooker is found by multiplying the incidence solar radiation and aperture area.

$$P_{available} = 697.5 \text{ W/m}^2 \text{ X } 0.80\text{m}^2 = 558\text{W}$$

Thus, the utilization efficiency of the tube type direct solar cooker for bread test one will be;

$$\eta_{eff} = \frac{P_{useful}}{P_{available}} = 16.5\%$$

In the second bread baking test, the core temperature of a 1Kg bread dough raised from 26.97 ºC up to 92.80 ºC in 40mins at an average solar insolation of 691 W/m².

$$P_{useful} = 285\text{KJ} / 40\text{mins} = 119\text{W}$$

$$P_{available} = 691\text{W/m}^2 \text{ X } 0.80\text{m}^2 = 553\text{W}$$

$$\eta_{eff} = \frac{P_{useful}}{P_{available}} = 21.5\%$$

And on the third bread baking test, the core temperature of a 1Kg bread dough raised from 26.11 ºC up to 95.47 ºC in 40mins at an average solar insolation of 641.3 W/m².

$$P_{useful} = 295\text{KJ} / 40\text{mins} = 123\text{W}$$

$$P_{available} = 641.3\text{W/m}^2 \text{ X } 0.80\text{m}^2 = 513\text{W}$$

$$\eta_{eff} = \frac{P_{useful}}{P_{available}} = 24.0\%$$

The utilization efficiency of the tube type direct solar oven increases as the solar radiation decreases. This is because the insulation of the solar oven is an air tight transparent chamber. And the thermal conductivity of air increases with increase in air temperature. Thus, the insulation property of the air tight chamber reduces for high oven wall temperature.

The texture and color of the final baked bread using the prototype is compared with Sheger bread. The result shows that the bread baked using the tube type direct solar oven has similar texture and crust color (crust browning effect) with Sheger bread, as shown on figure 6.6 and 6.7.

Figure 6.6: Sheger bread

Figure 6.7: Bread baked using the tube type direct solar oven

CHAPTER SEVEN:
ECONOMIC ANALYSIS

Simple payback period

The cost breakdown for producing one unit of a tube type direct solar oven is shown in table 7.1. The total cost is Birr 5,500 ($100). The aim of the economic analysis is to determine the payback period of the solar oven compared to biomass baking, since biomass is a widely used fuel source for baking in Ethiopia.

Table 7.1: Cost breakdown of one unit tube type direct solar oven

No.	Item	Size (quantity) required	Unit Price (ETB)	Total Price (ETB)	Remark
1	Acrylic sheet	1m X 0.6m	700/m²	420	
2	Aluminum sheet metal for reflector Aluminum sheet metal for oven Aluminum sheet metal for tray	1.15m X 1m 0.35m X 1m 0.16 X 1m	1,200/m²	2,000	
3	Silicon sealant	1	350	350	
4	RHS iron for support	9m	1,100/6m	1,650	
5	Fiberglass board for reflector support	0.65m²	550/m²	360	A wooden board is used for the experiment
6	Miscellaneous costs			720	
	Total Cost			**5,500**	

Note: Miscellaneous costs include rubber seal, wooden handle, nails, bolts, labor and unexpected costs.

According to research by FAO, 0.8 – 1.5 kg of wood is required for baking 1 kg of bread. The actual amount of wood used depends on the combustion chamber configuration, type of wood, moisture content of wood, and the degree of attention given to the fire by the baker. Thus, taking the minimum fire wood consumption for our payback period analysis, the cost of fire wood to bake one kilogram of bread can be determined. In Addis Ababa, the cost of one bundle of wood is around 50 BIRR and the cost of one kilogram of wood is 10birr. Thus, baking of one kilogram of bread will require 8 birr of wood energy.

According to repeated bread baking tests on the manufactured tube type direct solar oven, an average solar radiation of more than 500W/m² is required to bake one kilogram of bread under 1hr. Thus, estimated effective working hour of the solar oven in a day is calculated from the past five years solar radiation data of Addis Ababa. The data was filtered to give the number of hours in a day that would guarantee a monthly solar radiation average of more than 500W/m². Thus, according to the filtration process, an average effective bread baking hours shown in table 7.2 was obtained for the manufactured solar oven. it should be noted that, bread can be baked in the remaining hours of the day also, other than the effective baking hours. But the baking time will take longer than 1hr. Therefore, to calculate a more assuring payback period, we will only consider the effective baking hours.

Table 7.2: Monthly average effective baking hours

Month	Effective baking hours per day	Monthly average solar radiation for the effective baking hours (W/m²)					Monthly average of 5 years
		2016	2017	2018	2019	2020	
January	7hrs	503.26	601.78	578.71	628.25	482.72	558.94
February	7hrs	602.43	561.97	509.43	562.60	562.12	559.71
March	7hrs	560.74	584.52	464.43	562.89	0.00	543.15
April	5hrs	482.00	624.25	515.54	581.98	0.00	550.94
May	5hrs	547.85	539.33	480.30	513.23	0.00	520.18
June	4hrs	529.09	528.46	525.67	524.97	547.96	531.23
July	2hrs	576.27	600.12	627.24	556.87	499.70	572.04
August	3hrs	554.54	568.33	596.35	577.67	502.57	559.89
September	5hrs	0.00	538.96	609.09	495.98	515.73	539.94
October	7hrs	0.00	532.84	507.75	581.42	567.92	547.48
November	7hrs	0.00	573.99	543.11	487.14	552.84	539.27
December	7hrs	607.49	532.82	577.49	509.52	534.44	552.35

In the effective baking hours, the solar oven will take less than 1hr to bake one kilogram of bread. Thus, the tube type direct solar oven will save a cost of its effective baking hour multiplied by the cost of fire wood to bake one kilogram of bread.

$$\text{Cost saved per day} = \text{Effective baking hour per day} \times 8\text{birr}$$

So, the payback period will depend on the month the saving started and the baking quantity of the user. Table 7.3 shows cost saved for each month of the year if the whole effective baking hours were used.

Table 7.3: Monthly cost saving of the tube type direct solar oven

Month	Effective baking hours per day	Cost saved per month (BIRR)
January	7hrs	1,736.00
February	7hrs	1,568.00
March	7hrs	1,736.00
April	5hrs	1,200.00
May	5hrs	1,240.00
June	4hrs	960.00
July	2hrs	496.00
August	3hrs	744.00
September	5hrs	1,200.00
October	7hrs	1,736.00
November	7hrs	1,680.00
December	7hrs	1,736.00
Total saving per year		**16,032.00**

Thus, if a user starts to use the tube type direct solar oven on January, he will pay back the cost in 3months and 12days. And if he starts using it in July, he will pay back the cost in 4months and 24days, using a simple payback analysis.

CHAPTER EIGHT:
CONCLUSION AND RECOMMENDATION

8.1. Conclusion

The design of the tube type direct solar oven using MATLAB simplifies the process of changing different parameters of the solar oven, such as baking capacity, solar isolation and amount of output power required, to predict the thermal performance of the oven and find the minimum reflector area required. The CFD simulation of the solar oven based on the design predicts the outcome of the experimental analysis at different test conditions. It also helps to verify some aspects of the design such as, ray trajectory and time taken for bread baking. Thus, the COMSOL Multiphysics CFD software has resulted in a baking time that is 5mins longer than the analytical design. But the rays simulated by COMSOL, that have landed on the parabolic trough, all reaches the receiver (oven) for a 0^{o} incidence angle. Finally, the different tests conducted on the fabricated solar oven shows that the oven has a quick pre heat time and a maximum stagnation temperature of $127^{o}C$ for an average solar radiation of $654W/m^2$. The thermal efficiency of the solar oven was found to be 17.3% and the utilization efficiency was found to be 24.0% for an average solar radiation of $692.5W/m^2$ and $641.3W/m^2$, respectively. Performance evaluation shows that the standard cooking power of the solar oven at $700W/m^2$ is 98W. The actual bread baking time of the oven was longer than the designed and simulated results due to quality in manufacturing and quality of materials used. This has affected parameters such as reflector surface roughness and optical losses. But economic analysis shows that even with this quality, the tube type direct solar oven is a low-cost effective baking tool with a short payback period compared to biomass energy. Thus, it is the conclusion of this research that the tube type direct solar oven is an easy to manufacture, easy to use low-cost direct solar oven that has a potential of being widely accepted by the Ethiopian society for its economic and environmental advantages. Thus, after making design for mass manufacturing such type of direct tube solar ovens could be disseminated for those areas with abundant solar energy resources.

8.2. Recommendation

Different systems and modifications can be incorporated into the design of the tube type direct solar oven in order to make it more reliable and user friendly. Thus, the following recommendation are indicated for further work by this research.

- Integration of the tube type direct solar oven with electrical heating coil for areas that have access to electrical power.
- Using of multiple joints and alternate materials to improve the tube type direct solar oven's portability and reduce its storage space.
- Quality assuring manufacturing steps for mass production of the tube type direct solar oven at local markets of Ethiopia.

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Appendixes

I. MATLAB code for calculating the energy required for bread baking

```
m=0.075;        % mass of dough before oven (Kg)

Ti=298;          % Initial dough temperature (K)

Q1=0;                 % Initializing the energy required

Tf=368;          % Final bread temperature

for
T=Ti:1:Tf

cp=(0.077*T*T)-(68.94*T)+16646;

Q=(Q1+cp*m);

Q1=Q;

end

Qu=Q+(2260000*m*0.06);       % Considering a 6% moisture loss during baking

Qu                                        % Display useful energy required
```

II. MATLAB code for calculating thermal loss of the tube type direct solar oven

```
D_o=0.1;                          % Oven diameter (m)
s_g=0.14;                         % Side length of transparent cover (m)
v=3.5;                            % wind speed (m/s)
Eg=0.88;                          % Emissivity of outer cover
Eo=0.9;                           % Emissivity of oven material
D_g= 1.3*(s_g^2)^0.625/(2*s_g)^0.25;   % equivalent diameter of cover (m)
L=1.0;                            % length of receiver
Ar=pi*D_o*L;                      % Area of receiver (m2)
B=5.67*10^-8;                     % Boltzmann constant
T_a=298;                          % Ambient temperature (K)
Qb=148;                           % power required for bread baking (W)
x=(D_g-D_o)/2;                    % Average distance between cover and oven (m)
j=0;
for i=348:5:423
   j=j+1;
   T_o(1,j)=i;                    % Oven temperature matrix from 348K up to 423K
end
loss(1,1:1:16)=zeros;
for a=1:1:16
   T_g1=(T_o(1,a)+T_a)/2;         % Assumed temperature of outer cover (K)
   diff=1;                        % Initializing error
if diff>0.45                      % starting the iteration by limiting the error below 0.45
   T_g=T_g1;
   T_avk1=(T_g+T_a)/2;
   T_avc1=T_avk1-273;
   [den, con, u]= airprop(T_avc1);
   Re=den*v*s_g/u;
   Nu=0.3*Re^0.6;
   hc_g_a=Nu*con/s_g;
   hr_g_a=B*Eg*4*T_avk1^3;
   hr_o_g=(B*(T_o(1,a)^2+T_g^2)*(T_o(1,a)+T_g))/(((1-Eo)/Eo)+1+(1-Eg)*D_o/(Eg*D_g));
   T_avk2=(T_o(1,a)+T_g)/2;
   T_avc2=T_avk2-273;
   [den, con, u]= airprop(T_avc2);
   hcn_o_g=con/x;
   T_g1=((T_o(1,a)-273)*D_o*(hr_o_g+hcn_o_g)+(T_a-
```

```
        273)*D_g*(hr_g_a+hc_g_a))/(D_o*(hr_o_g+hcn_o_g)+D_g*(hr_g_a+hc_g_a))+273;
    m=(T_g-T_g1)^2;
    diff=sqrt(m);
else
end
Ul=((1/(hc_g_a+hr_g_a))+(1/(hr_o_g+hcn_o_g)))^-1;          % Total loss coefficient
loss(1,a)=Ar*Ul*(T_o(1,a)-T_a)*L;                           % Total oven loss
end
plot (T_o(1,:),loss(1,:), 'o')                              % Plot temperature Vs loss graph
hold
plot (T_o(1,:),loss(1,:), '-')
xlabel('Temperature (K)')
ylabel('Oven Loss (W)')
title('Receiver Temperature VS Oven Loss')
```

III. MATLAB code for calculating aperture area required

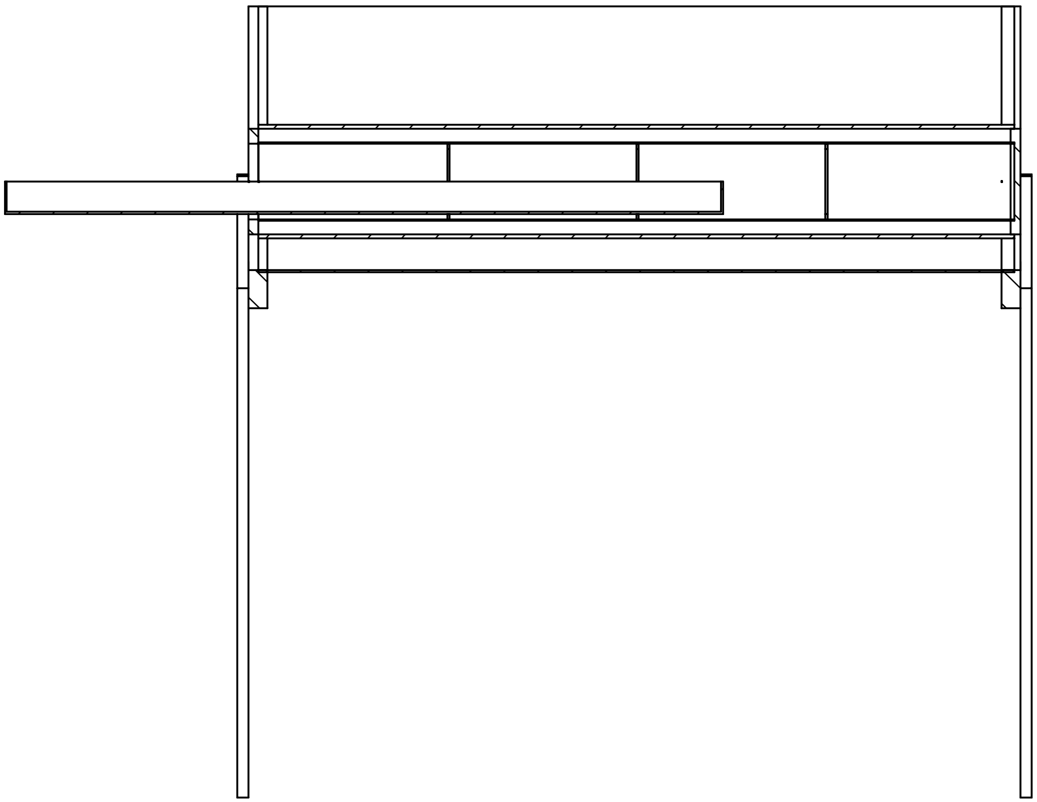
```
D_o=0.10;                               % Oven diameter (m)
s_g=0.14;                               % Side length of transparent cover (m)
v=3.5;                                  % wind speed (m/s)
Eg=0.88;                                % Emissivity of outer cover
Eo=0.9;                                 % Emissivity of oven material
D_g= 1.3*(s_g^2)^0.625/(2*s_g)^0.25;    % equivalent diameter of cover (m)
L=1.0;                                  % length of receiver
Ar=pi*D_o*L;                            % Area of receiver (m2)
B=5.67*10^-8;                           % Boltzmann constant
T_a=298;                                % Ambient temperature (K)
Qb=148;                                 % power required for bread baking (W)
x=(D_g-D_o)/2;                          % Average distance between cover and oven (m)

j=0;
for i=348:5:423
    j=j+1;
    T_o(1,j)=i;                         % Oven temperature matrix from 348K up to 423K
End

for a=1:1:16
    T_g1=(T_o(1,a)+T_a)/2;              % Assumed temperature of outer cover (K)
```

```
    diff=1;                                       % Initializing error
if diff>0.45                                      % starting the iteration by limiting the error below 0.45
    T_g=T_g1;
    T_avk1=(T_g+T_a)/2;
    T_avc1=T_avk1-273;
    [den, con, u]= airprop(T_avc1);
    Re=den*v*s_g/u;
    Nu=0.3*Re^0.6;
    hc_g_a=Nu*con/s_g;
    hr_g_a=B*Eg*4*T_avk1^3;
    hr_o_g=(B*(T_o(1,a)^2+T_g^2)*(T_o(1,a)+T_g))/(((1-Eo)/Eo)+1+(1-Eg)*D_o/(Eg*D_g));
    T_avk2=(T_o(1,a)+T_g)/2;
    T_avc2=T_avk2-273;
    [den, con, u]= airprop(T_avc2);
    hcn_o_g=con/x;
    T_g1=((T_o(1,a)-273)*D_o*(hr_o_g+hcn_o_g)+(T_a-
       273)*D_g*(hr_g_a+hc_g_a))/(D_o*(hr_o_g+hcn_o_g)+D_g*(hr_g_a+hc_g_a))+273;
    m=(T_g-T_g1)^2;
    diff=sqrt(m);
else
end
Ul=((1/(hc_g_a+hr_g_a))+(1/(hr_o_g+hcn_o_g)))^-1;    % Total loss coefficient
A_s(1,a) = (Qb + Ar*Ul*(T_o(1,a)-T_a))*L;            % Aperture area*S matrix
end
for j=1:1:16
    for i=1:1:21
        Ap(i,j)=A_s(1,j)/S(1,i);                      % Aperture area matrix with oven temp and S
        i=i+1;
    end
    j=j+1;
end
mesh(T_o,S,Ap)                                    % for 2D color plot, change the mesh function to surface
xlabel('Temperature (K)')
ylabel('Solar radiation on aperture (W/m2)')
zlabel('Aperture area (m2)')
title('Aperture area graph')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

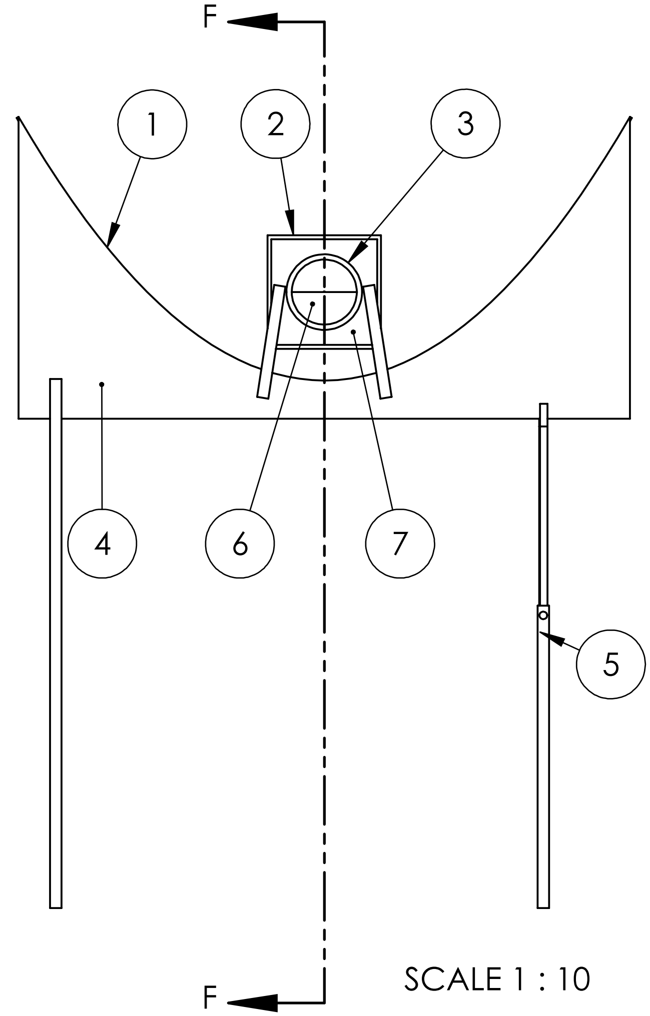
```
function [den, con, u]= airprop(T_av)
if T_av==25

den=1.184; con=0.02551; u=0.00001849;

elseif T_av<30 && T_av>25

den=1.184-(T_av-25)*0.004; con=0.02551+(T_av-25)*0.00037/5; u=0.00001849+(T_av-25)*0.00000023/5;

elseif T_av==30

den=1.164; con=0.02588; u=0.00001872;

elseif T_av<35 && T_av>30

den=1.164-(T_av-30)*0.019/5; con=0.02588+(T_av-30)*0.00037/5; u=0.00001872+(T_av-30)*0.00000023/5;

elseif T_av==35

den=1.145; con=0.02625; u=0.00001895;

elseif T_av<40 && T_av>35

den=1.145-(T_av-35)*0.018/5; con=0.02625+(T_av-35)*0.00037/5; u=0.00001895+(T_av-35)*0.00000023/5;

elseif T_av==40

den=1.127; con=0.02662; u=0.00001918;

elseif T_av<45 && T_av>40

den=1.127-(T_av-40)*0.018/5; con=0.02662+(T_av-40)*0.00037/5; u=0.00001918+(T_av-40)*0.00000023/5;

elseif T_av==45

den=1.109; con=0.02699; u=0.00001941;

elseif T_av<50 && T_av>45

den=1.109-(T_av-45)*0.017/5; con=0.02699+(T_av-45)*0.00036/5; u=0.00001941+(T_av-45)*0.00000022/5;

elseif T_av==50

den=1.092; con=0.02735; u=0.00001963;

elseif T_av<60 && T_av>50

den=1.092-(T_av-50)*0.0033; con=0.02735+(T_av-50)*0.000073; u=0.00001963+(T_av-50)*0.000000045;

elseif T_av==60

den=1.059; con=0.02808; u=0.00002008;

elseif T_av<70 && T_av>60
```

```
den=1.059-(T_av-60)*0.0031; con=0.02808+(T_av-60)*0.000073; u=0.00002008+(T_av-60)*0.000000044;
elseif T_av==70

den=1.028; con=0.02881; u=0.00002052;

elseif T_av<80 && T_av>70

den=1.028-(T_av-70)*0.0034; con=0.02881+(T_av-70)*0.000072; u=0.00002052+(T_av-70)*0.000000044;

elseif T_av==80

den=0.9994; con=0.02953; u=0.00002096;

elseif T_av<90 && T_av>80

den=0.9994-(T_av-80)*0.00276; con=0.02953+(T_av-80)*0.000071; u=0.00002096+(T_av-80)*0.000000043;

elseif T_av==90

den=0.9718; con=0.03024; u=0.00002139;

elseif T_av<100 && T_av>90

den=0.9718-(T_av-90)*0.00260; con=0.03024+(T_av-90)*0.000071; u=0.00002139+(T_av-90)*0.000000042;

elseif T_av==100

den=0.9458; con=0.03095; u=0.00002181;

elseif T_av<120 && T_av>100

den=0.9458-(T_av-100)*0.00491; con=0.03095+(T_av-100)*0.000140; u=0.00002181+(T_av- 100)*0.000000083;

elseif T_av==120

den=0.8977; con=0.03235; u=0.00002264;

elseif T_av<140 && T_av>120

den=0.8977-(T_av-120)*0.00435; con=0.03235+(T_av-120)*0.000139; u=0.00002264+(T_av- 120)*0.000000081;

elseif T_av==140

den=0.8542; con=0.03374; u=0.00002345;

else end
```

IV. Workshop drawings of designed prototype using SOLIDWORKS



SECTION F-F
SCALE 1 : 10



SCALE 1 : 10

07	Air-tight chamber
06	Sliding tray
05	Flexible stand
04	Reflector support
03	Oven
02	Transparent cover
01	Parabolic reflector
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN METERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Yonael	3/5/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

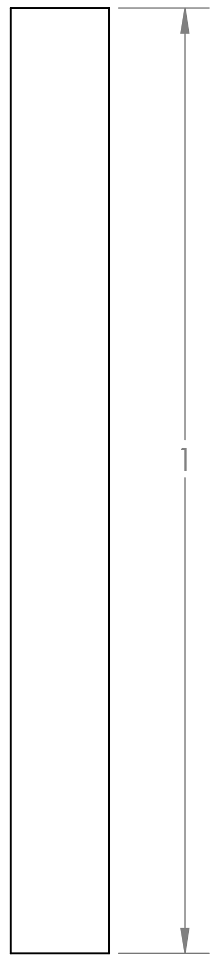
TITLE:

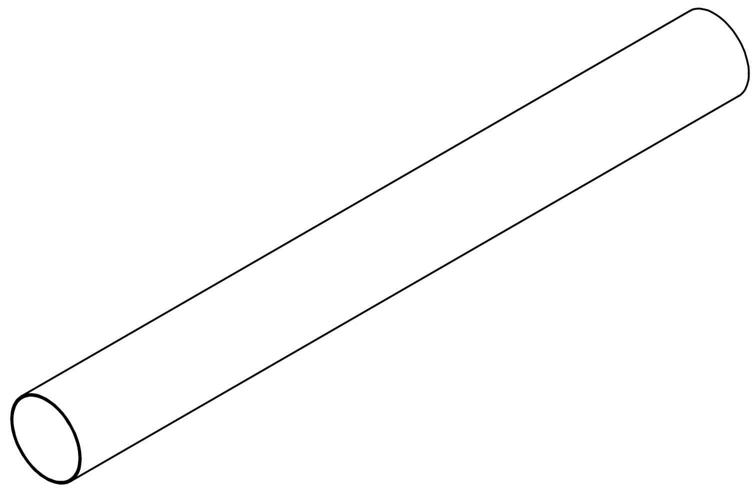
Assembly

SIZE	DWG. NO.	REV
A	000	

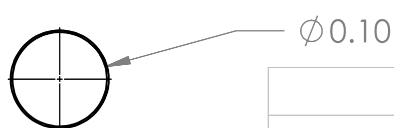
SCALE: 1:10 WEIGHT: SHEET 1 OF 10

5 4 3 2 1





SCALE 1 : 8

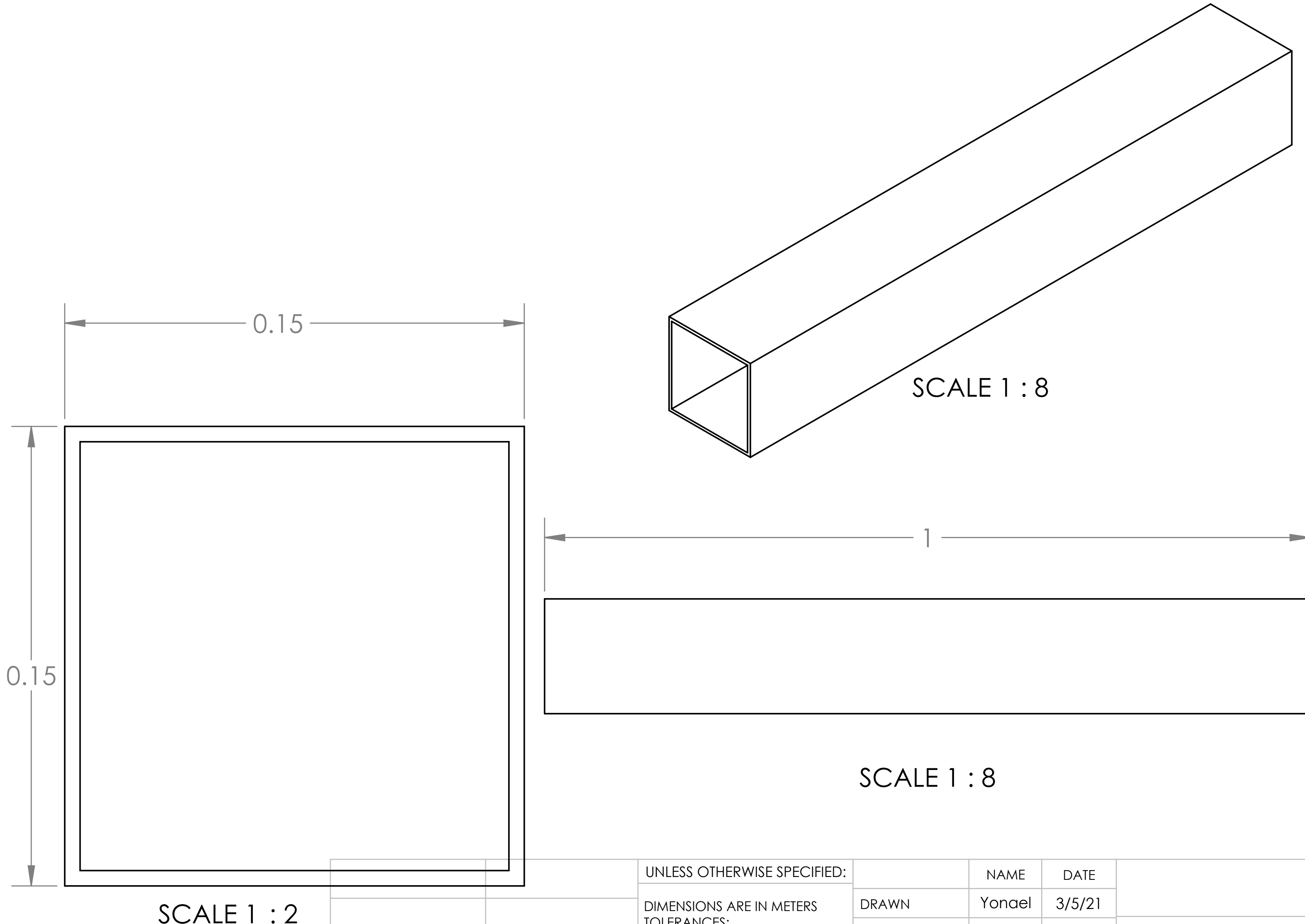


SCALE 1 : 8

UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	Yonael	3/5/21	TITLE:	
	CHECKED			Oven Cover	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL Aluminum Sheet	COMMENTS:			SIZE A	DWG. NO. 001 / REV
Thickness 1mm					
DO NOT SCALE DRAWING				SCALE: 1:8	WEIGHT: / SHEET 2 OF 10

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1



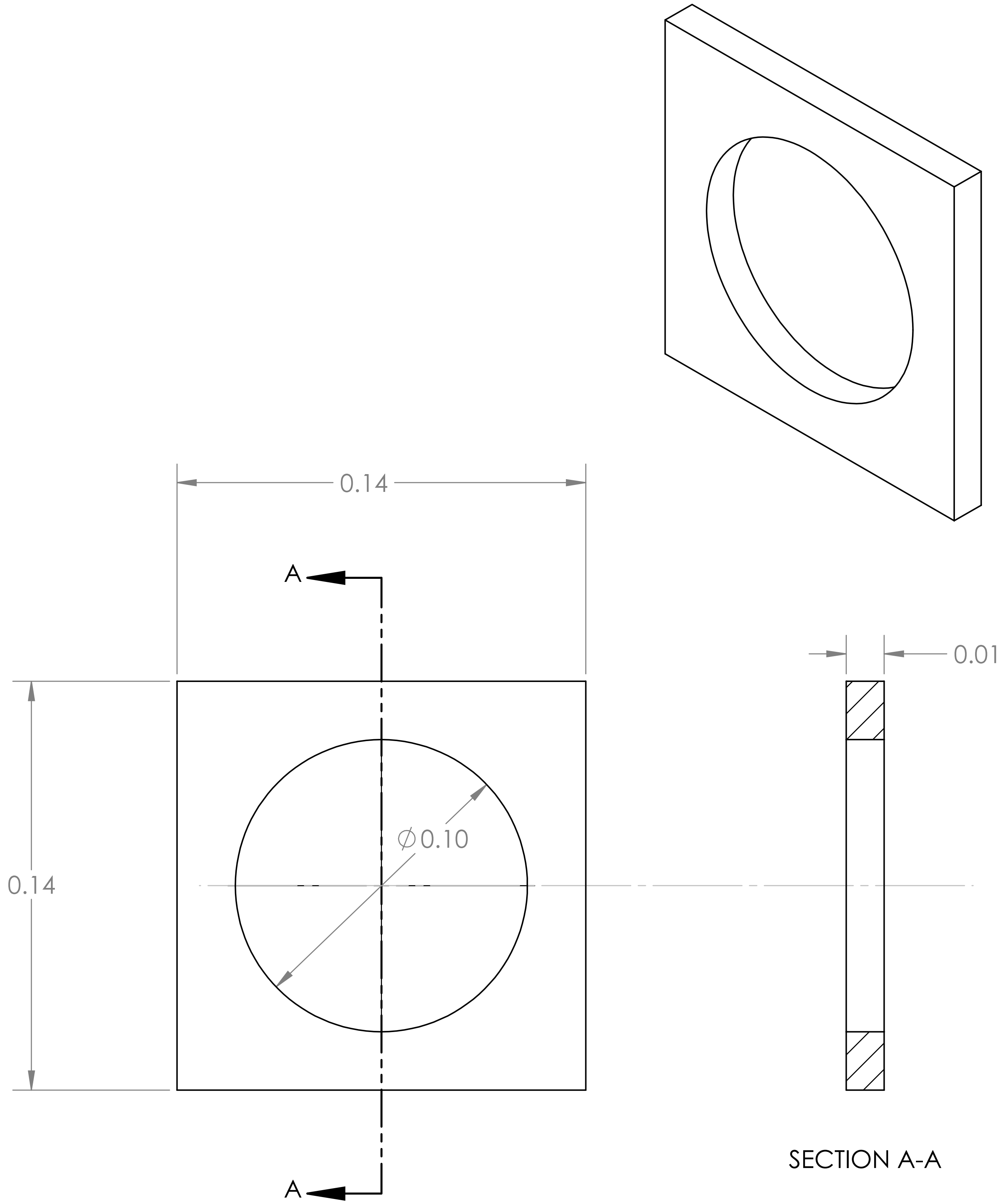
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	Yonael	3/5/21
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Acrylic	COMMENTS:		
MATERIAL THICKNESS 4mm			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

Transparent Cover

SIZE	DWG. NO.	REV
A	002	
SCALE: 1:8	WEIGHT:	SHEET 3 OF 10

5 4 3 2 1

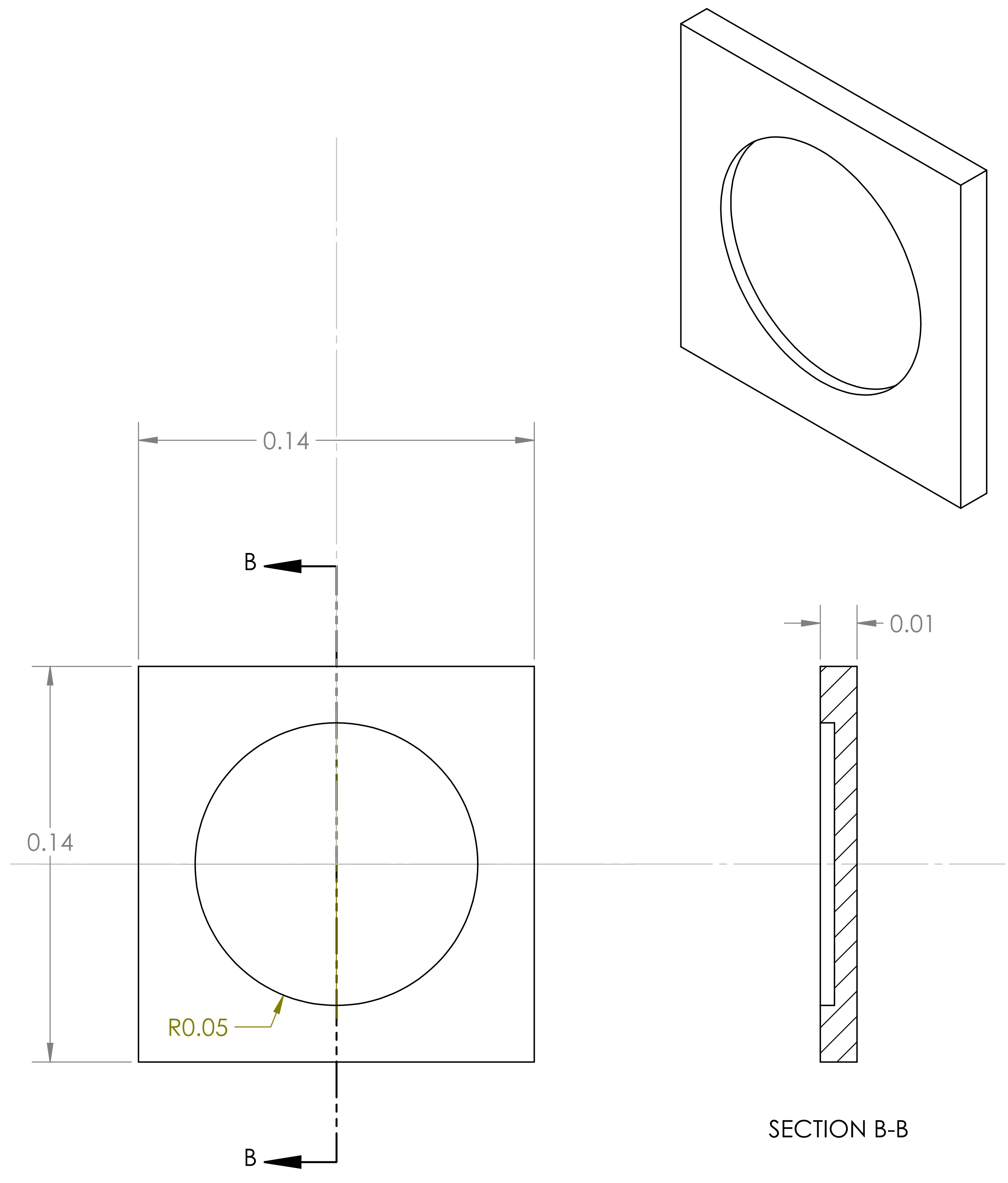


SECTION A-A

DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE		
	DRAWN	Yonael	3/5/21		
	CHECKED			Front Seal	
	ENG APPR.				
	MFG APPR.				
MATERIAL wOOD	Q.A.				
FINISH	COMMENTS:			SIZE A · DWG. NO. 003	REV.
DO NOT SCALE DRAWING				SCALE:1:2 · WEIGHT:	SHEET 4 OF 10

NEXT ASSY	USED ON
APPLICATION	

3/5/21



DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±		NAME	DATE	
	DRAWN	Yonael	3/5/21	
	CHECKED			
	ENG APPR.			
	MFG APPR.			
MATERIAL WOOD	Q.A.			
FINISH	COMMENTS:			
DO NOT SCALE DRAWING				

NEXT ASSY | USED ON

APPLICATION

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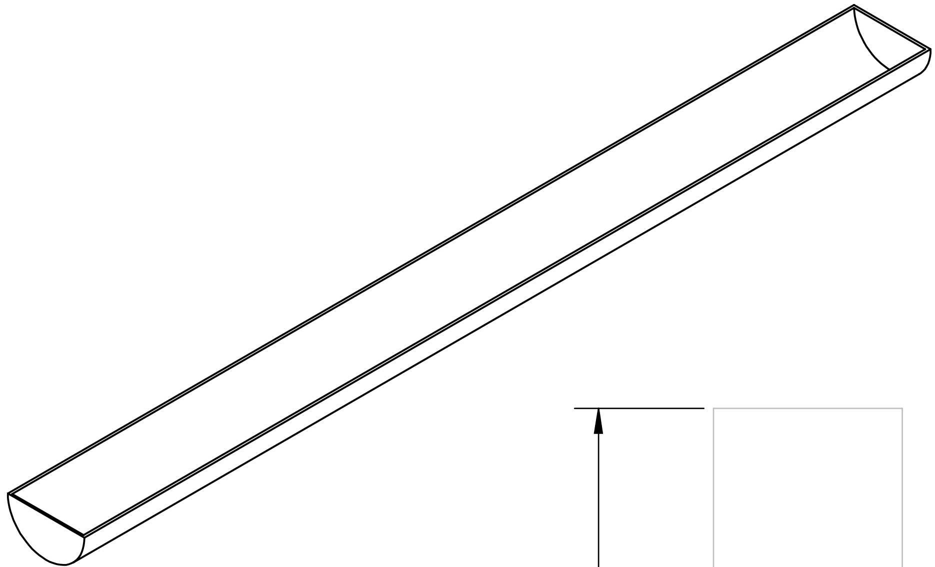
End Seal

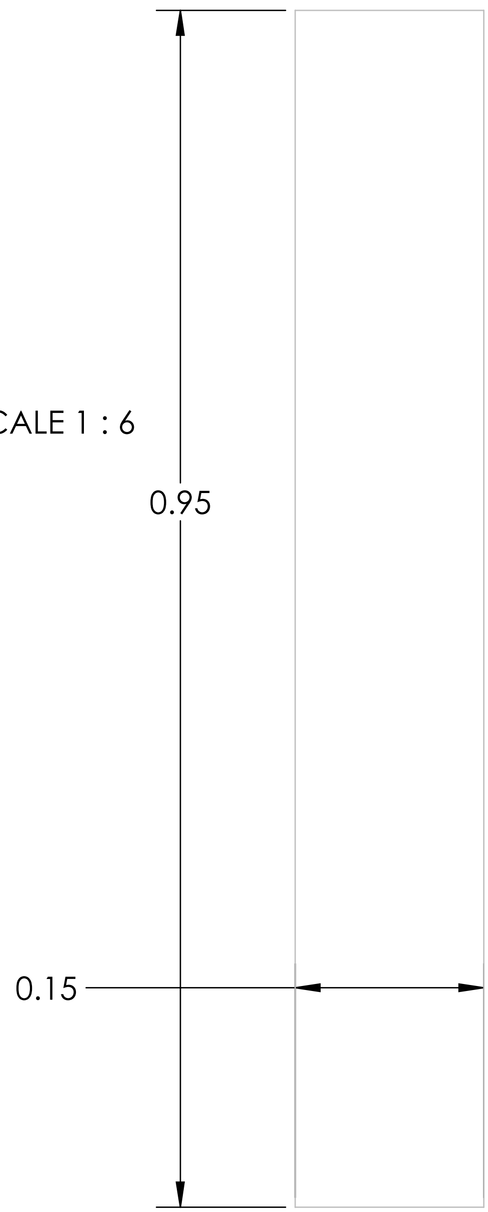
SIZE A | DWG. NO. 004 | REV.

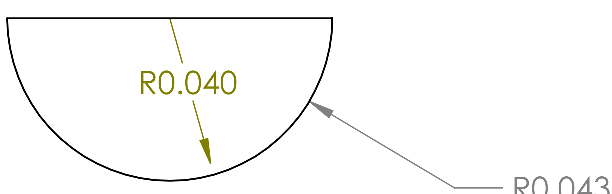
SCALE:1:2 | WEIGHT: | SHEET 5 OF 10

SCALE 1 : 6



SCALE 1 : 6





SCALE 1 : 2

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NEXT ASSY	USED ON
APPLICATION	

DIMENSIONS ARE IN METERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

MATERIAL
ALUMINUM SHEET

MATERIAL THICKNESS
1mm

DO NOT SCALE DRAWING

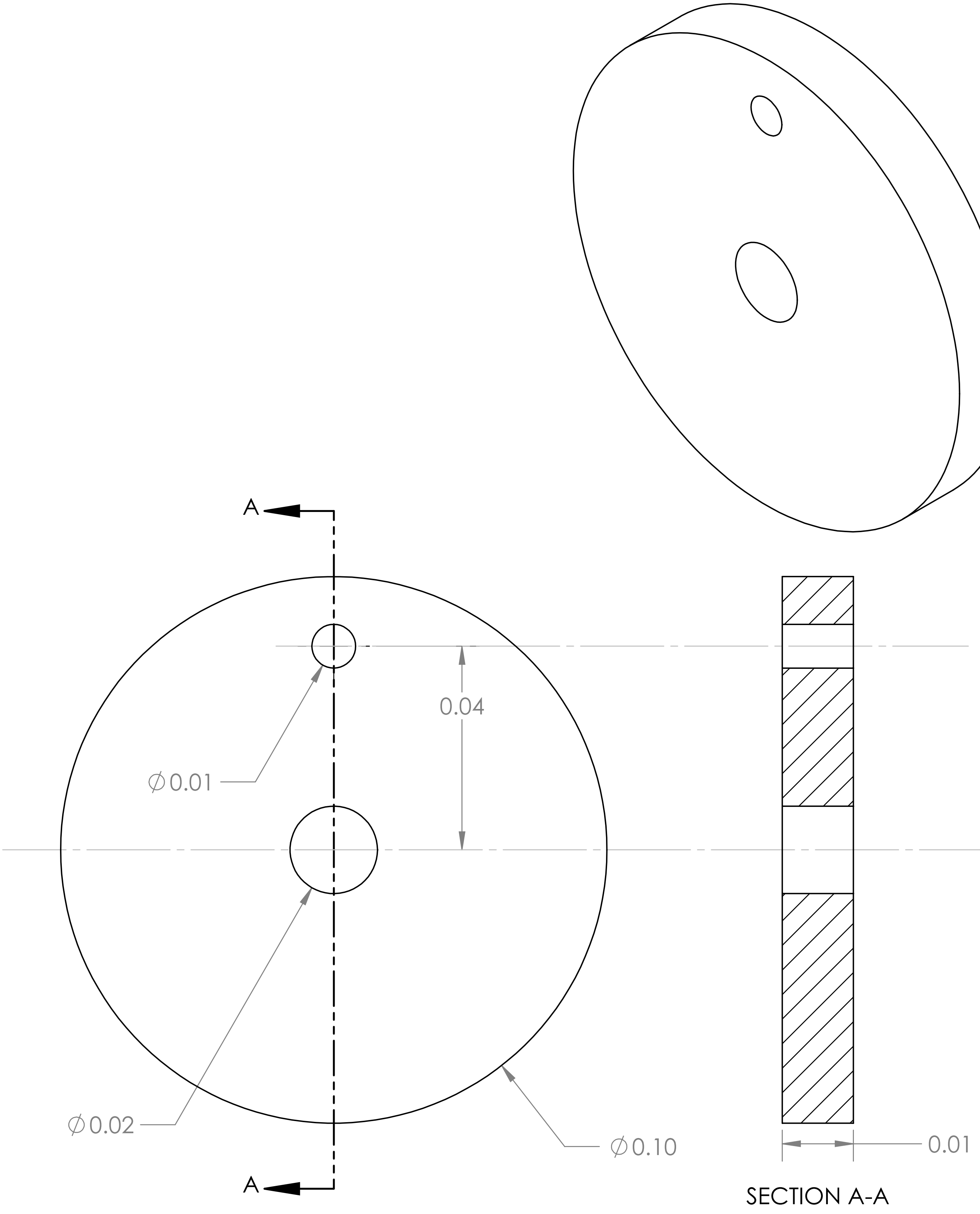
	NAME	DATE
DRAWN	Yonael	3/5/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

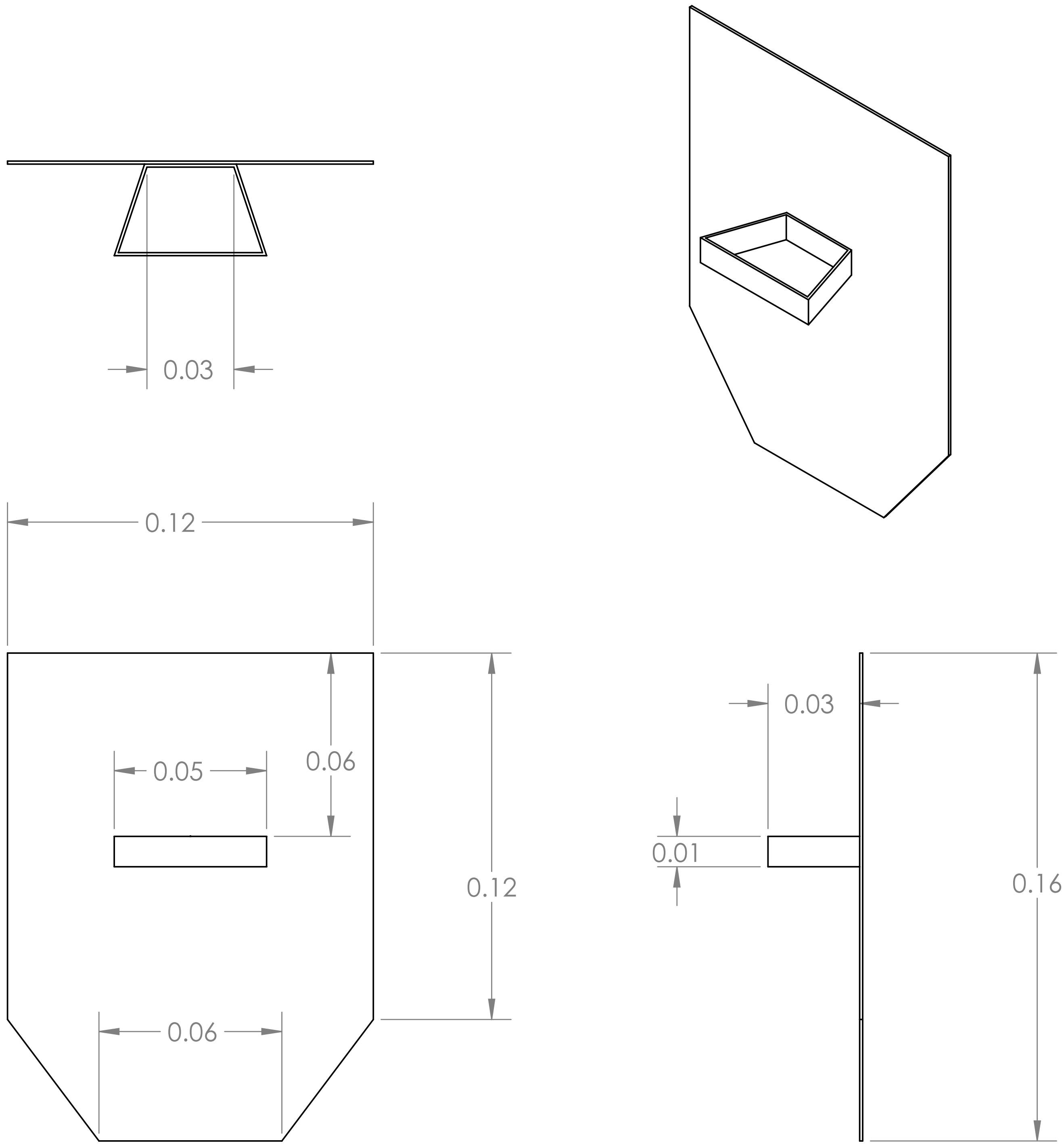
Sliding Tray

SIZE	DWG. NO.	REV.
A	005	

SCALE: 1:6 | WEIGHT: | SHEET 6 OF 10



				NAME	DATE	
		DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	Yonael	3/5/21	
			CHECKED			Oven Door
			ENG APPR.			
			MFG APPR.			
			Q.A.			
		MATERIAL Rubber	COMMENTS:			
NEXT ASSY	USED ON	MATERIAL THICKNESS				SIZE A DWG. NO. 006 REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:1 WEIGHT: SHEET 7 OF 10



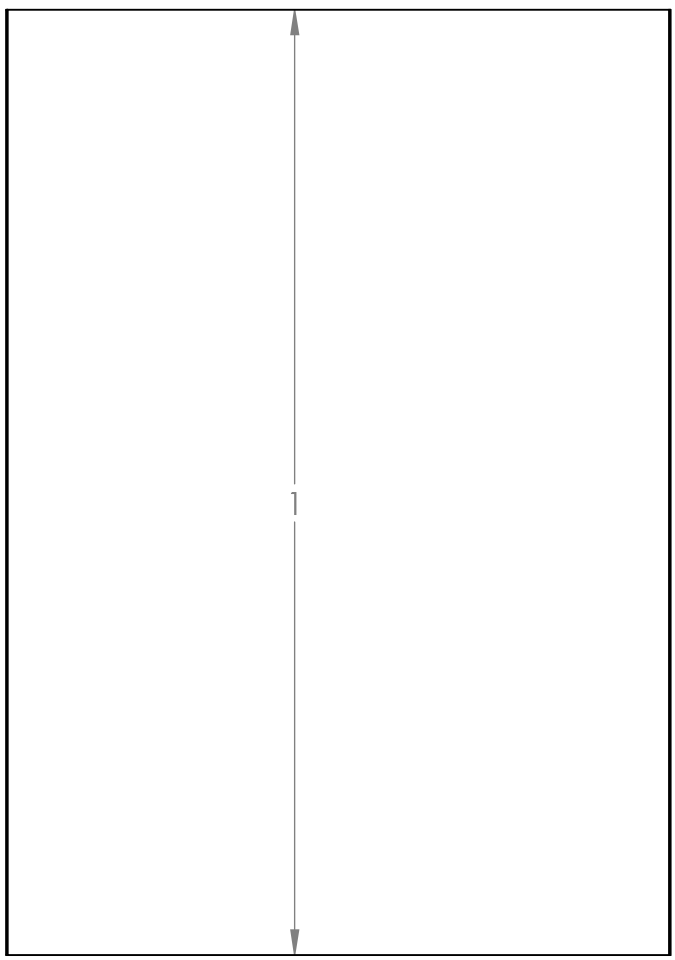
		DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±
		MATERIAL Aluminum Sheet
		MATERIAL THICKNESS 1mm
NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Yonael	3/5/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

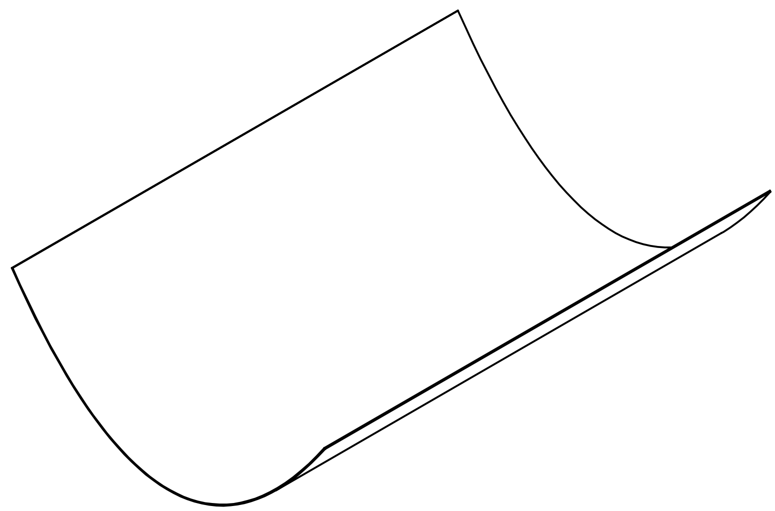
PROPRIETARY AND CONFIDENTIAL

Door Plate

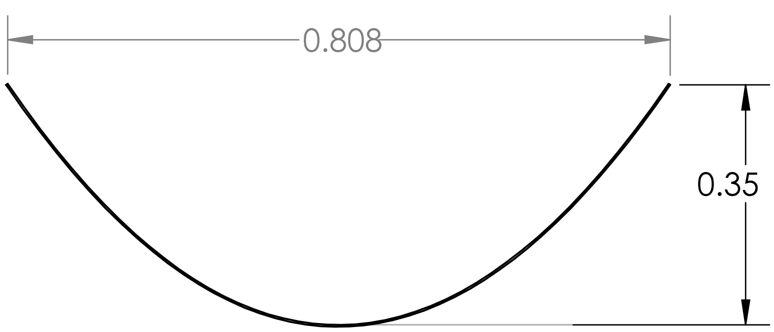
SIZE	DWG. NO.	REV.
A	007	
SCALE:1:2	WEIGHT:	SHEET 8 OF 10



SCALE 1 : 8



SCALE 1 : 12



SCALE 1 : 8

DIMENSIONS ARE IN METERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

	NAME	DATE
DRAWN	Yonael	3/5/21
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Parabolic Trough

MATERIAL
Aluminum Sheet Metal

MATERIAL THICKNESS
1mm

DO NOT SCALE DRAWING

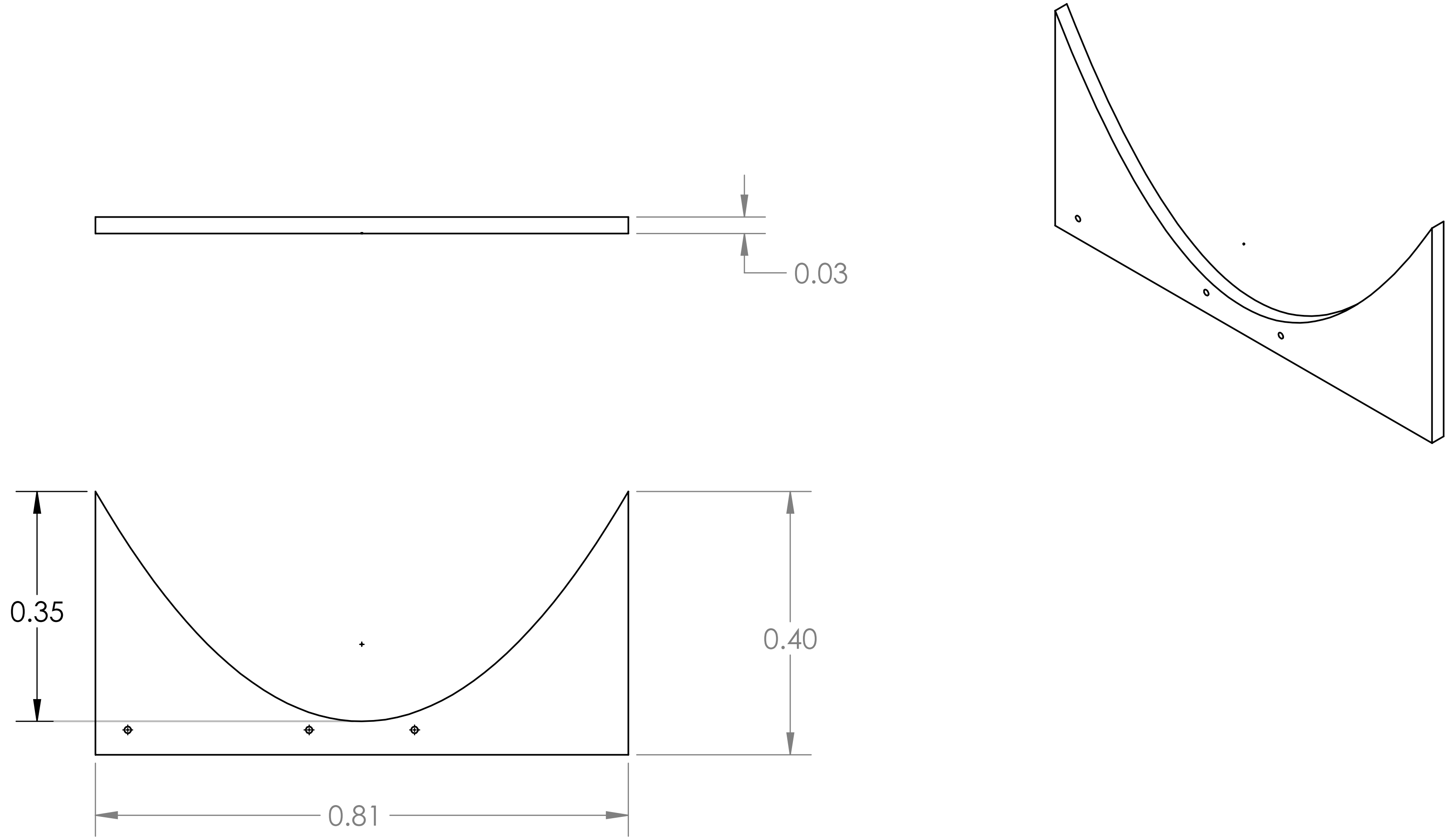
NEXT ASSY | USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

SIZE A | DWG. NO. 008 | REV.

SCALE:1:8 | WEIGHT: |



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN METERS TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	Yonael	3/5/21
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL WOOD	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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TITLE:

Reflector Support

SIZE A | DWG. NO. 009 | REV

SCALE: 1:10 | WEIGHT: | SHEET 10 OF 10

5 4 3 2 1