DEVELOPMENT AND PERFOMANCE EVALUATION OF A SOLAR-POWERED OVEN WITH PHASE CHANGE MATERIAL AS THERMAL STORAGE TO DRY VEGETABLES

BY

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MEng/SEET/2017/7523

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY MINNA, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING (M.Eng) IN MECHANICAL ENGINEERING (THERMO-FLUID AND POWER PLANT OPTION)

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ABSTRACT

In a bid to forestall the problems amounted with the use of other energy sources for drying vegetables, this research work focused on the development of solar oven utilizing a phase change material (PCM) as heat storage system. Solar oven with the size of (457.20 x 457.20 x 457.20) mm^3 was designed and constructed. It comprises of a two-layer drying tray and box-type phase change material, a molten salt, i.e. Sodium Nitrate and Potassium Nitrate ($NaNO_3$ – KNO_3) was selected as PCM and used for the research, with weight ratio 60 %:40 %. The 60 % $NaNO_3$ – 40 % KNO_3 has a phase change temperature of about 220 ^oC and stable thermal properties of 660 ^oC. Performance evaluation was carried out. Thus, dark green coloured okra was selected for the study. The okra was thoroughly washed and sliced using a sharp knife. The slices were weighed exactly 110 g for both oven-dry and the traditional sun-drying method. For sun drying, the weighed okra slices were taken in drying pan and kept on the open floor on the top of terrace. For solar drying, the weighed okra slices were taken in drying pan and kept inside the solar drying chamber. Observations on physiological loss in weight in each sample were recorded at the particular interval of 1 hour in both drying methods. The change in colour of slices was observed for further analysis. The maximum oven temperature during the study was recorded to be 68 ^oC and the ambient temperature was 46 ^oC. The fabricated oven was tested during the dry season for 9 hours each for three days and the efficiency of 52 % was obtained. The oven was lagged with glass fibre as insulator to prevent heat losses to the environment.

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LIST OF GLOSSARIES

Symbol	Description	Unit
Q	Sensible heat stored in the material	KJ
V	Volume of the Substance	m^3
m	Mass of substance	kg
C_p	Specific heat capacity of the substance	$Jkg^{-1}\,{}^oC^{-1}$
dt	Temperature Change	${}^oC$
a_r	Fraction reacted	
h_r	Endothermic heat fraction	KJ
Q_{store}	Energy Stored by PCM	KJ
C_{pcm}	Specific heat capacity of Change material	$Jkg^{-1}\,{}^oC^{-1}$
M_{pcm}	Mass of PCM	kg
$T_{pcm}\ max$	Maximum temperature of PCM	${}^oC$
T_m	Melting temperature of PCM	${}^oC$
T_a	Ambient temperature of PCM	${}^oC$
L_{pcm}	Latent heat of fusion of the PCM	
KJ/kg		
μ_m	Micro metre	
A	Area collector	
m^2		
t	Insulator wall thickness	mm
k	Thermal conductivity of the wall material	
W/mk		
$T_2 - T_1$	Thermal conductivity of the wall material	${}^oC$
U	Overall heat coefficient	W/m^2k

h_1	Convective heat transfer coefficient of air	W/m^2k
k_1	Thermal conductivity of the sheet metal cover	W/mk
k_2	Thermal conductivity of the insulator	W/mk

Symbol	**Description**	**Unit**
k_3	Thermal conductivity of al sheet metal	W/mk
t_1	Thickness of the sheet metal	mm
t_2	Thickness of the glass fibre	mm
t_3	Thickness of the absorber plate	mm
ΔT	Temperature difference	^oC
L	Latent heat of vaporisation of water	KJ/kg
$C_{p,}1$	Specific heat capacity of PCM at initial phase	$Jkg^{-1}\,^oC^{-1}$
$C_{p,}2$	Specific heat capacity of PCM at final phase	$Jkg^{-1}\,^oC^{-1}$
η	Oven efficiency	%
I_{av}	Average beam intensity	W/m^2
t	Time of Drying	h
M_i	Mass of sample before drying	kg
M_f	Mass of sample after drying	kg
M_f	Mass of sample after drying	kg
ρ_{pcm}	Density of PCM	kg/m^3

A_{ref}	Total area of the reflector	m^2
M_{g2}	Heat capacity of lower cover	J/K
T_{g2}	Temperature of lower cover	K
I_{in}	Solar Radiation	W/m^2
α_g	Absorptivity of the glass	
τ_g	Transmissivity of the glass	
A_c	Area covered	m^2
A_v	Area covered in the vessel	m^2

Symbol	**Description**	**Unit**
A_{vb}	Area covered in the vessel base	m^2
T_{amb}	Temperature of the ambient air	K
n	No. of Vessels	
T_p	Temperature of the absorber plate	K
T_a	Temperature of the internal air	K
h_c	Convective Heat Transfer Coefficient	W/m^2K
h_r	Radioactive Heat Transfer Coefficient	W/m^2K
A	Area	m^2
M	Heat Capacity	J/K
C_p	Specific Heat at Constant Temperature	kJ/kg-K

T	Temperature	K
x	Thickness of Insulation	m
k	Thermal Conductivity of Insulating Material	
W/mK		
amb	Ambient air	
A	internal air	
f	fluid	
v	vessel	
vb	vessel base	
g_1	top cover	
g_2	lower cover	
p	absorber plate	
vf	wetted with fluid	
α	Absorptivity	
τ	Transmissivity	

ABBREVIATIONS

Al	Aluminium
$CaCl_2.6H_2O$	Calcium Chloride Hexahydrate
CFCs	Chlorofluorocarbon
CH_4	Methane
CO_2	Carbondioxide
CSP	Concentrated Solar Power
KNO_3	Potassium Nitrate
LHS	Latent Heat Storage
LPG	Liquefied Petroleum Gas

MC	Moisture Content
$Mg(NO_3)_2.6H_2O$	Magnesium Nitrate Hexahydrate
ML	Moisture Loss
N_2O	Nitrous Oxide
$NaNO_3$	Sodium Nitrate
PCM	Phase Change Material
PCMs	Phase Change Materials
SHS	Sensible Heat Storage
Sqr	Square
TES	Thermal Energy Storage
UV	Ultraviolet
wb	Wet Basis

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

According to Nagaraj *et al.* (2016), the daily consumption of petrol, gas and electricity which are basically popular energy sources makes up to 50 percent of commercial sources of energy. It is necessary to exploit other sources of energy by humans and one of the alternative available energy sources is the renewable energy. For the sake of clean and healthy environment, it is essential for a community to use alternative energy sources. Solar energy appears to be the most promising resource, in terms of both immediate availability and existing technology. Among other renewable energy resources such as wind, hydro, tidal and geothermal, solar energy is the most available, abundant and more evenly distributed. It is free, safe, and the most environmentally clean of all energy (Sharma *et al*., 2000).

In the late 1950s, the scientist Maria Telkes was the person who worked on box type solar cooker. Later, the mid of the 20th Century showed a number of individuals and groups experimenting projects on solar cookers. The simplest type of solar cooker is the box cooker which was first built by Horace de Saussure in 1767 (Nagaraj *et al*., 2016). A basic box cooker consists of an insulated container with a transparent lid (Nagaraj *et al*., 2016). Solar cooking has been identified as an appropriate technology as it has numerous advantages such as no recurring cost, potential to reduce drudgery of firewood collection, high nutritional value of the cooked food and high durability of the cookers (Manabhanjan and Ivan, 2006). Solar cookers are heat exchangers designed to use solar energy in the cooking process. All solar cookers use the basic principles of concentrating light and heat from the sun into a small cooking area, converting light to heat and trapping the heat by isolating the air inside the cooker from the air outside the cooker using the Greenhouse Effect. The efficiency of solar cookers increases with the temperature of the heat source. To achieve high temperatures in solar thermal energy plants, solar radiation is concentrated by mirrors or lenses - a technique called Concentrated Solar Power (CSP) (SolarPACE, 2019).

The collector performance is dependable on temperature and also makes the whole system performance sensitive to temperature (Duffie and Beckman, 2013). Solar cookers are broadly categorized under two groups: Solar cookers without energy storage and solar cookers with storage. The consumption energy for cooking in third world countries is a major component of the total energy consumption, including commercial and non-commercial energy sources (Sharma and Singh, 2015). The most abundant source of energy in Nigeria is the wood fuel. Wood fuel consumption in Nigeria is so high that 70 % of the country's households depend directly on it as their main source of energy, with daily consumption estimated at 27.5 million kg/day (Zaku *et al*., 2013).

Food cooked with solar energy has astounding and excellent results. Moisture content and nutrients in the food are well retained because of its sluggish cooking rate and does not burn as compared with other energy sources **(**Chukwuneke *et al*., 2018). Many organizations are introducing solar cooking to the world's less developed regions to prevent deforestation in fuel-starved areas. High-performance parabolic solar ovens and vacuum tube ovens can attain temperatures above 290 °C. They can be used to grill meats, stir-fry vegetables, make soup, bake bread, and boil water in minutes. Vacuum tube type ovens can heat up even in the clouds and freezing cold. Conventional solar ovens attain temperatures up to 165 °C. They can sterilize water or prepare most foods that can be made in a stove, including bread, vegetables and meat over a period of hours. Solar ovens used no liquid or solid fuel and on therefore, it saves cost and reduces environmental damage caused by the use of fuels. Solar Ovens has a lot of economic and environmental benefits by reducing deforestation and desertification due to the fact that more than 2.5 billion people cook on open fires using biomass fuel **(**Chukwuneke *et al*., 2018).

The demand for wood fuel, charcoal combined with the high cost of kerosene has pushed low-income earners residing in towns to use charcoal as the cheaper option. The use of liquefied petroleum gas (LPG) and electricity for cooking and lighting is out of reach to most Nigerians due to the high cost. Wood energy is becoming scarce and more expensive and is of great concern since deforestation leads to serious consequences such as soil erosion, floods and desertification. Petroleum fuels are the most important source of commercial energy in Nigeria, and are mainly used in the transport, commercial and industrial sectors. Nigeria uses a lot of resources on imported petroleum products; hence there is need for alternative sources of energy. The indirect solar ovens use solar radiation to heat thermal fluids that transport heat to the place of the cooking process while the direct solar ovens use solar radiation directly to the cooking process. These ovens have been used effectively with partially overcast skies and will typically reach temperatures of 150 °C (Hussein and Nada, 2008). When higher temperatures are required, it becomes necessary to concentrate solar radiation. This is achieved using focusing or concentrating solar collectors (Shireesh and Nishith, 2017). To increase heat production, the reflectors is used to increase the irradiance on the receiver (Kwan and Bannerot, 1984). Solar energy is intermittent by its nature and at night there is no sunshine. Unreliability is the biggest retarding factor for extensive solar energy utilization (Sharma and Singh, 2015). Foods have been found to cook faster in the period between two hours before and two hours after the local solar noon than it does in either the early morning or the late afternoon**.** Most of the meals are prepared late in the evening when there is no enough solar energy for cooking.

The application of solar ovens is restricted if they are not equipped with energy storage system since it is impossible to use solar energy in cloudy conditions, evenings and at night (Kenisarin and Mahkamov, 2007). Energy storage may be in form of sensible heat of a liquid or solid medium, as heat of fusion in chemical systems, or as chemical energy of products in a reversible chemical reaction (Duffie and Beckman, 2013). The technical concept of solar cooker can be evaluated by thermal storage potential and energy is stored by raising the temperature of a storage medium; therefore, phase change materials (PCM) play important role in the present scenario (Xie *et al*., 2017). These materials have the ability to store large amounts of thermal energy under isothermal conditions, which means they can deliver or store energy at constant temperature and excrete the heat whenever there is a difference in the degree of the temperature.

1.2 Statement of the Research Problem

The need to preserve foods such as vegetables cannot be overemphasized. With the rising cost of petroleum products and the epileptic power supply combined with deforestation and desertification through the use of woodfuel in Nigeria, there is need to exploit solar energy for drying and heating applications. Solar energy has been an alternative energy source for powering oven, cookstoves, water heaters just to mention a few, based on its pollution free, clean and abundant availability. Nevertheless, solar energy powered device such as oven has its own setback due to its inability to operate during cloudy condition as well as late evening when the intensity of the sun is low.

In order to forestall the aforementioned problems associated with solar powered oven, there is need for energy storage. So, in this study, a solar-powered oven with phase change material as energy storage was developed.

1.3 Aim and Objectives of the Study

The aim of this study is to develop a solar-powered oven with phase change material as thermal storage for drying vegetables. To achieve this, are the following objectives

I. Construct a phase change material solar-powered Oven with energy storage.

II. Carry out design analysis of a Phase Change Material Solar-powered oven (dryer) with energy storage.

III. Evaluate the performance of the solar-powered Oven with energy storage (PCM).

IV. Carry out cost-benefit analysis of solar Oven with energy storage.

1.4 Significance of the Study

For centuries, people of various nations have been preserving vegetables, fruits, other crops, meat and fish by drying. Drying is also beneficial for hay, copra, tea and other income producing non-food crops. With solar energy being available everywhere, the availability of all these farm produce can be greatly increased. It is worth noting that until around the end of the 18th century when canning was developed, drying was virtually the only method of food preservation. (Bena and Fuller, 2002). Also, food scientists have found that by reducing the moisture content of food to 10 to 20 %, bacteria, yeast, mold and enzymes are all prevented from spoiling it (Gallali *et al.*, 2000). Microorganisms are effectively killed when the internal temperature of food reaches 63 °C. The flavour and most of the nutritional value of dried food is preserved and concentrated. Dried foods do not require any special storage equipment and are easy to transport (Waewsak *et al.*, 2006). Dehydration of vegetables and other food crop by traditional methods of open-air sun drying is not satisfactory, because the products deteriorate rapidly, studies showed that food items dried in a solar dryer were superior to those which are sun dried when evaluated in terms of taste, colour and mold counts (Gallali *et al*., 2000). Solar dried food are quality products that can be stored for extended periods, easily transported at less cost while still providing excellent nutritive value (Alamu *et al*., 2010).

1.5 Justification of the Study

Knowing the fact that solar ovens (dryers) are a simple and effective way to provide the energy needed for drying to people without access to other energy sources. This research focuses on maximizing solar energy through thermal storage, which will help to checkmate other challenges from existing dryers such as cost, convenience, safety, wind resistance, heating capacity, the durability, simplicity of instructions and the quality of the dried vegetables.

1.6 Scope and Limitation of the Study

It was designed and developed to dry only vegetables for both domestic and commercial storage and consumption. Limitations are based on the fact that solar ovens (dryers) are less useful in cloudy weather or tropical area. So, an alternative drying source is still required in these conditions.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Drying

Drying is one of the oldest methods using solar energy where the product such as vegetables, fruits, fish, and meat are to be dried by direct exposure to the sun (Harmain, 2012). It is a simple process of removing moisture from a product so as to attain the moisture content or standard specification and its operation is an energy intensive (Krishna *et al.*, 2018, Harmain, 2012). The main aim of drying besides extended storage life is enhancement of quality, ease of handling and sanitation and perhaps the oldest method of preserving food practiced by mankind (Abrog *et al.*, 2014) stated by Krishna *et al.* (2018). Sun drying method is more economical; as a result, it is cheaper in operating costs in comparison to the improvised or artificial means of drying using machines (Orioha, 2021). However, this method has many disadvantages such as spoilt products due to rain, wind, dust, insect infestation, animal attack and fungi. Hence, the solar dryer technology will become an alternative method which can process the products in clean, safe, hygienic and produce better quality and more nutritious foods.

Direct, indirect, and mixed mode solar dryers are the three types available. The sun radiation is immediately absorbed by the product to be dried in a direct solar drier. In the indirect solar dryer, the system's solar radiation is used to heat the air moving around the product to be dried, whereas in the mixed mode, the dryer obtains energy from the sun's rays that enter through the collector (Dronachari and Shriramulu, 2019).

Food and crop materials are extremely susceptible to drying conditions. When drying takes place at a fast pace for a short period of time, the quality of the dried product suffers as a result of excess or under drying. One of the most significant elements to consider is the drying temperature, as it affects the colour, texture, flavour, and value of the product (Orioha, 2021).

2.2 Drying of Vegetables

Drying is a crucial step in the preservation of agricultural products. Temperature range of 45 – 70 ^{0}C is required for the safe drying of food products such as fruits and vegetables. Drying vegetables under controlled temperature and humidity conditions allows them to dry quickly and efficiently to low and safe moisture content while maintaining high quality (Sharma *et al.,* 1995). Food drying is straightforward, safe, and simple to understand. Fruit leathers, banana chips, and beef jerky may all be dried at home year-round with modern food dehydrators (Babagana *et al.*, 2012).

2.2.1 Drying preserves food

Drying removes the moisture from the food so bacteria, yeast and mold cannot grow and spoil the food. Drying also slows down the action of enzymes (naturally occurring substances) which cause foods to ripen, but does not inactivate them. This is possible because as drying removes moisture, the food becomes smaller and lighter in weight but when the food is ready for use, the water is added back, and the food returns to its original shape. Foods can be dried in the sun, in an oven or in a food dehydrator by using the right combination of warm temperatures, low humidity and air current. In drying, warm temperatures cause the moisture to evaporate. Low humidity allows moisture to move quickly from the food to the air. Air current speeds up drying by moving the surrounding moist air away from the food (Bala, 2009; Bitog *et al.,* 2009).

Preservation of vegetables, fruits and other foods are essential for keeping them for a long time without further deterioration in the quality. Several process technologies have been employed on an industrial scale to preserve vegetables; the major ones are canning, freezing, and dehydration (Mujumdar, 2007). Among these, drying is especially suited for developing countries with poorly established low-temperature and thermal processing facilities (Wankhade *et al*., 2013). It offers a highly effective and practical means of preservation to reduce post-harvest losses and balance the shortages in supply. The prime objective of drying apart from extended storage life can also be quality enhancement, ease of handling, further processing and sanitation and is probably the oldest method of food preservation practiced by humankind (Mujumdar, 2007).

According to Hassan *et al.* (2013), fresh vegetables have higher moisture content and, if not handled properly, will decay in a short amount of time. Refrigeration and controlled atmospheres are expensive storage solutions because they require constant energy for system operation throughout the supply chain. As a result, the adoption of drying procedures is encouraged since it decreases postharvest losses, makes storage and transportation easier, and maintains product availability throughout the year. Traditional methods of drying vegetables, such as sun or open-air drying have been proven to be slow and may result in a lower-quality product due to contamination (Uthman *et al.*, 2017). Various modern drying techniques including solar, microwave, vacuum, infrared, freeze, oven drying, and various hybrid drying technologies, have been developed and effectively employed for a variety of fruits and vegetables around the world (Hassan *et al.*, 2013).

2.2.2 Sun drying

Meats are high in protein, which makes them ideal for microbial development when temperature and humidity are not controlled (Schmutz and Hoyle, 1999). The greatest days for drying in the sun are those that are hot, dry, and windy. A minimum of 28 °C is required, with greater temperatures being better. Foods must be dried outside for several days. Sun drying has its limitations due to the unpredictability of the weather (Zhang *et al*., 2011).

Also, high humidity is a problem and humidity below 60 percent is best for sun drying. Often these ideal conditions are not available when fruit ripens. Fruits dried in the sun are placed on trays made of screen or wooden dowels. Screens need to be safe for contact with food. The best screens are stainless steel, teflon coated fibreglass or plastic. Avoid screens made from hardware cloth such as galvanized metal cloth that is coated with cadmium or zinc. These materials can oxidize, leaving harmful residues on the food. Also, avoid copper and aluminium screening due to the fact that Copper destroys vitamin C and increases oxidation while Aluminium tends to undergo discoloration from the effect of corrosion (Tibebu, 2015).

A good number of woods are fine for making trays. However, it is not advisable to use green wood, pine, cedar, oak or redwood. These woods warp, stain the food or cause off-flavours in the food. Because the ground may be moist, it is best to place the racks or screens on a concrete. The reflection of the sun on the metal increases the drying temperature. Cover the trays with cheesecloth to help protect the fruit from birds or insects. Fruits dried in the sun must be covered or brought under shelter at night so as to reduce the chances of moisture getting back to the product through the condensation of the cool night air thus, slowing down the drying process (Bitog *et al.,* 2009).

2.3 Solar Drying of Vegetables

A lot of work has been done on solar drying of vegetables notable among them are: a solar cabinet dryer, made up of a solar air heater and a drying cabinet, was utilized in drying thin layers of pumpkin, green pepper, filled pepper, green bean, and onion by Yaldyz and Ertekyn (2001). This was done by the researchers to test the impact of three different drying air velocities on drying time. Three different drying air velocities were used. Natural sun drying was used to dry the fresh materials. Different moisture ratio models were run and evaluated based on their determination coefficients in order to explain the drying curves of these products by the researchers. The temperature of drying air might rose to around 46 °C, according to their findings. The drying air velocity has a big impact on the drying process. The solar drying period varied between 30.29 and 90.43 hours for various vegetables. For natural sun drying, the time ranged between 48.59 and 121.81 hours.

Patel *et al.* (2013) presented a review of a solar dryer and remarked that solar dryers can be made locally of any size and capacity and are economical if cash crops are dried. They reported various design of the solar dryer in the literature.

Khalifa *et al.* (2012) investigated experimentally the performance of a solely solar drying system and a system equipped with an auxiliary heater as a supplement to the solar heat. They carried comparative performances analysis of both with that of natural drying. They found that the efficiency of the mixed drying system increased by 25 % to 40 % compared to the solely solar drying. It was that a best fit to the experimental data of peas and beans was obtained by six exponential equations for the various systems with a correlation coefficient in the range 0.93 and 0.99.

Hii *et al.* (2019) posited that product quality improvement is highly associated with solar dried products as compared to sun dried and to some extent oven/hot air-dried products. They however remarked that the uptakes of this technology especially among farmers in developing countries are still low despite the many years of research and technology advancement. Nevertheless, some successful application of solar drying has been reported in countries such as Indonesia, Laos, Zimbabwe, Tanzania, Brazil, Uganda, Kenya and Senegal.

Alonge (2008) used locally accessible materials to design and build two passive (direct and indirect) sun dryers, which were then tested to determine the drying rate of vegetables. He came to the conclusion that, the vegetables dried faster in the direct solar dryer than in the indirect passive solar dryer because the direct solar dryer reached the greatest temperature.

Baradey *et al.* (2016) investigated the performance of a solar dryer for fruit and vegetables using both natural and forced convection solar dryer to examined drying rate, weight losses, and removal of moisture content. They concluded that drying process is the most common method of food preservation because it increases the storage life.

Okaiyeto *et al.* (2020) conducted research to supply local farmers with on-farm solar dryers to reduce vegetable post-harvest losses. Two sun dryers (Mixed mode and indirect mode on-farm solar dryers) were built utilising locally accessible materials to determine the experimental outcomes. A blower, a collector area, and a drying chamber are the main components of the dryers. Inside the collector, an aluminium sheet serves as the absorbent medium. The average system drying, energy collection, and pick-up efficiencies for the three test crops were 16.35 %, 21.10 %, and 8.05 % for the mixed mode drier, and 28.63 %, 45.30 %, and 0.30 % for the indirect mode dryer, respectively and 28.63 %, 45.30 % and 0.30 % for indirect mode dryer, respectively.

Eke (2014) embarked on research on investigation of low-cost solar collector for drying vegetables in rural areas (Zaria) in Nigeria. The research was aimed at investigating suitable solar collector material that is available, affordable and can easily be worked on by rural farmers. Metal, wood, cement and mud which are commonly available local materials were used to fabricate four types of solar dryers and the dryers were mounted truly facing south. From the analysis, the dryers' savings in drying time over the open sun drying for wood, cement, mud and metal dryers were 131.25 %, 131.25 %, 136.17 % and 192.11 % respectively. Average ambient wind speed during the drying period was 0.98 m/s, while that of relative humidity was 23.85 %. The metal dryer dried sliced tomato 18 hours ahead of mud dryer, while cement and wood dryers dried the sliced tomato 2 hours longer than the samples dried in the mud dryer. Sliced tomato samples were used for performance test of the dryers. Moisture content of the samples, dryer temperature, wind speed, relative humidity and solar radiation were monitored at 2 hours intervals. Results from this work indicated that mud direct mode natural convection solar dryer is best suited for Zaria and it related geographical locations.

Based on proximate, vitamin, mineral, and microbial studies on vegetable samples, Ukegbu and Okereke (2013), conducted a comparison experiment on the sun and a locally produced solar oven to assess the influence of solar and sun drying on the nutritional makeup of three vegetable species. They discovered that solar drying preserved more nutrients than sun drying and that it may be a better drying strategy because it is more hygienic and has a lower microbial burden.

Khawale and Thakare (2016) studied the advancement of solar ovens used for drying agricultural food product. They revealed that technical and economical results showed that solar drying of agriculture food product drying is possible. Space availability difficulty in urban areas, sunshine irregularity, higher initial costs and convenience issues are the main hurdles in its propagation and unwillingness to acceptance. For reducing all these factors, further research and development work should be continued. To improve the acceptability of farmer, it is necessary to develop a large scale and low-cost attractive solar dryer. Research and development work on solar drying technology has been made significant progress. A review on advancement of solar drying technology is appropriate for future development as remarked by the researchers.

2.3.1 Semi artificial solar dryers for vegetables

According to Lokesh *et al.* (2015) semi artificial solar dryers for vegetables are direct heated solar convective dryers. In these dryers, air is preheated by solar energy in a collector. The drying system consists of a solar collector and a fan for maintaining a specified air flow through the drying space. These dryers are cheap to construct and can be employed where the drying material is not sensitive to periodic changes in the drying conditions caused by periodic nature of the solar radiation and changing atmospheric conditions. Bena and Fuller (2002) and his co-workers had developed a multipurpose solar tunnel dryer consisting of a fan, solar heater, and tunnel dryer. The use of this dryer had reduced the drying time considerably with better end product quality (Sulzbacher and Rathbauer, 2014).

2.3.2 Solar assisted or indirect type solar dryer for vegetables

In this type of dryer, solar energy is used to heat a fluid or sand pebble, which in turn heats up the air to dryness. These usually have auxiliary energy source, such as a thermo-generator fueled by biomass, natural gas or oil, to be used in situations where solar energy collected is insufficient for drying purpose. Better control of temperature results in a better-quality product (Sulzbacher and Rathbauer, 2014). The solar dryer developed by Bena and Fuller (2002) consisted of a flat plate solar air heater connected to a cabinet, acting as a drying chamber.

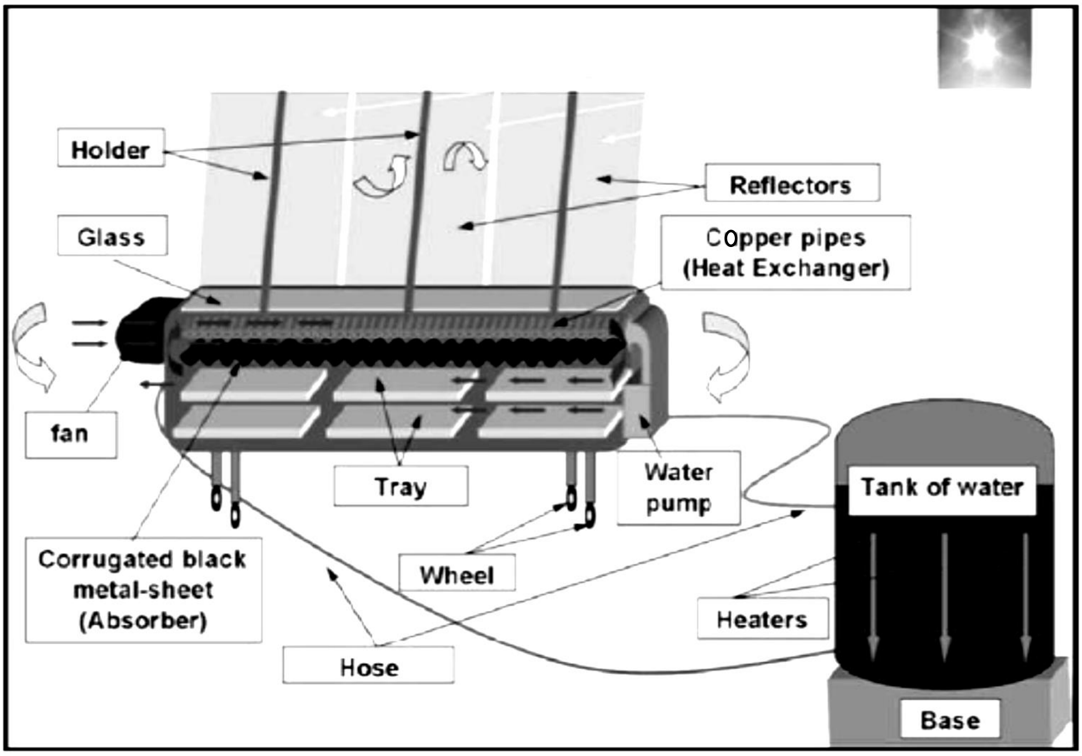

Figure 2.1: Indirect Type Infused Solar Dryer (Source: Bena and Fuller, 2002)

The air heater is designed to insert various storage materials under the absorber plate to improve the drying process. Sand is used as a storage material. Since heat dissipated by sand is gradual, it reduces the drying time by 12 hours and the total drying time can be achieved in eight hours with suitable pre-treatment given to the fruits.

2.3.3 The hohenheim solar dryer for vegetables

The original design for this solar dryer was developed at the Institute for Agricultural Engineering in the Tropics and Subtropics at Hohenheim University in Germany known as the Hohenheim solar dryer (Lokesh *et al.,* 2015). The dryer is one of the direct type families of solar dryers and can be conveniently described as a long low transparent tunnel. In its standard form, the solar dryer is 18 m long and 2 m wide. It consists of two sections or zones. The first eight metres of the unit act as the solar collector and the second ten metres are used for the drying bed. Each zone has the same cross-section and is covered with a transparent film glazing as shown in Figure 2.2 and therefore, both the solar collector surface and the crop simultaneously absorb any solar radiation incident on the unit (Lokesh *et al.*, 2015).

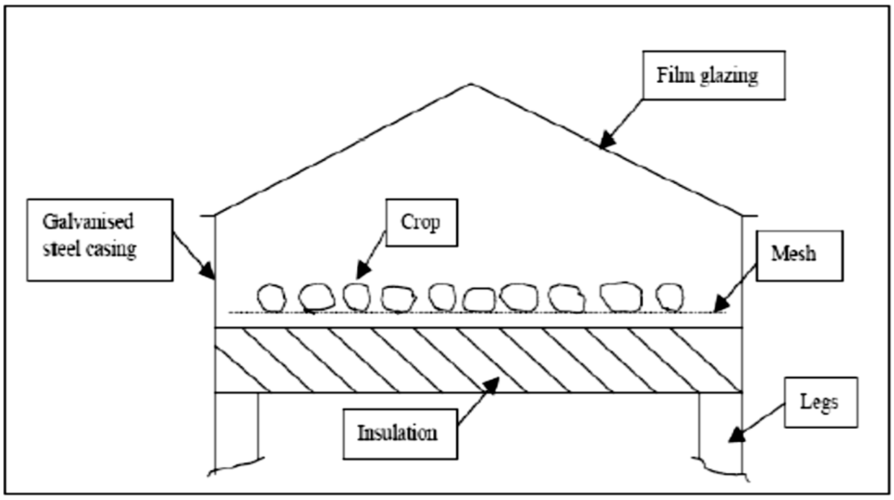

Figure 2.2: Cross section through the Hohenheim solar dryer (Source: Lokesh *et al.*, 2015**)**

2.4 Oven Drying for Vegetables

By combining the factors of heat, low humidity and air flow, an oven can be used as a dehydrator. An oven is ideal for occasional drying of meat jerkies, fruit leathers, and banana chips or for preserving excess produce like celery or mushrooms. Because the oven is needed for every day cooking, it may not be satisfactory for preserving abundant garden produce. Oven drying is slower than dehydrators because it does not have a built-in fan for the air movement. However, some convection ovens do have a fan. It takes about two times longer to dry food in an oven than it does in a dehydrator. Thus, the oven is not as efficient as a dehydrator and uses more energy. Vegetables can also be preserved by drying. Because they contain less acid than fruits, vegetables are dried until they are brittle (Siddique and Wright, 2003).

2.5 Thermal Energy Storage Materials for Solar Oven

Karthick *et al.* (2019) evaluated thermal energy storage materials for solar cooking and estimated that 730 million tonnes of biomass are burned for cooking each year in poor nations, resulting in over 1 billion tonnes of CO_2 build-up in the atmosphere. Unfortunately, millions of people continue to die as a result of diseases brought on by inhaling smoke from open cooking fires. Furthermore, cutting firewood for cooking results in deforestation, this leads to desertification. As a result, solar cooking, often known as "cook without wood," is regarded the finest answer for not only reducing public health concerns but also reducing global warming. In rural areas of Africa, wood, agriculture wastes, and animal dung cake are the primary energy sources for cooking, whereas in urban areas, kerosene and liquefied petroleum gas (LPG) are the primary energy sources. Cutting down trees for firewood creates desertification, while using animal dung cakes pollutes the ecosystem. Furthermore, the constant rise in fuel prices and demand for fuel availability shows that there is an urgent need to effectively employ diverse renewable energy sources for culinary purposes. Africa is fortunate in that it receives a lot of solar radiation. As a result, solar cookers have a bright future in Africa. Solar cookers without thermal storage have the drawback of only being able to cook during daylight hours. To address this constraint, solar cookers are equipped with a thermal storage medium, which allows food to be cooked even when the sun is not shining.

In addition, Panwara *et al*. (2011) examined renewable energy sources in terms of environmental protection and concluded that solar energy is an environmentally benign energy source, will not affect climate conditions and human health. But unlike fossil fuel and some other energy sources, which releases green air gases such as CO_2, CH_4, N_2O, and CFC_s raising Earth's surface temperature.

Major renewable energy gadgets for domestic and industrial applications such as solar water heaters, solar cookers, dryers, wind energy, biogas technology, biomass gasifiers, improved solar cooking systems and biodiesel was made. The use of solar drying of agricultural produce has good potential for energy conversion in the world. The improved solar cooking systems provide better kitchen environment to people living in rural areas and reduces fuel collection burden on them.

Sharma *et al.* (2005) reviews applications on a latent heat storage system with phase change materials (PCMs) for an efficient storage of thermal energy also summarizes the investigation and analysis of the available thermal energy storage (TES) systems incorporates with PCMs for different applications. With the storage unit, food can be cooked at late evening, while late evening cooking was not possible with a normal solar cooker. So therefore, solar cooker with storage unit is very beneficial for humans and as well as energy conservation.

2.6 Different Advancements in Solar Drying

2.6.1 Solar drying system using phase changing material

A phase-change material (PCM) is a substance with the properties like a high heat of fusion (Latent Heat), melting and solidifying at a certain temperature and capable of storing and releasing large amounts of heat energy during phase change. It is also known as Latent Heat Storage (LHS) units.

Broadly, heat energy is of two types: Sensible Heat (changes Temperature), Latent Heat (No change in Temperature). PCMs changes its phase at a constant temperature, by storing a large amount of latent heat and again changes back its phase by releasing the stored heat, which is used for heating or drying purpose. Solid-liquid PCMs are commonly employed because material handling is easier at this stage. When a substance transitions occur from solid to liquid or liquid to solid, thermal energy transfer happens. These solid–liquid PCMs behave like traditional storage materials at first; their temperature rises as heat is absorbed (Balladin & Headley., 1999). At a fairly constant temperature, PCMs absorb and release heat. They store 5-14 times the amount of heat per unit volume as sensible storage materials like water (Barnwal & Tiwari., 2008).

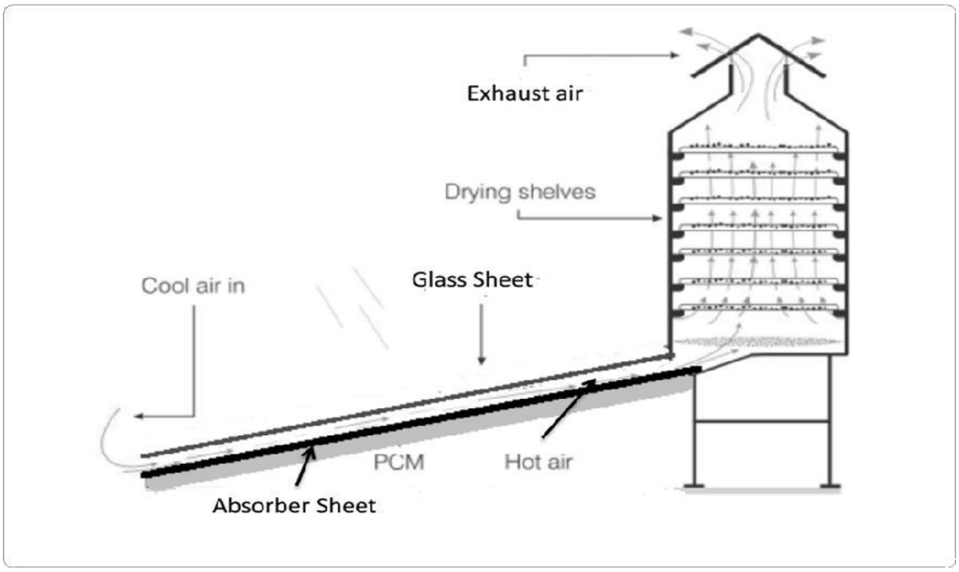

Figure 2.3: A schematic diagram of PCM assisted solar dryer
(Source: Balladin and Headley, 1999)

2.6.2 Solar drying system using the V-groove solar collector.

According to Fudholi *et al*. (2008), V-groove type solar collector with a collector area of roughly 15 m^2 and an air flow rate of 15.10 m^3/min may attain an average output temperature of 50 °C for an average solar radiation of 700 W/m^2. The efficacy of a sun aided drying system on herbal tea, chilies, and noodles has been studied in the lab. The outlet duct, which is strategically situated for optimum performance, discharged hot air into the drying chamber. A 10 kW auxiliary heat source has been used for continuous operation and more effective temperature control. Herbal tea or green tea contains many organic compounds and the processing requirements differ depending on specifications on the types of tea to be produced. Discoloration of herbal tea will occur if the drying process is delayed.

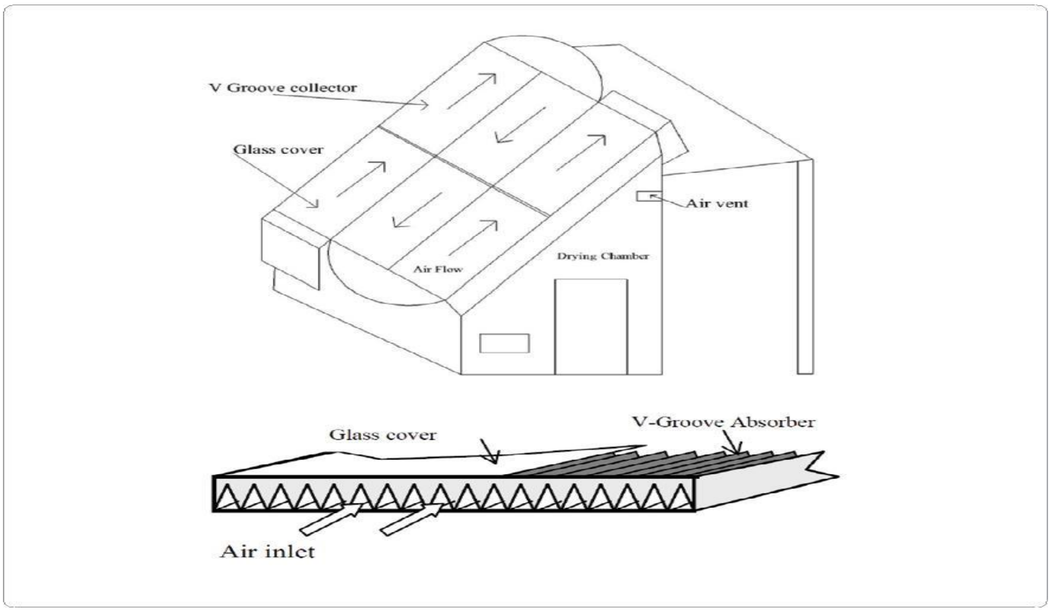

Figure 2.4: Solar drying system using the V-groove solar collector

(Source: Fudholi *et al.*, 2008)

Fresh tea leaves have an initial moisture content of 87 % (wb). Drying is required to lower the final moisture content of 54 % (wb). This will allow the green colour of the tea to be maintained. The auxiliary heater is on if the drying chamber temperature is below 50 °C. The flow rate is fixed at 15.10 m^3/min. The initial weight of the fresh tea leaves is 10.03 kg and the final weight is 2.86 kg.

2.7 Double Pass Solar Collector with Fins

In double pass solar collector with fins system, ambient air is initially passed over the black absorbing surface then through fins which are used to increase the heat transfer area. In this way the temperature of the air can be increased significantly to dry the product. Sopian *et al.* (2009) has advanced this drying system with capacity of up to 300 kg. Solar collecting array, secondary heater, blower, and drying chamber are the primary components. The chamber is 4.8 m long, 1 m width, and 0.6 m tall. The four collectors are connected in a series with a total area of 11.52 m^2, a mass flow rate of 0.05 - 012 kg/s, and a drying temperature of 50 °C to 65 °C. In Semporna, Sabah, the technique is used to dry seaweed (Eucheuma Cottonii) and is a source of income. Communities, associations, and individuals have all participated in the seaweed industry. Currently, seaweed is widely employed in the manufacturing of food and medical items. Problems faced by seaweed farmers are raining days, requirement of large space for open drying and long drying time. Under open sun drying conditions usually it take 10-14 days for it to be 10 % of original weight. The initial and final moisture content of seaweed are 90 % (wb) and 10% (wb) respectively. The drying time is about 14 hours at average solar radiation of about 544 W/m^2 and air flow rate 0.06 kg/s. The collector, drying system and pick-up efficiencies were found to be 37 %, 27 % and 92 % respectively for 40 kg of material.

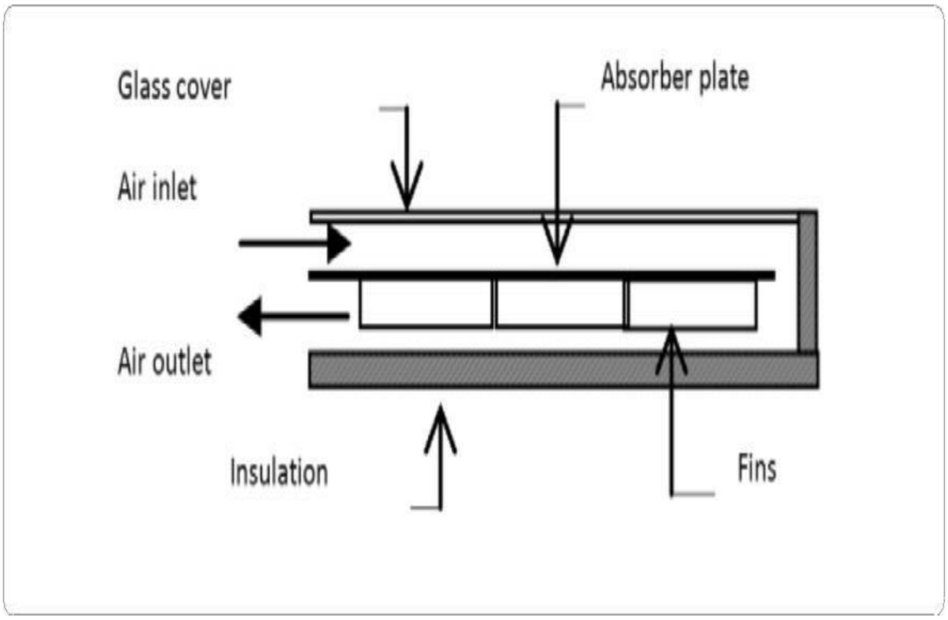

Figure 2.5: Double pass solar collector with fins (Source: Sopian *et al.*, 2001)

2.7.1 Indirect active hybrid solar–electrical dryer system

In hybrid type of solar dryer, an additional source of heating air is provided along with solar collector so that the overall temperature of the drying air can be increased. This system is also applicable where continuous drying is required and solar radiation is not available. Boughali *et al.* (2009) had studied the indirect active hybrid solar–Electrical dryer in the eastern Algerian Septentrional Sahara. The indirect active hybrid solar–electrical dryer was fabricated and installed at LENREZA laboratory (Laboratory of New and Renewable Energy in Arid Zones), university of Ouargla, Algeria. It consisted mainly of a flat plate solar collector, drying chamber, electrical fan, resistance heater (3.75 kW: accuracy ± 2 %) and a temperature controller. The solar air collector has an area of 2.45 m^2, and was inclined at an angle of 31° (latitude of Ouargla city) with the horizontal facing south all the time and used a black painted metal of 0.002 m thickness to absorb most of the falling solar radiation.

The cover losses were minimized by placing a glass cover of 0.005 m thickness over the top of the black absorbing metal sheet, and a layer of polystyrene was sandwiched between two parallel metal sheets and back insulator to provide insulation. The air was passed under the glass sheet, between the glass and the absorber. The solar collector was connected directly to the drying chamber without any air ducts to reduce pressure drop. The drying cabinet constructed with a galvanized iron box with insulated polystyrene walls of dimensions 1.65 m × 0.60 m × 1.00 m containing six product trays each tray has an area of 0.4 m² with possibilities to extend up to eight product trays. The drying trays were made of a wooden frame on all four sides and a wire mesh on the bottom to contain the samples and/or to change the position of the trays. The door of the dryer was properly sealed to forbid air leakage. In solar drying process, the auxiliary heater was used to adjust the drying air temperature. The preliminary heating of air was done by solar radiation which was again heated by electrical resistance, if its temperature was less than drying temperature required; which is controlled thermostatically and then ventilated by an exhaust fan through the product to the environment. The exhaust fan of 20 cm diameter was manually controlled by a valve, allowing the choice of the desired air mass flow. The fan was fixed below product trays at the bottom of the dryer to check an even distribution of air and to remove the humidity of the product to the surrounding.

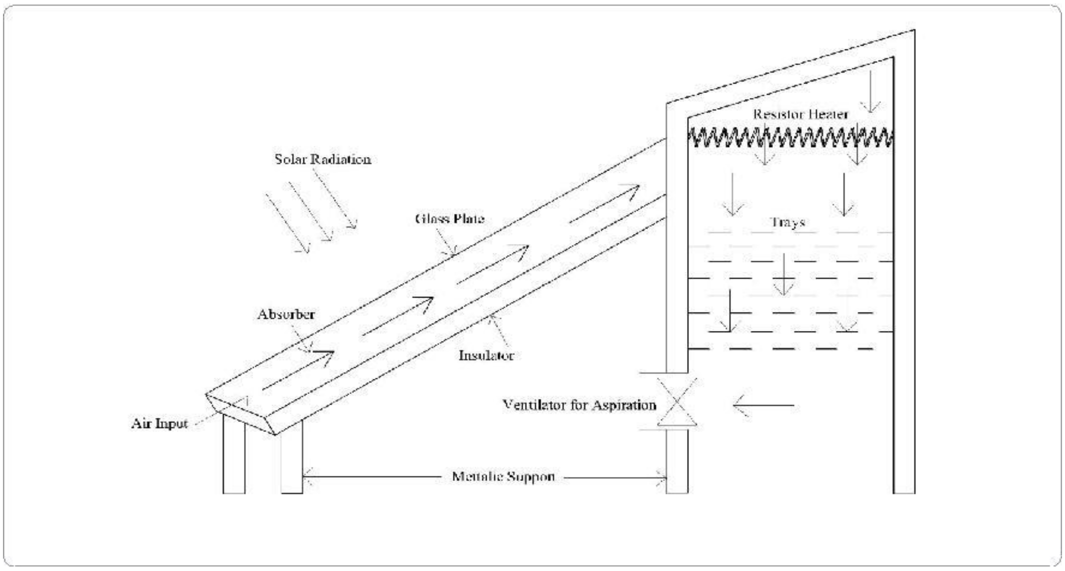

Figure 2.6: Solar Drying System with Indirect Heating (Source: Boughali *et al.,* 2009)

2.7.2 Solar drying system with chemical heat pump

Heat is created in a chemical heat pump assisted sun dryer by introducing exothermic chemical processes. This heat is used to warm the surrounding air. Chemical reactions in this type of system are often reversible, with solar energy being used to replenish compounds for future usage. The solar-assisted chemical heat system was designed by Ibrahim *et al*. (2009) and consists of four main components: a solar collector (evacuated tubes type), a storage tank, a chemical heat pump unit, and a dryer chamber. As a storage tank, a cylindrical tank was chosen in this investigation. Reactor, evaporator, and condenser made up the chemical heat pump unit. A solid gas reactor with a condenser or evaporator is used in a chemical heat pump. The salt in the reactor reacts with the gas; the reactions used in this investigation were: $CaCl_2.2NH_3 + 6NH_3 \rightarrow CaCl_2.8NH_3 + 6\Delta H$.

Fadhel *et al*. (2010) designed a drying chamber with many trays to contain the drying material while exposing it to air flow. Adsorption and desorption are the two steps of a chemical heat pump's operation. The cold production stage is the adsorption stage, which is followed by the regeneration stage, which is when decomposition occurs. The liquid-gas transformation of ammonia produced cold at low temperature in the evaporator during the production phase. Simultaneously, a chemical interaction between gaseous ammonia and a solid would produce heat at a greater temperature. The condensing refrigerant (ammonia) heated the incoming air, which enters the dryer inlet at the drying condition and performs drying. Following the drying process, a portion of the wet air stream exiting the drying chamber is diverted into the evaporator, where it is cooled, and dehumidification occurs as heat is transferred to the refrigerant (ammonia). The air was then directed to the condenser, where it was reheated by the condensing refrigerant, before being directed to the drying chamber. As a drying material, lemon grass was employed.

2.7.3 Solar dryer with dehumidification system

The temperature of air in drying process affects the quality, evaporation capacity as well as drying period. In addition, shorted time period is required for higher temperature drying. At higher temperature, pure water vapour pressure becomes higher; therefore, the difference between water vapour partial pressure and pure water vapour pressure becomes higher. This pressure difference is the driving force of water evaporation to the air. This driving force is directly proportional to the evaporation rate of water to air. However, drying at high temperature is not suitable for the materials which are sensitive to heat because it can cause cracks, browning which further reduce the taste of final product as well as the evaporation of the active ingredients such as in medicinal herbs. Yahya *et al.* (2008) developed a solar dehumidification system for medicinal herbs. The system consisted of a solar collector, an energy storage tank and auxiliary heater, water to air heat exchanger, a water circulating pump, drying chamber, and adsorbent. It was made up of essentially three processes, namely regeneration, dehumidification, and batch drying. During regeneration process, the air outside the dryer is heated with the heat exchanger and is supplied to the adsorbent. The adsorbent is heated with this hot air and water content rate is reduced, removing the water content. The water content is evaporated by the hot air and leaves the dryer. During dehumidification (adsorption) process, the air inside the dryer passes through the heat exchanger by use of the blower. However, since no hot water is circulated in the heat exchanger, the air reaches the adsorbent. The air is dehumidified with the adsorbent and is supplied the drying load as the dry air. The relative humidity and temperature of the drying chamber were 40 % and 35 °C respectively.

2.8 Domestic Cooking Technologies

According to Mwaura, (2013), many African homes rely on four basic sources of energy for cooking. Woodfuel (fuelwood and charcoal), kerosene, electricity, and liquefied petroleum gas (LPG) are some of the options. The high cost of petroleum products and electricity has made them out of reach of the low-income households. For about 75 % of the population living in the rural areas in Africa, wood fuel is the predominant source of energy, accounting for over 95 % of the total household consumption. In most African countries, rural households rely mostly on fuelwood, whilst urban households rely primarily on charcoal, with the former accounting for 80 % and the latter 15 % respectively (Bhagavan and Karekezi, 1992). This has put a lot of strain on biomass resource utilisation, as firewood cutting produces deforestation, which contributes to desertification (Nahar, 1998). As fuel-wood supplies are getting exhausted, more and more animal and crop residues are burned depriving the soil of valuable nutrients and organic conditioning materials (Wankhade *et al.*, 2013).

2.9 Solar Cooking Technologies

Along with its numerous advantages, such as no recurring costs, the potential to reduce the hardship of firewood gathering, high nutritional value of cooked food, and high cooker durability, solar cooking has been recognized as an excellent technology (Manabhanjan & Ivan, 2016). Solar cookers are heat exchangers that use solar energy to cook. All solar cookers work by concentrating light and heat from the sun into a tiny cooking area, converting sunlight, and trapping the heat by separating the air inside the cooker from the air outside the cooker using the Greenhouse Effect. The effectiveness of solar cookers improves as the temperature of the heat source rises. In solar thermal energy plants, solar radiation is focussed by mirrors or lenses to achieve high temperatures, a technique known as Concentrated Solar Power (CSP) (Solar PACES, 2019). Since this collector's performance is dependent on temperature, the entire system's performance is affected by temperature (Duffie and Beckman, 2013).

2.9.1 Solar cookers without storage

There are around 60 different varieties of solar cookers, which are grouped into three categories. The three types are concentrator, box-type designs (direct type), and indirect types (Hussein and Nada, 2008; Muthusivagami *et al*., 2010).

2.9.2 Concentrator type solar cooker

In concentrating solar cookers, reflectors focus sunlight on a cooking container. The most common reflector geometries are flat plate, disc, and parabolic trough. Concentrating cookers, like conventional cookers, can attain temperatures of up to 350 °C and cook any type of food. They are difficult to construct, and the focus point produces a deadly glare, necessitating the use of sun glasses to protect the cook's eyes. The concentrator must be adjusted frequently to track the sun, and the food must be constantly monitored (Ashok, 1989).

Plate I: Parabolic solar cooler (Source: Ashok, 1998)

2.9.3 Box-type solar cookers

A box cooker is made up of a series of mirrored panels that direct their beams toward an insulated box construction with a clear top that allows solar radiation to pass through. Inside the box are black-painted cooking pots and pans. Insulation is used to fill the area between the two boxes. On top of the insulated box, there is a double-glazed door. Inside the inside box, the food is placed. Reflectors can be added to the box cooker to improve its efficiency. The solar box cooker typically reaches a temperature of 150 °C (300 °F) and food can be left in the cooker for longer period of time (Ashok, 1998).

Solar box cookers have been widely accepted in India and other countries where energy is scarce and biomass resources are limited. Hot solar box cookers are simple to construct, handle, and operate, are inexpensive, and require little attention during the cooking process (Hussein and Nada, 2018; Manabhanjan and Ivan, 2016).

Plate II: Solar box cooker with two reflectors (Source: Ashok, 1998)

The cookers are more stable, can keep food warm for a long time. Cookers do not produce glare and have no risk of fire and burns. The performance of the hotbox solar cooker with a single reflector is very good but it requires tracking towards the sun every 60 minutes while one with two reflectors requires tracking every 180 minutes (Ashok, 1998). Plate II and III are photographs of some of the box type solar cookers.

Plate III: Hot - box cooker (Source: Ashok, 1998)

2.9.4 Indirect solar cookers

Solar radiation heats a thermal fluid, which transfers the water and heat to the cooking area in indirect solar cookers (Hussein and Nada, 2018). The indirect solar cooker consists of a central pipe containing a heat transfer fluid which is heated by a cylindro-parabolic mirror and the pipe is connected to an insulated cooking box inside the house. Indirect solar cookers provide high thermal power and temperatures without tracking and allow cooking in the shade or even in a conventional kitchen (Ashok, 1998).

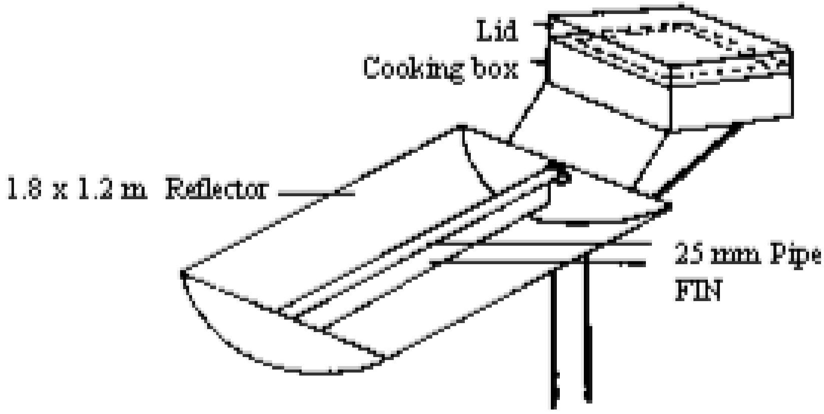

Figure 2.7: Indirect one phase solar dryer (Source: Ashok, 1998)

2.10 Solar Cookers with Heat Energy Storage

Cooking during cloudy periods and late afternoon is not possible with many solar cookers due to a lack of thermal storage (Hussein and Nada, 2008). Solar cookers' utility is limited if they are not fitted with a heat storage device, as they cannot be used in cloudy or evening situations (Kenisarin and Mahkamov, 2007). There are three practical ways of storing thermal energy; as sensible heat, as latent heat and as heat of a reversible thermochemical reaction (Brousseau and Lacroix, 1996).

The following major characteristics of a thermal energy storage system were given by (Duffie and Beckman, 2013). Temperature range over which it operates, that is the temperature at which heat is added to and removed from the system;

The means of addition and removal of heat and the temperature differences associated there with;

- Temperature stratification in the storage unit;
- The power requirements for additional or removal of heat;
- The container, tanks or other structural elements associated with the storage system;
- The means of controlling thermal losses from the storage system, and
- Its cost.

Heat is delivered to a thermal storage medium in an insulated reservoir during the day, and it is withdrawn for cooking at night. Thermal storage media include pressurized steam, concrete, a variety of phase change materials, and molten salts like sodium and potassium nitrate (Akanksha *et al*., 2015).

2.10.1 Sensible heat storage

The temperature of a solid or liquid is raised to retain thermal energy in sensible heat storage (SHS). The SHS system makes use of the material's heat capacity and temperature change during the charging and discharging processes. The specific heat of the medium, temperature changes, and the number of storage materials available all influence the amount of heat stored (Sharma *et al.*, 2000). The heat stored can be calculated

$$Q = VC_p \, dt \; or \quad Q = MC_p d\,t \tag{2.1}$$

Where; Q = Sensible heat stored in the material (kJ)

V = Volume of the substance (m^3) = Density of the substance (kgm^{-3})

M = Mass of substance (kg)

C_p= Specific heat capacity of the substance ($Jkg^{-1}\,°C^{-1}$)

dt = Temperature change (°C)

Sensible heat storage of thermal energy is perhaps the most fundamental type of thermal energy storage. In its most simple configuration, the hot fluid from the solar collector field heats the cold fluid in an insulated tank to a greater temperature. One disadvantage of a sensible-heat system is that most materials have a limited ability to hold heat sensibly. They have a thermal capacity of 0.5 - 0.7 times that of water (Sharma *et al.*, 2000).

2.10.2 Thermochemical energy storage

The basis for thermochemical systems is the energy collected and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. The storage medium, the endothermic heat of reaction, and the degree of conversion all influence the quantity of heat stored (Sharma *et al.*, 2000). The heat stored is given by

$$Q_{store} = a_r \, m h_r \tag{2.2}$$

Where;

Q_{store} = Heat stored (kJ)

a_r = fraction reacted

m = mass of heat storage medium (kg)

h_r = endothermic heat of reaction (kJ) (Sharma *et al.*, 2005).

2.10.3 Latent heat energy storage

The absorption or release of heat when a storage substance transitions from solid to liquid, liquid to gas, or gas to liquid, or vice versa, is known as latent heat storage (LHS). The storage medium undergoes a phase transition in latent heat storage by absorbing and releasing heat in an almost isothermal manner. They also have a large potential for storing energy (Brousseau and Lacroix, 1996). Sharma *et al*. (2000); Duffie and Beckman, (2013) gave the following equation for the energy stored by the phase change material (PCM)

$$Q_{store} = M_{pcm} C_{pcm} (T_m \, T_a) \, L_{pcm} \, (T_{pcm} max \, \_ T_m) \tag{2.3}$$

Where;

Q_{store} = Energy stored by the phase change material (PCM) (kJ)

M_{pcm} = Mass of PCM (kg)

C_{pcm} = Specific heat capacity of the PCM $(KJkg^{-1} \, {}^oC^{-1})$

$T_{pcm}max$ = Maximum temperature of PCM (°C)

T_m = Melting temperature of PCM (°C)

T_a = Ambient temperature (°C)

L_{pcm} = latent heat of fusion of the PCM ($KJkg^{-1}$)

Latent heat thermal energy storage is particularly appealing among the above thermal heat storage techniques because of its ability to provide a compact and efficient storage system due to its high energy storage density and its ability to store heat at a constant temperature corresponding to the phase transition temperature of phase change material (PCM) (Abhat, 1983; Bansal and Buddhi, 1992; Sharma *et al.,* 2005; Farid *et al*., 2004).

Solid to gas and liquid to gas transitions have higher latent heat of phase transition, but have large volume change on phase transition associated with containment problems which rule out their potential utility in thermal storage systems. Solid to liquid transformations have small change in volume are attractive for use in thermal energy storage systems (Sharma *et al*., 2000).

2.10.4 Latent heat storage materials

The thermal features of PCM use in thermal storage systems should include a sufficient phase transition temperature, a high latent heat of transition, and strong heat conductivity. Physical characteristics include favourable phase equilibrium; high density, small volume change, and low vapour pressure. Two kinetic characteristics are the absence of supercooling and a proper crystallisation rate. Long-term chemical stability, compatibility with construction materials, no flammability, and nontoxicity are all chemical characteristics. Abundance, availability, and cost effectiveness are some of the economic characteristics (Sharma *et al.*, 2005; Kenisarin and Mahkamov, 2007). Phase-change materials (PCMs) offer an alternative solution to energy storage and have a potential of providing a more efficient means of storage (Sharma *et al*., 2000). The choice of the material PCM is based on the melting temperature, the latent heat of fusion, density and other considerations such as toxicity, corrosiveness and cost (Sharma *et al*., 2005).

Gas – liquid, solid – gas, solid to solid, and solid – liquid are the four types of phase shift for latent heat storage materials. Although solid – gas and liquid – gas transitions have a higher latent heat of phase transition, their large volume increases during phase transition cause containment challenges, excluding them from usage in thermal storage systems. Conversions from solid to liquid have less latent heat than liquid to gas conversions, although they only involve slight volume changes. Solid–liquid transitions have proven to be cost-effective in thermal energy storage systems (Sharma *et al*., 2000).

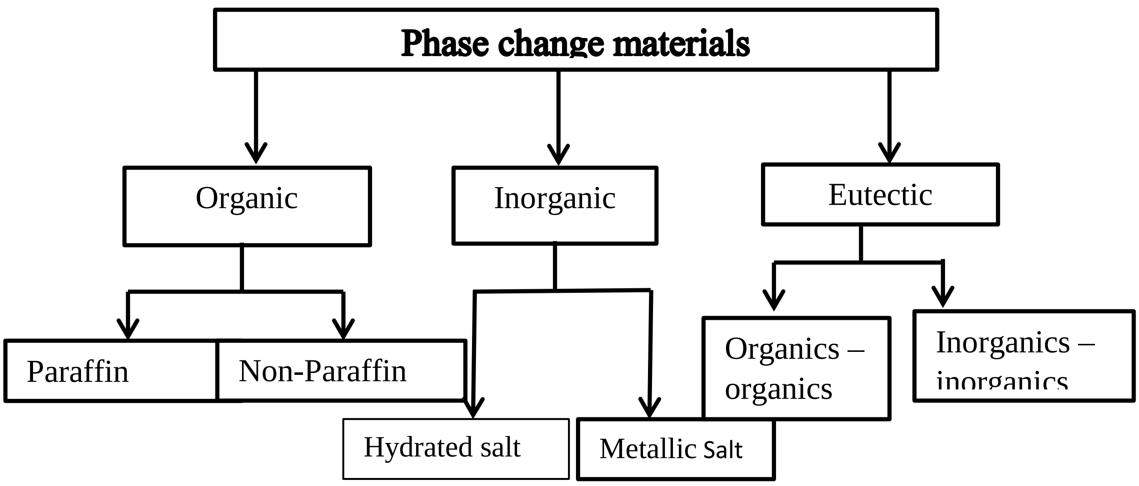

Figure 2.8: Classification of PCMs (Source: Sharma *et al*., 2005)

PCMs can be subdivided into organic, inorganic and Eutectics. A vast range of organic and inorganic chemical compounds that can be recognised as PCM based on melting temperature and latent heat of fusion but fail to meet the criteria for suitable storage media. No one material can possess all of the qualities necessary for an excellent thermal-storage medium (Sharma *et al*., 2005). Practical difficulties include; low thermal conductivity, density change, stability of properties under extended cycling, phase segregation and sub-cooling of PCM (Sharma *et al*., 2000).

Commercial paraffin waxes melt at roughly 55 °C and have moderate thermal storage densities of 200 kJ/kg. They are also inexpensive. They are chemically inert and stable, with little phase segregation, and they undergo very little sub-cooling. They do, however, have a low heat conductivity of 0.2 W/m°C, which limits their use (Sharma *et al*., 2005). Most salt hydrates like, calcium chloride hexahydrate ($CaCl_2.6H_2O$), magnesium chloride hexahydrate ($MgCl_2.6H_2O$) and magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$) have the disadvantage that during extraction of stored heat the material sub-cools before freezing. This reduces the utility of the material (Farid *et al.,* 2004).

Organic materials are not corrosive, have low or no undercooling and have chemical and thermal stability. However, they have low phase change enthalpy, low thermal conductivity and are inflammable. Inorganic materials have great phase change enthalpy but undergo corrosion, phase separation, phase segregation and lack thermal stability (Zalba *et al*., 2003). Non-paraffin organic compounds and fatty acids are two subcategories of organic materials. Fatty acids have high heats of fusion comparable to paraffin and display consistent melting and freezing behaviour with no supercooling, making them suitable PCMs. Their main disadvantage is that they are 2 – 2.5 times more expensive than technical grade paraffin and are somewhat caustic (Sharma *et al*., 2005).

2.10.5 Solar cookers with latent heat storage

Few studies have been conducted with latent heat storage materials to cook food in the late evening. Zalba *et al*. (2003) used magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$) as a PCM for heat storage medium for a box type solar cooker designed to cook food in the evening hours and non- sunshine hours. Buddhi and Sahoo (1997) designed and conducted experimental testing on a solar cooker with latent heat storage for cooking food in the evening. They used commercial-grade stearic acid (melting point 55.10 °C and latent heat of fusion of 160 kJ/kg) as PCM and filled it below the absorber plate of the box type solar cooker. Sharma *et al.* (2000) designed and developed a cylindrical PCM storage unit for a box type solar cooker to cook food in the late evening. They used acetamide (melting point 82 °C) as the latent heat storage material.

According to their findings, storing solar energy for evening cooking had no effect on the solar cooker's performance for noon cooking, and they recommended that the melting temperature of a PCM for evening cooking be between 105 °C and 110 °C.

Buddhi *et al*. (2003) devised and constructed an acetanilide-based storage unit for a box-type solar cooker to store more solar energy. For the cooking pot, a cylindrical latent heat storage unit was used, as well as a solar box cooker with three reflectors. A mechanism was installed in each of the three reflectors to enable for sun tracking and to maintain the reflected solar radiation on the absorber surface.

2.11 Summary of Literature Review

Some research efforts on the development of solar oven or cooker have focused on issues of environmentally-friendly and hazard, cost of production optimum and the feasibility studies on the development of solar oven or cooker. Some of the research findings are presented below.

According to Nagaraj *et al.* (2016), solar energy is an alternative source of non-renewable energy. Sultanate of Oman government should show initiation into utilization of solar energy for domestic applications. Conversion of solar radiation into useful heat is the simplest application of solar energy, in which it can be used for late evening cooking. In this context, present work highlighted the design and development of solar cooker for Oman climatic conditions. Their work signified usage of solar cooker for late evening cooking using stearic acid and acetanilide as phase change materials (PCM). Solar cooker parts were developed in-house and connected to water heating system compounded within evacuated tubes solar collector and storage tank. The circumference of cooker unit was incorporated with spiral stainless-steel heat exchanger and annulus area of the pot was filled with PCM material. PCM releases heat at late evening and effective cooking up to 7:30 pm was noticed by the researchers. The experimental results indicated the cooker efficiency of 30 % and collector efficiency of 60 – 65 % during the study. Overall, experiments showed satisfactory performance on the developed cooker.

Sharma *et al.* (2005) investigated the thermal performance of solar cookers based on an evacuated tube solar collector with PCM storage unit. The experiment results indicated that the noon cooking did not affect the evening cooking and that evening cooking using PCM heat storage unit is faster than noon cooking.

Similarly, Agrawal and Yadav (2015) carried out experiments with solar cooker with two sensible heat storage materials for evening cooking. They used a parabolic type of solar cooker and sensible heat storage materials like iron grits and iron balls. In their study relationship between the temperature and the solar radiation intensity for both sensible heat materials were noticed; experimental results highlighted the fact that solar cooker is more efficient when filling the iron balls in the inner space and the iron grits in the outer space.

Sharma and Singh (2015) designed, developed, and performed evaluation of the latent heat storage unit for evening cooking of solar cooker. Cooking experiments were conducted with different loads and loading times during the summer and winter seasons. The experimental results showed that evening cooking is possible with a solar cooker having the PCM storage unit and is not possible in a standard solar cooker.

Kassem (2012) carried out experiment on box type solar cooker with heat storage unit. The experiment setup included solar water heating that contained evacuated tubes solar collectors and storage unit. Paraffin was used as the phase change material in heat storage unit. He found that solar cooker based on evacuated tubes solar collector with PCM unit gave good performance in the conditions of high elevation.

Saini *et al.* (2015) studied the concept of solar cooker and designed a solar cooker for late cooking. Their study demonstrated different designs for solar cooker and studied the performance of solar collector. The study results revealed that solar cookers are helpful in minimizing CO_2 emissions and the cylindrical storage unit is preferred over rectangular storage unit.

In addition, solar cookers having PCM which melts above 100 °C are more promising for the storage unit of the solar cooker. With this thought, present work signifies the design, development, and comparison of the performance of the solar cooker using stearic acid and acetanilide as phase change materials for Oman conditions. Thermal calculations are made for evacuated tube collector, PCM storage system, and studying the performance at different loadings.

Nigeria, like other countries, is endowed with plenty of solar energy with a mean sunshine duration of about 7 - 8 hours. Nigeria receives an average solar radiation of about 700 W/m² and this solar energy is freely available even in remote places with little access to conventional energy supplies. The high cost of petroleum products, electricity and the diminishing biomass resource leaves Nigeria with solar energy as an alternative. The application of solar ovens is restricted if they are not equipped with a heat storage system since it is impossible to use them in cloudy conditions or evenings. In this study, solar box cooker with four reflectors and an energy storage unit using phase change materials was used.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The materials and the equipment used to carry out the test are as follows

1. PCM (Sodium Nitrate and Potassium Nitrate)
2. Insulator – carbon fibre
3. Solar reflectors (Aluminium Foils)
4. Supporting frame - mild steel
5. Sheet metal cover
6. Trays
7. Glass-tube thermometer

8. 10 kg Kitchen Scale

9. Drying Pans

3.2 Working Principle or Description of the Model

The solar oven uses solar energy for drying of vegetables. The reflectors direct the solar radiation through a glass into the oven thereby increasing the temperature inside the drying chamber. The concentrated light passes through glass into the drying chamber continuously, thereby increasing the chamber's temperature. The PCM is kept inside an aluminium container at the wall of the chamber. The PCM absorb heat from the sun light as well as the drying material. The solar oven has a supporting frame that houses the PCM container and the insulating material. The insulator is covered with a sheet metal from the outside. The cover has two drying trays inside the chamber. During the day, the PCM absorb heat and store it until later when the sun light is out, it releases the heat into the drying chamber.

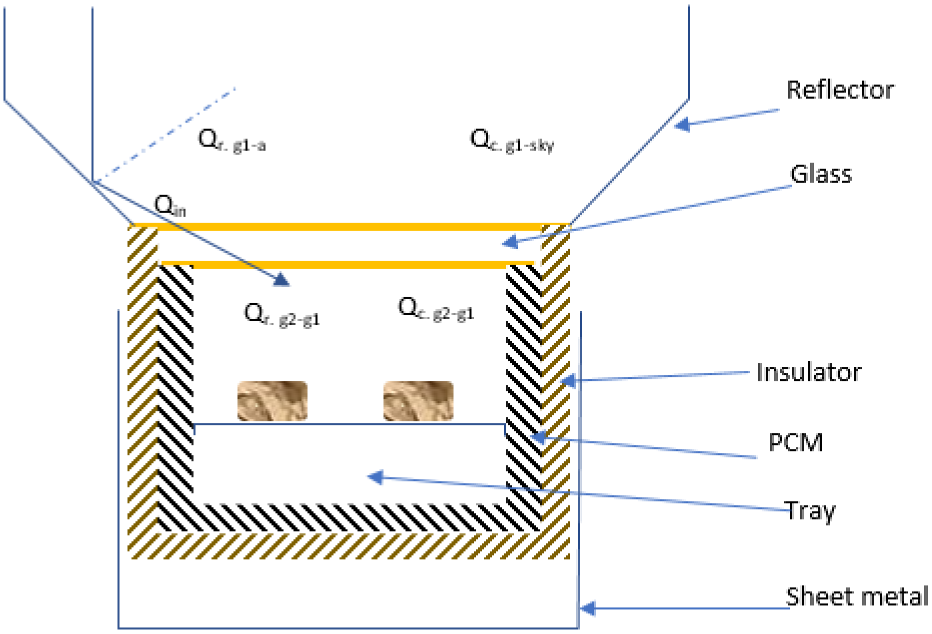

Figure 3.1: Schematics of PCM Solar Over

3.3 Selection of Phase Change Material

The type of PCMs used directly affects the heat transfer and heat storage performance of the solar oven. A PCM suitable for a particular application most have a phase-change temperature within the application temperature range. Materials with too low phase-change temperature will decompose or gasify under the sun for a long time, and the material with too high temperature is not suitable for cooking food because it has a longer period of phase change. A molten salt, Sodium Nitrate and Potassium Nitrate ($NaNO_3$ – KNO_3) was selected as PCM and used for the research, with weight ratio 60 %:40 %. The 60 % $NaNO_3$ – 40 % KNO_3 has a phase change temperature of about 220 ^oC and stable thermal properties of 660 ^{o} C (Bauer *et al.*, 2019) and (Wu *et al.*, 2017) are shown in Table 3.1

Table 3.1: Properties of PCM Material

Properties	$NaNO_3$ (Solid/Liquid)	KNO_3 (Solid/Liquid)
Density kg/m^3	2197	1837
Thermal Capacity (kJ/kgK)	0.76	0.519
Heat Capacity (kJ/K)	1.05	1.5
Latent Heat of Phase Change (kJ/kg)	161	161

3.4 Design Methods

3.4.1 Material selection

3.4.1.1 Materials for the oven's body

The body of the oven is required to retain the maximum heat possible within the oven chamber. The oven body comprises of the mild steel covering the insulator (glass fibre), the inside of the carbon fibre is covered with an Al-alloy sheet of 2 mm thickness. The glass fibre insulations, generally offer a lower thermal conductivity of 0.03 - 0.04 W/mk.

3.4.1.2 Top cover

The top cover is supposed to allow the passage of light ray/heat into the oven chamber and be strong enough to support the reflectors. A glass of 4 mm thickness was selected since the transitivity of the glass is close to 1, and installed in a wooden frame. The wooden frame was selected since wood is a good insulator.

3.4.1.3 Reflecting surface

Material selected is Aluminium foil, it reflects approximately 98 % of radiant heat and light and also it transmits no light and is a total barrier to light including the UV spectrum. The Al-foil has a melting point of 660 $^{\circ}$C and therefore suitable for use as a reflector for this oven. It has a brightly polished surface of about 40 μm, non-absorbent and very sterile.

3.4.1.4 Material for PCM container

The container used to store the PCM is made from Al-sheet due to availability. This is because the container needs to allow the free movement of heat to and fro to the PCM. Also, the container needs to be corrosion resistance, malleable and have high thermal conductivity. From the survey, it was understood that Aluminium is not only cheap and easily available, but also has a very good specific heat per cubic centimetre. In order to retain the heat for a longer time, the vessel was painted black from outside.

3.5 Design procedure for the solar oven

The design parameters considered included the energy requirements, daily average insolation, size of PCM containment and melting temperature of the PCM. According to Raghavan *et al.* (2005), the minimum theoretical amount of energy required for drying sliced agricultural product ranges from 5.21 to 90.40 MJ/kg. The energy requirement for cooking per person is about 900 kJ of fuel equivalent per meal. Design consideration was of 4 people at 2 meals per person per day gives an energy requirement of 7.2 MJ per day; anticipated daily average insolation (I) of 700 W/m^2 with an assumed collector day average efficiency of 0.50. The required solar energy collection area is given by:

$$\mathrm{A} = \frac{7200000}{700\times0.5\times6\times3600} = 0.952\ m^2 \tag{3.1}$$

The absorber area of 2 m x 0.45 m (0.9 m^2) was considered to cook for a family of four people per day.

The box unit consists of a double walled box. The inner and outer boxes were made of black sheet metal. Nahar (1998) recommended that the dimensions of the box are such that the ratio of length to width of the reflectors and glass window is about 4 to 1. This allows maximum radiation to fall on the glass window and it helps in eliminating the azimuth tracking towards the sun.

The dimensions of the outer box are 2200 mm × 650 mm ×280 mm and of the inner box are 2000 mm × 450 mm × 180 mm. Ashok (1995) suggested that the depth of the inner box should not be more than 10 – 15 cm. This depth is a critical parameter as a greater depth would introduce a shade effect, but the width and breadth could be of any dimension. The space between the two boxes was maintained at 10 cm and was filled with vermiculite insulation.

The width of the gap between the two boxes varies with the type of insulation used. Fibre glass provides adequate insulation with a gap size of less than 6 cm, but its poses health risks because it inflames the respiratory track. Styrofoam would make a lightweight box due to its low density but it melts at relatively low temperatures.

Concrete or brick are commonly available and are recommended for small baking units but have high density therefore not suitable as they would increase the weight of the entire system. The inner side of the box was painted black. Two clear window glass panels 4mm thicknesses were fixed over the box with an openable wooden frame. The absorber area covered 0.90 m^2.

3.6 Energy Balance of the Solar Oven

The solar oven with internal energy storage using PCM has the following elements that were considered in developing the energy balance of the solar oven:

1. Two glass cover with a clearance between them.

2. PCM.
3. Internal reflectors made in commercial Aluminium paper placed inside the oven.
4. Thermal insulator that covers the oven
5. The Drying material

The solar oven is locked air tightly; this allows reaching considerable temperatures in the test fluid inside the drying chamber. The mathematical model was developed by considering the energy gain into the oven and energy lost to the environment for each of the elements listed above. The following assumptions from Punia *et al*. (2012) were made in balancing the energy for the oven shown in Figure 3.4, so as to simplify the model.

1. The solar radiations received by the vertical walls of the vessel are you negligible.
2. There is good thermal contact between the vessel and absorber plate.
3. The temperature gradient across the thickness of covers and cooking vessel has been neglected.
4. The heat exchange through air enclosed in the cooking vessel is negligible.

The energy absorbed or given off by each element of the solar oven are:

The Upper Glass Cover:

The energy balance equation for upper glaze cover may be written according to (Punia, *et al.*, 2012) as

$$M_{g1}\frac{dT_{g1}}{dt} = I_{in}\alpha_g A_c + Q_{r,g2-g1} + Q_{c,g2-g1} - Q_{r,g1-sky} - Q_{c,g1-amb} \qquad (3.2)$$

Where;

$$Q_{r,g2-g1} = h_{r,g2-g1}A_c\left(T_{g2} - T_{g1}\right) \qquad (3.3)$$

$$Q_{c,g2-g1} = h_{c,g2-g1}A_c(T_{g2} - T_{g1}) \quad (3.4)$$

$$Q_{r,g1-sky} = h_{r,g1-sky}A_c(T_{g1} - T_{sky}) \quad (3.5)$$

$$Q_{c,g1-amb} = h_{c,g1-amb}A_c(T_{g1} - T_{amb}) \quad . \quad (3.6)$$

$$T_{sky} = T_{amb} - 6 \quad (3.7)$$

M_{g1} = Heat capacity of top cover (J/K)

T_{g1} = Temperature of top cover (K)

I_{in} = Solar Radiation (W/m^2)

α_g= Absorptivity of the glass

A_c = Area covered (m^2)

T_{amb}= Temperature of the ambient air

C_p = Specific Heat at Constant Temperature (kJ/kgK)

h_c= Convective Heat Transfer Coefficient (W/m^{2}K)

h_r = Radioactive Heat Transfer Coefficient (W/m^{2}K)

The Lower Glass Cover

$$M_{g2}\frac{dT_{g2}}{dt} = I_{in}\alpha_g\tau_g A_c + Q_{r,p-g2} + Q_{r,v-g2} + Q_{c,a-g2} - Q_{r,g2-g1} - Q_{c,g2-g1} \quad (3.8)$$

Where;

$$Q_{r,p-g2} = h_{r,p-g2}(A_c - nA_{vb})(T_p - T_{g2}) \quad (3.9)$$

$$Q_{r,v-g2} = h_{r,v-g2}nA_{vb}(T_p - T_{g2}) \quad (3.10)$$

$$Q_{c,a-g2} = h_{c,a-g2}A_c(T_a - T_{g2}) \quad (3.11)$$

M_{g2} = Heat capacity of lower cover (J/K)

T_{g2} = Temperature of lower cover (K)

I_{in} = Solar Radiation (W/m^2)

α_g= Absorptivity of the glass

τ_g= Transmissivity of the glass

A_c = Area covered (m^2)

A_v = Area covered in the vessel (m^2)

A_{vb} = Area covered in the vessel base (m^2)

T_{amb}= Temperature of the ambient air (K)

n = No. of Vessels

T_p = Temperature of the absorber plate (K)

T_a = Temperature of the internal air (K)

h_c= Convective Heat Transfer Coefficient (W/m^{2}K)

h_r = Radioactive Heat Transfer Coefficient (W/m^{2}K)

A = Area (m^2)

C_p = Specific Heat at Constant Temperature (kJ/kg-K)

h_c= Convective Heat Transfer Coefficient (W/m^{2}K)

h_r = Radioactive Heat Transfer Coefficient (W/m^{2}K)

3.7 For Sill Air in the Drying Chamber

The energy balance equation for sill air in the drying chamber may be written according to (Punia *et al*., 2012) as

$$M_a \frac{dT_a}{dt} = Q_{c,p-a} + Q_{c,v-a} - Q_{c,v-g2} \quad (3.12)$$

Where;

$$Q_{c,p-a} = h_{c,p-a}(A_c - nA_{vb})\left(T_p - T_a\right) \quad (3.13)$$

$$Q_{c,v-a} = h_{c,v-a} n A_v (T_v - T_a) \quad (3.14)$$

Drying Tray:

$$M_t \frac{dT_t}{dt} = I_{in}\alpha_g\tau_g A_c + Q_{pcm} - Q_{c,t-b} - Q_{r,t-g2} - Q_{c,t-a} \quad (3.15)$$

$$Q_{pcm} = UnA_{tc}\left(T_{pcm} - T_t\right) \quad (3.16)$$

$$Q_{c,v-b} = h_{c,v-b}nA_v(T_v - T_b) \quad (3.17)$$

Drying Material:

$$M_b \frac{dT_b}{dt} = I_{in}\alpha_g\tau_g A_c + Q_{co,t-b} - Q_{c,b-a} \quad (3.18)$$

$$Q_{c,b-a} = h_{c,b-a}(A_c - nA_{vb})(T_b - T_a) \quad (3.19)$$

$$Q_{co,t-b} = k_t A_{tb}(T_t - T_b)/x \quad (3.20)$$

PCM:

$$M_{pcm} \frac{dT_{pcm}}{dt} = I_{in}\alpha_g\tau_g A_c + Q_{r,pcm-g2} - Q_{c,pcm-a} - Q_u - Q_t \quad (3.21)$$

$$Q_t = (U_b A_c + U_s A_s)\left(T_{pcm} - T_{amb}\right) \quad (3.22)$$

$$U_b = \left[\frac{xb}{ki} + \frac{1}{h_{c,g1-amb}}\right] \quad (3.23)$$

$$U_s = \left[\frac{xs}{ki} + \frac{1}{h_{c,g1-amb}}\right] \quad (3.24)$$

M_a= Heat capacity of the internal air (J/K)

M_b= Heat capacity of the drying material (J/K)

M_{pcm}= Heat capacity of the PCM (J/K)

M_t= Heat capacity of the tray (J/K)

T_a= Temperature of the internal air (K)

T_b= Temperature of the drying material (K)

T_{pcm}= Temperature of the PCM (K)

T_t= Temperature of the tray (K)

T_{g2} = Temperature of lower cover (K)

I_{in} = Solar Radiation (W/m^2)

α_g= Absorptivity of the glass

τ_g= Transmissivity of the glass

A_c = Area covered (m^2)

A_v = Area covered in the vessel (m^2)

A_{vb} = Area covered in the vessel base (m^2)

T_{amb}= Temperature of the ambient air (K)

n = No. of Vessels

T_p = Temperature of the absorber plate (K)

T_a = Temperature of the internal air (K)

h_c= Convective Heat Transfer Coefficient (W/m^2K)

h_r = Radioactive Heat Transfer Coefficient (W/m^2K)

k_t = Thermal Conductivity of Insulating Tray Material (W/mK)

A = Area (m^2)

x = Thickness of Insulation (m)

g_1= Heat capacity of top cover (J/K)

g_2 = Temperature of lower cover (K)

3.8 Determination of Insulator Thickness

The major source of heat loss in ovens is through wall of the oven. And the amount of heat that passes through a wall can be estimated by using equation (3.25)

$$Q = \frac{kA(T_2 - T_1)}{t} \tag{3.25}$$

Where;

t = Insulator wall thickness (m)

A = Wall area (0.45 m x 0.45 m) x 4

K = Thermal conductivity of the wall material (0.043 W/mK)

$T_2 – T_1$= Temperature difference (^oC)

$$t = \frac{kA(T_2 - T_1)}{Q} \tag{3.26}$$

$$t = \frac{0.043 \times 1.01\ (160 - 33)}{1{,}009.65} = 4.33\text{mm} \sim 5\text{mm}$$

The minimum insulator thickness required when using glass fibre is 5 mm.

For composite walls, equation (3.21) is expressed as equation (3.27)

$$Q = UA\Delta T \tag{3.27}$$

$$U = \frac{1}{\frac{1}{h_1}+\frac{t_1}{k_1}+\frac{t_2}{k_2}+\frac{t_3}{k_3}+\frac{1}{h_1}} \quad (3.28)$$

Where;

U = Overall heat coefficient (W/m^2 K).

h_1 = Convective heat transfer coefficient of air ($Wm^{-2}K$).

k_1 = Thermal conductivity of the sheet metal cover (W/mK).

k_2 = Thermal conductivity of the insulator (W/mK).

k_3 = Thermal conductivity of al-sheet (W/mK).

t_1 = Thickness of the sheet metal (2 mm)

t_2 = Thickness of the glass fibre (10 mm)

t_3 = Thickness of the absorber plate (2 mm)

$$U = \frac{1}{\frac{1}{25}+\frac{0.002}{54}+\frac{0.01}{0.043}+\frac{0.002}{205}+\frac{1}{25}} = \frac{1}{0.272604} = 3.67 \text{ W/m}^2\text{ K}$$

3.9 Quantity of Heat Required for Drying

According to Okedun and Ajav, (2007), specific heat of sliced okra with moisture content in the range of 10 - 80 % varied from 7.31 - 9.89 J/kg^{o}C. The heat required for drying 1 kg of okra is expressed according to Ezekoye and Enebe (2006) as:

$$Q = mc_p\Delta T_{+}mL \quad (3.29)$$

Where;

m – Mass of the drying material (1Kg).

C_p – Specific heat capacity of okra (19.8864 J/Kg ^{o}C).

ΔT – Temperature difference (^oC).

L – Latent heat of vaporization of water (kJ/kg).

$$Q = 1 \times 19.8864 \times (70 - 33) + 1 \times 2260 = 2995.797 \text{ J}$$

The amount of heat required to bake 1 kg of fruit vegetable (okra) from room temperature to about 70 ^oC is 2995.79 J.

3.10 Heat Stored by the PCM

The total energy stored by the PCM is expressed by equation (3.30),

$$E_{PCM} = \int_{T_1}^{T_{PC}} MC_{p,1}\Delta T + mL + \int_{T_{PC}}^{T_2} MC_{p.2}\Delta T \quad (3.30)$$

Cp,1 – specific heat capacity of the PCM at initial phase

Cp,2 – specific heat capacity of the PCM at final phase

L – Specific heat of phase transformation

Assuming cp,1 and cp,2 do not change with temperature, the equation (3.30) becomes equation (3.31)

$$E_{PCM} = M(C_{p,1}(T_{pc} - T_1) + mL + C_{p,2}(T_2 - T_{pc}) \quad (3.31)$$

$$\text{Efficiency}, \eta = \frac{Q}{A..I_G.t} \quad (3.32)$$

Where,

A – Area of the collector (m).

I_{av} – Average beam intensity (W/m^2).

t – Time of drying (h).

Therefore, substituting the values into equation 3.32 give the total energy stored by the PCM.

$$E_{PCM} = 0.11 \times (19.8864 \times (160 - 33) + 0.11 \times 161 + 19.8864 \times (160 - 126)$$
$$= 354.136 \text{ kJ}$$

The efficiency of the solar oven for drying for 9 hours is computed using equation (3.32).

$$\eta = \frac{Q}{A \times I \times t} = \frac{2995.797}{0.9 \times 700 \times 9} = 52\ \%$$

3.11 Moisture Content (M.C)

The moisture content can be determined according to Ezekoye and Enebe (2006) as:

$$M.C = \frac{(M_i - M_f)}{M_i} \times 100 \qquad (3.33)$$

Where;

M_i – Mass of sample before drying (kg).

M_f – Mass of sample after drying (kg).

3.12 Moisture Loss (M.L)

The moisture loss (M.L) can be determined according to Ezekoye and Enebe (2006).

$$M.L = M_i - M_f \qquad (3.34)$$

Other measured parameters included, the solar radiation, ambient air temperature, temperatures of the different components of the solar cooker, load temperature and wind speed. The data values were read and recorded by use of a data logger at regular intervals of 10 minutes. Data analysis was done using statistical measures. An average stagnation temperature of 85.90 ± 24 °C and 82.70 ± 24.30 °C was achieved in the two pots. The average solar radiation was 637.10 ± 212 W/m². The cooking power tests achieved a coefficient of performance of 0.75. The results showed that the double reflector solar cooker with energy storage can be used to cook meals throughout the day and in the evening.

3.13 Construction Details

3.13.1 The reflector

Plywood of 5 mm thick was cut to the required dimensions and the Aluminium foil was stick to the plywood with the aid of a gum. Four of the reflectors were produced using this method. A 25.40 mm thick Aluminium was screwed to the base of the reflector to provide the support and an interface for securing it to the top cover.

3.13.2 The top cover

The oven cover was produced from a 4 mm thick glass cover secured into a wooden frame via a silicon gum in a 5 mm groove. The glass size is 457.20 mm by 457.20 mm and 8 mm thick rubber insulator was placed at the bottom of the oven cover by using a gum. The oven cover was hinged to the oven body by using a 3 inches' hinge.

3.13.3 The oven tray

A two-layer oven tray was produced from a 4 mm thick iron net, secured within a frame made from a 25.40 mm flat mild steel bar. The tray frame is screwed to the 38.10 mm square hollow pipe support for the oven body. The tray location is provided on the drawing in appendix A.

3.13.4 PCM container

The size of the PCM container is (457.20 x 457.20 x 38.10) mm^3 and made from an Aluminium alloy sheet of 2 mm thick. The end of the container was sealed with potty so as to avoid leakages. The development of the Aluminium sheet was carried out, the result shape folded into the PCM container.

3.13.5 The oven body

A 38.10 mm square hollow pipe was cut with the aid of a hack saw to the required dimension and welded by using an arc welding machine. The result frame was cover with an absorber plate (2 mm Al-sheet painted black). The absorber plate is then covered with glass fibre (insulator), wrap with a masking tape. Then, the fibre glass is then cover with a riveted sheet metal. Plastic rollers were fitted at the bottom of the oven for make it mobile.

The fabricated parts and assembled oven are shown in plates IV -IX.

Plate IV: The Supporting Frame **Plate V: Insulator and Supporting Frame**

Plate VI: Drying Chamber **Plate VII: The complete Oven**

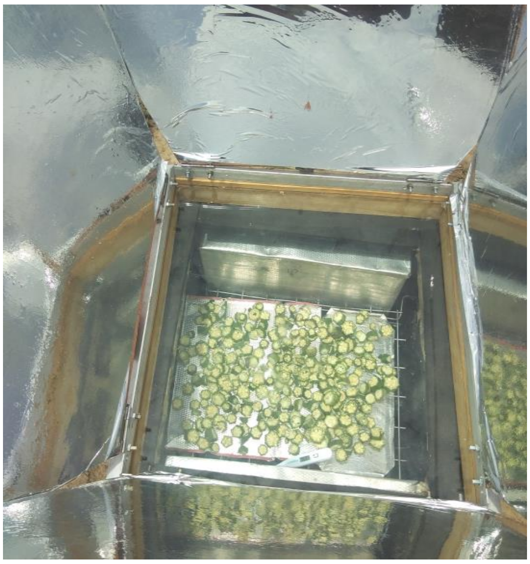

Plate VIII: Oven with Reflectors and Absorber **Plate IX: Okra inside the Oven**

3.14 Cost Analysis

The total cost of this project is estimated as presented as follows:

3.14.1 The material cost

The costs of the materials purchased in the course of producing this oven are listed in Table 3.2.

Table 3.2: Cost of the materials used

Item	Quantity	Unit Price (₦)	Amount (₦)
38.1mm Sqr Hollow Pipe	1	2,200.00	2,200.00
Gauge 18 mild steel sheet	1	6,000.00	6,000.00
Fibre glass	5	1,200.00	6,000.00
2 mm Al-sheet	0.5	7,500.00	3,750.00
4 mm thick rod	1	1,500.00	1,500.00
25.4 mm flat bar	0.5	1,200.00	600.00
50.8 x 50.8 mm white wood	1	2,800.00	2,800.00
4 mm thick glass	1	2,200.00	2,200.00

Silicon gum 1,250.00

Table 3.2: Cost of the materials used continue

Item	Quantity	Unit Price (₦)	Amount (₦)
8 mm rubber insulator	1	1,200.00	1,200.00
3 inches Hinges	2	50.00	100.00
Al- foil reflector	2	2,000.00	4,000.00
6 mm plywood	1	1,800.00	1,800.00
Screws	20	10.00	200.00
Bolts and nut	10	40.00	400.00
Black paint	1	2,500.00	2,500.00
Aluminium paint	1	2,500.00	2,500.00
Rollers	4	500.00	2,000.00
NaNO3	0.5	8,000.00	8,000.00
KNO3	0.5	7,000.00	7,000.00
Total			**56,000.00**

3.14.2 Labour cost

The labour cost of the project was estimated at **₦ 14,000.00.** The breakdown of the labour cost of the oven is presented in Table 3.3.

Table 3.3: Labour cost

Labour	Cost (₦)
Cutting of Mild Steel Pipe	1,500
Production of PCM Material	1,000
Cutting of Absorber/glass	1,000
Production of the drying chambers	1,000
Welding of the frame	3,500

Painting	1,000
Complete assembly of the oven	5,000
Total	**14,000**

3.14.3 Overhead cost

The overhead was taken at 10 % of the total material cost.

Overhead = ₦ 5,600.00

Total Project cost = ₦ 75,600.00

3.15 Test Procedure

After the construction of the oven, two tests were conducted. One, the oven was test without the PCM and the other was with the PCM. The two were conducted from 10 am to 6 pm. During the test period the temperature of the oven was recorded on the hourly basis using thermometer. The performance of the solar oven with PCM was studied in Federal University of Technology, Minna, Nigeria. The test was initially conducted with water loaded in the solar oven of four reflectors. The solar oven was placed outside about 10 am; the PCM was poured into its container and placed inside the oven. During the testing a known quantity of sliced okra was place on the oven tray and observed during the testing. The slices were then weighed exactly 110 g for each treatment. These were kept for drying in two duplications. The solar drying was carried by drying the samples inside the oven. For sun drying, the weighed okra slices were taken in drying pan made of aluminium plate and kept on the open floor on the top of terrace. Observations on physiological loss in weight in each sample were recorded at the particular interval of 1 hour in both drying methods. Temperature in the open sun drying and solar drying was recorded throughout the drying period using a glass-tube thermometer. The samples of average initial moisture content of around 110 g were dried to the final moisture content 11 g in oven and 33 g in sun. The moisture loss of samples was determined with the help of a digital electronic balance.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Design Analysis Results

The numerical equations (3.1) – (3.31) were solved and the design solutions are listed as follows:

Volume of PCM required = 0.01106 m^3

Density of the PCM Mixture, $\rho_{PCM} = 1981\ kg/m^3$

Oven Efficiency, η = 52 %

Energy Stored by the PCM = 354.136 kJ

Energy required for drying 1 Kg of Okra = 2995.797 kJ

Overall heat transfer coefficient = 3.67 $W/m^2\ K$

Total area of the reflector, A_{ref} = 1.3 m^2.

Volume of the Oven Cabinet = 0.055 m^3.

Thickness of the insulator, = 5 mm.

4.2 Performance evaluation of the Solar Oven

Three days' experiments were conducted with the solar oven and average values are recorded on the table below. The samples of average initial moisture content of around 110 g were dried to the final moisture content 11 g in oven and 33 g in sun as shown in Table 4.2. The moisture loss of samples was determined with the help of a digital electronic balance scale. It is evident from these curves in Figure 4.1 and Figure 4.3, the moisture content decreases continuously with the drying time. As expected, the ambient temperature had a significant effect on the moisture content of the samples.

Table 4.1: Measured Ambient, PCM and Oven Temperatures

Time (period) (hrs)	T-amb (ºC)	T-oven (ºC)	T-pcm (ºC)
9-10 am (1)	34.9	50	45
10-11am (2)	37	53	50
11-12pm (3)	41	57	54
12-13pm (4)	43	63	57
13-14pm (5)	46	67	60
14-15pm (6)	46	68	64
15-16pm (7)	42	64	60
16-17pm (8)	37.4	59	55
17-18pm (9)	34.6	45	40

Table 4.2: Calculated Weight Loss and Moisture Content

Time (period) (h)	Oven-drying of Okra (g)	Sun-drying of Okra (g)	M-L of Okra in Oven (g)	M-L of Okra in Sun (g)	M-C of Okra in Oven (%)	M-C of Okra in Sun (%)
9-10 am (1)	110	110	0	0	89	89
10-11am (2)	76	81	34	29	69	74
11-12pm (3)	41	56	69	54	37	51
12-13pm (4)	23	44	87	66	21	40
13-14pm (5)	15	40	95	70	14	36

14-15pm (6)	13	38	97	72	12	35
15-16pm (7)	13	36	97	74	12	33
16-17pm (8)	12	35	98	75	11	32
17-18pm (9)	11	33	99	77	10	30

The experiment was conducted on effect of drying on storage and dried quality of okra. The fresh okra fruits were collected from local market in Niger state, Minna during May, 2021. Dark green coloured okra was selected for the study. The okra was thoroughly washed and sliced using sharp knife. The slices were weighed exactly 110g for both oven-dry and the traditional sun-drying method. For sun drying, the weighed okra slices were taken in drying pan and kept on the open floor on the top of terrace. For solar drying, the weighed okra slices were taken in drying pan and kept inside the solar drying chamber. Observations on physiological loss in weight in each sample were recorded at the particular interval of 1 hour in both drying methods. The change in colour of slices was observed for further analysis.

Temperature in the open sun drying and solar drying was recorded throughout the drying period using a glass-tube thermometer. Moisture losses of samples were recorded at same intervals. The open sun and solar drying experiments were carried out during the periods of May, 2021 at the department of Mechanical Engineering, Federal University of Technology Minna, Niger State of Nigeria. Each experiment started at 9:00 am and continued till 6:00 pm. Fresh harvested okra has a very high moisture content (88 – 90 % wet basis), whereas the safe moisture level to store okra is 10 % wet basis (Shivhare *et al*., 2000). To determine the moisture loss of drying samples during experiments, okra samples were taken out of the solar dryer and weighed at every 1 hour. The moisture content and moisture loss of the okra were calculated using the relationship in equation 3.32 and 3.33. To compare the performance of the solar dryer with open sun drying, both samples were dried simultaneously under the same weather conditions.

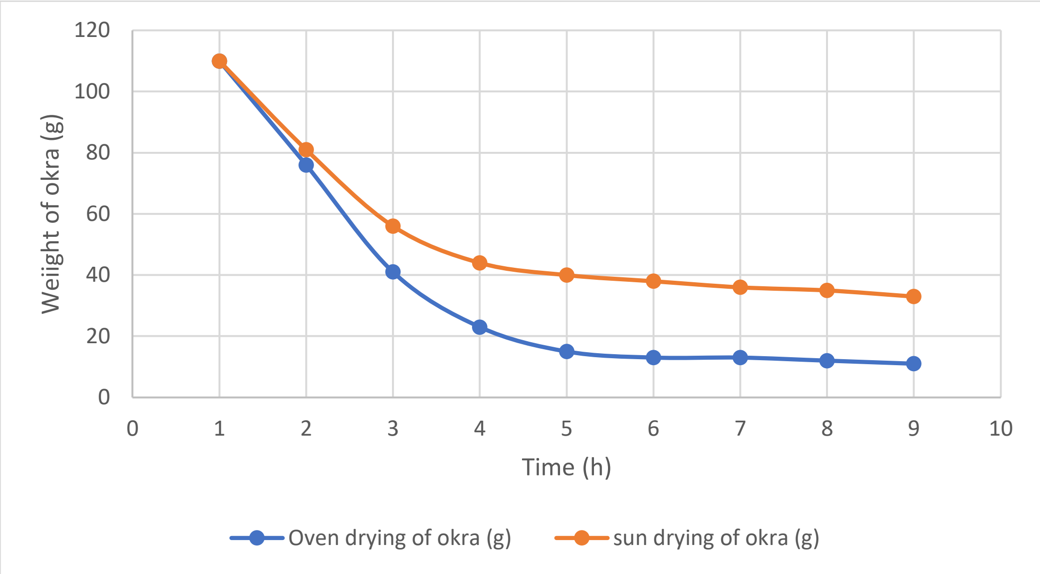

Figure 4.1: Variation of weight of okra with time

The result shown that, there was a general decline in moisture content of the sample from 110 g to 11 g and 33 g in both methods of drying. The results pertaining to drying of okra as recorded in two different methods, that is, open sun drying and solar drying are shown in Figure 4.1, 4.3 and 4.4. The data indicated that the loss of moisture was at its highest magnitude in the first hour of drying however the moisture loss was slowed down in the subsequent drying period. The samples of average initial moisture content of around 110 g were dried to the final moisture content 11 g in oven and 33 g in sun. It is evident from these curves that the moisture content decreases continuously with the drying time. As expected, the ambient temperature had a significant effect on the moisture content of samples. Figure 4.2 shows the variations of the ambient and oven temperature during the solar dryer and open sun drying of okra in the day.

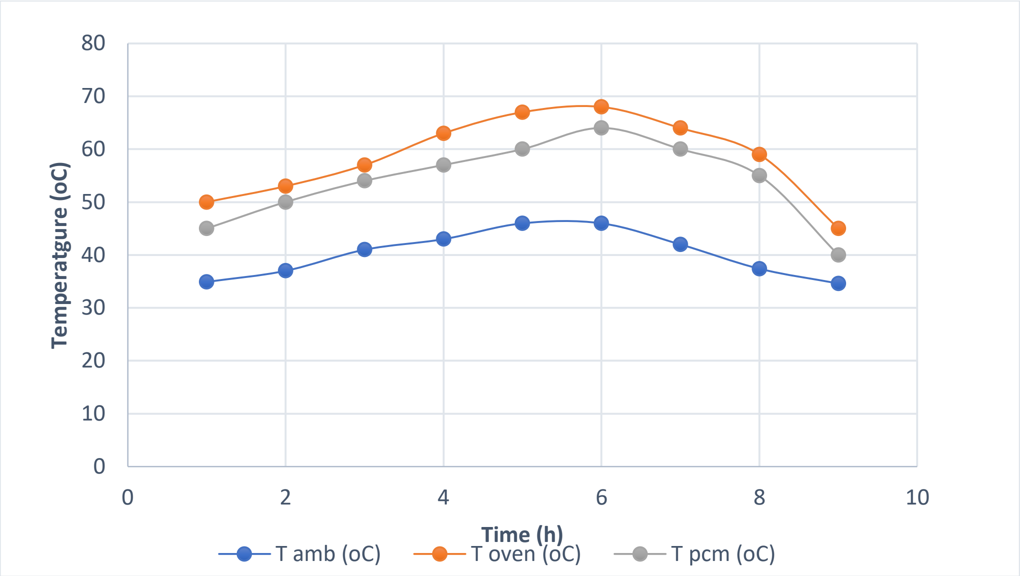

Figure 4.2: Variation of temperature with time

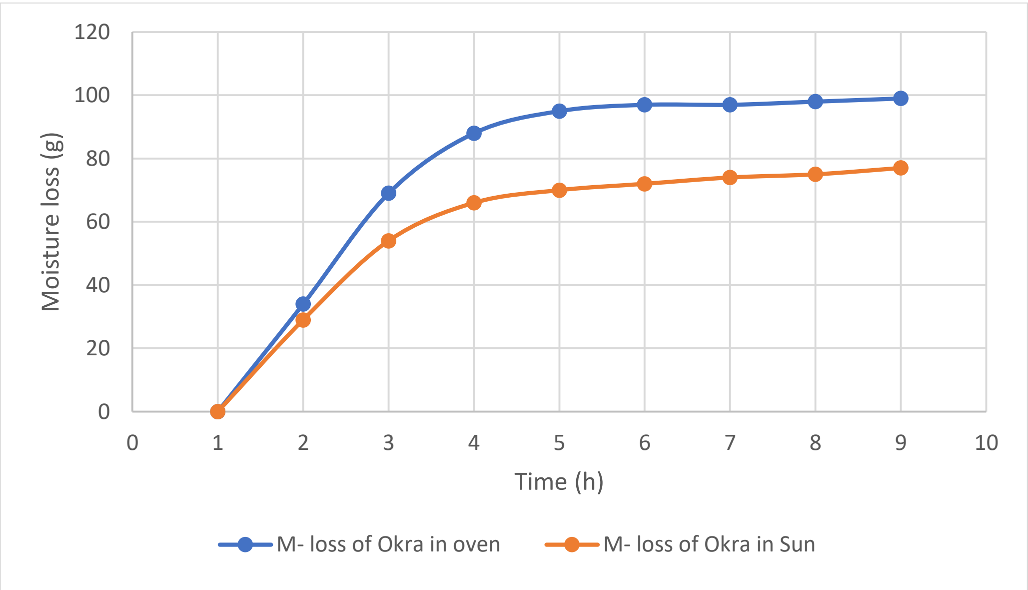

Figure 4.3: Variation of moisture loss with time

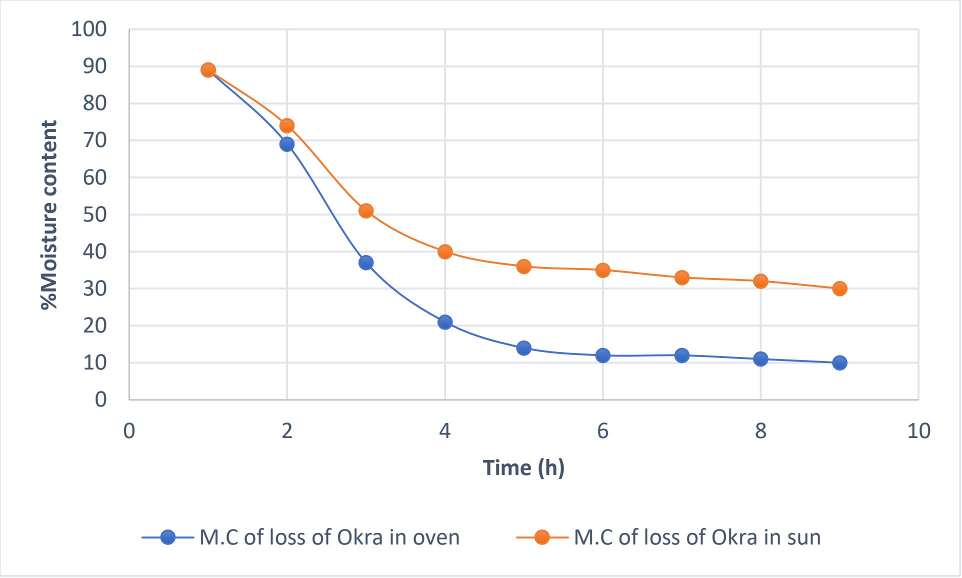

Figure 4.4: Variation of Moisture content with time

During the drying experiments, the weather was generally sunny. The ambient temperatures reached the highest figures between 14:00 and 15:00. Inside the solar oven was warmer than outside. This clearly indicates that the drying rate in the solar drying would be higher than open sun drying. Plate X and XI show the solar oven and open sun drying of the okra.

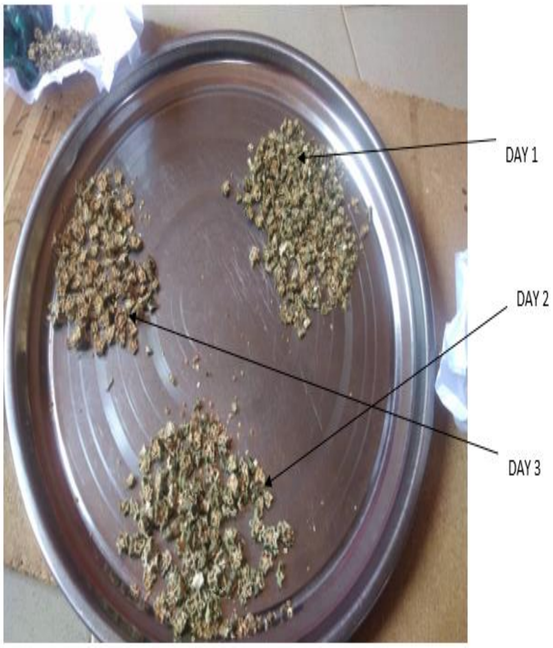

Plate X: Oven dried okra **Plate XI:** Sun dried okra

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A solar-powered oven using a phase change material was designed, constructed and its performance evaluation was carried out. The solar oven is a box type with a volume of 0.0511 m^3 (457.20 mm x 457.20 mm x 457.20 mm). The thermal energy storage PCM (60 % $NaNO_3$: 40 % KNO_3) was used. The two drying methods used, greatly affected the drying characteristics of okra. The solar oven was found to be more efficient than the open sun drying. In addition, the samples on the solar oven were completely protected from insects, birds, rain and dusts. The drying characteristic and time required for drying of okra was studied and final dry weight of the okra slices were estimated. It was found that okra samples, dried by solar oven were reported to take minimum time around 2 pm for drying with maximum removal of moisture, (10 % w.b). At the end of the experiment, it was found that the efficiency of the solar oven is 52 %. During the testing, a maximum temperature of 68 ^oC was recorded for the oven and the temperature of the PCM was 64 ^oC, also the ambient temperature was recorded to be 46 ^oC. The overall cost of the oven was estimated to be ₦ 75,600.00.

5.2 Recommendations

The solar oven (dryer) was successfully conducted and the following recommendations were deemed necessary for further research work.

1. Optimization of the reflector area based on the solar condition of the used location.

2. Parabolic solar reflector may be used so as to obtain a better efficiency of the oven.

5.3 Contribution to Knowledge

The research work has contributed to knowledge in the sense that a solar-powered oven dryer with a capacity of (457.20 x 457.20 x 457.20) mm^3 which can dry vegetables (okra) for 9 hours with an efficiency of 52 % was developed to improve on the challenges experienced in traditional open sun drying.

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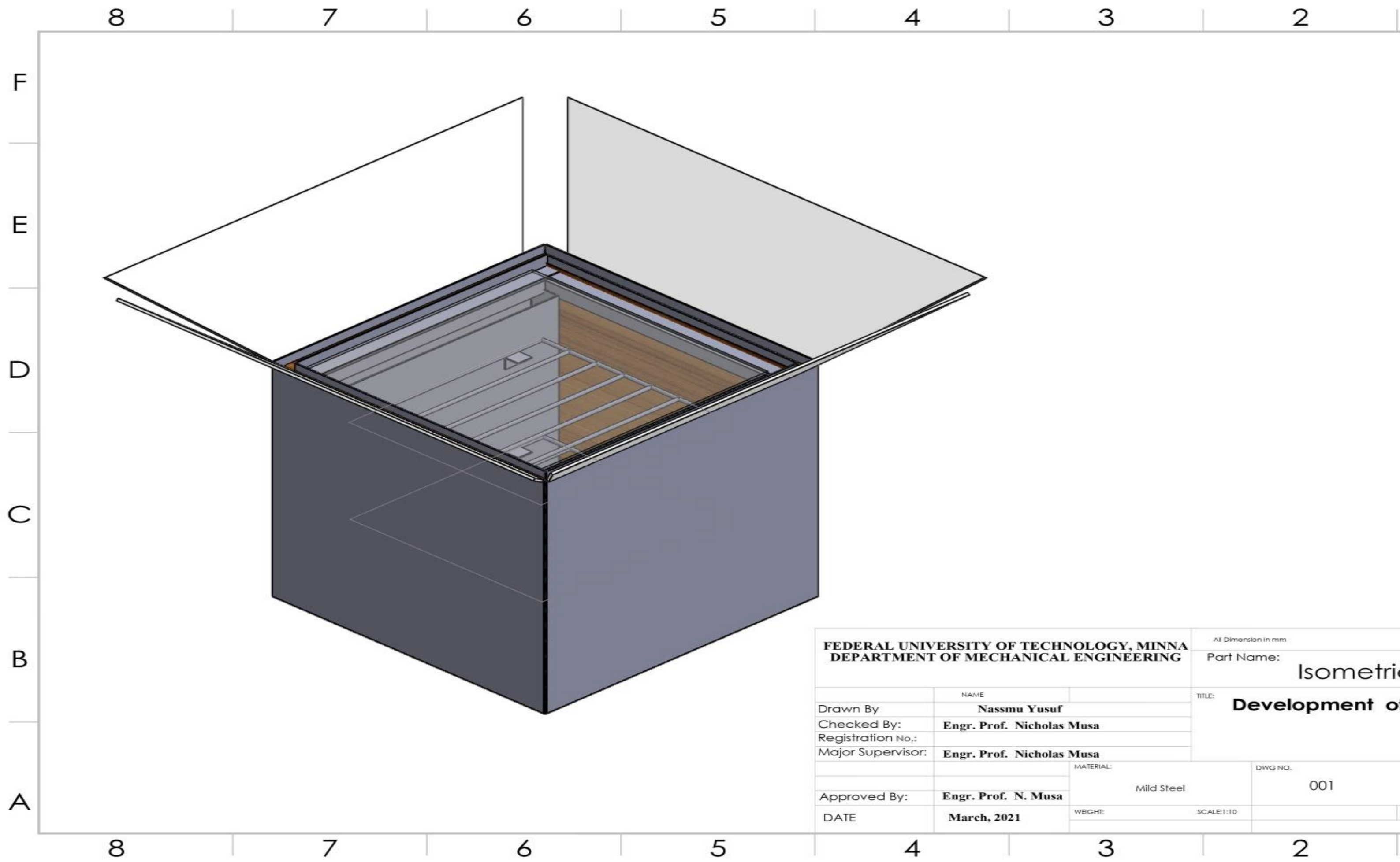
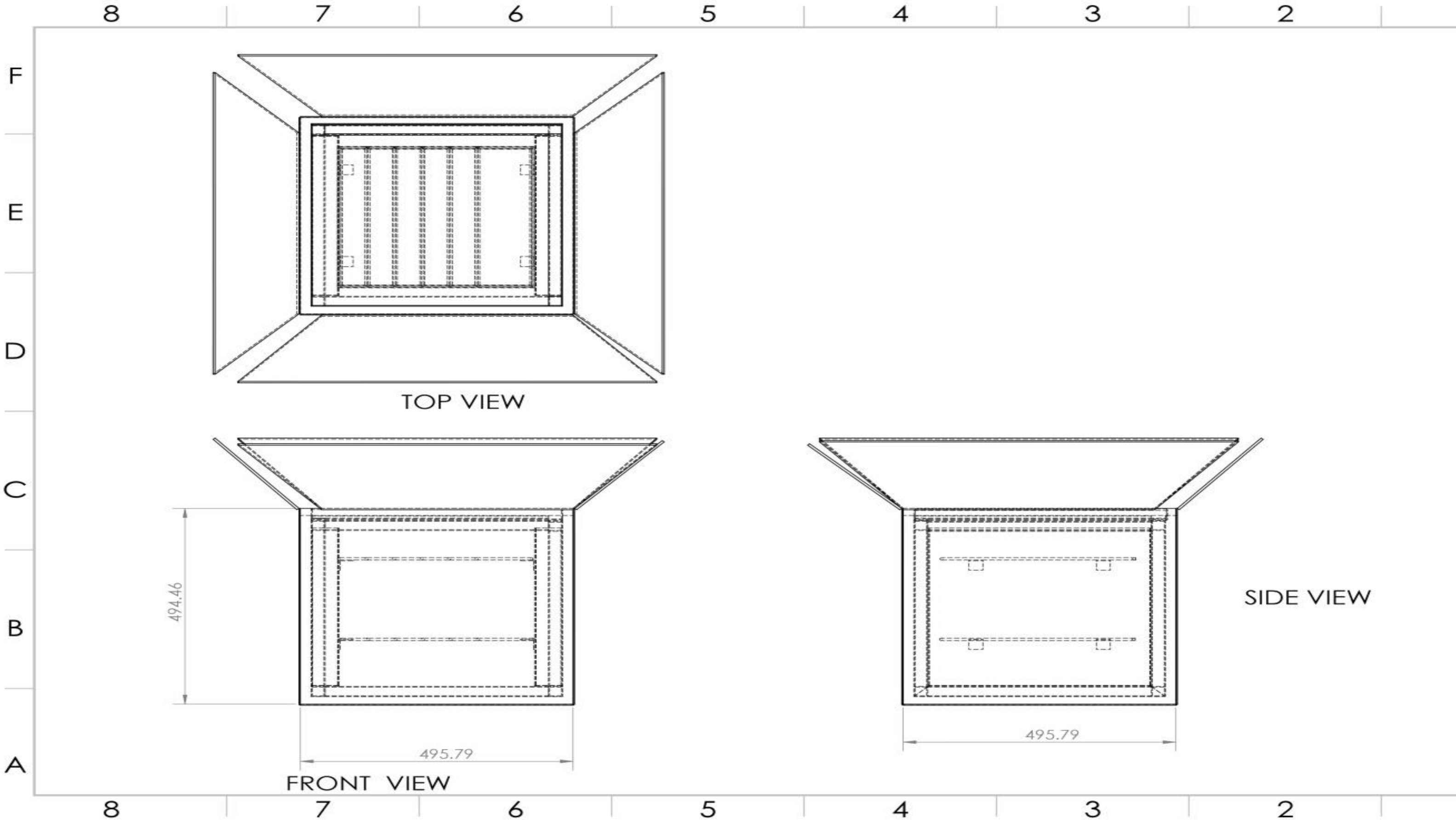
APPENDIX

Solid work drawings



Isometric Drawing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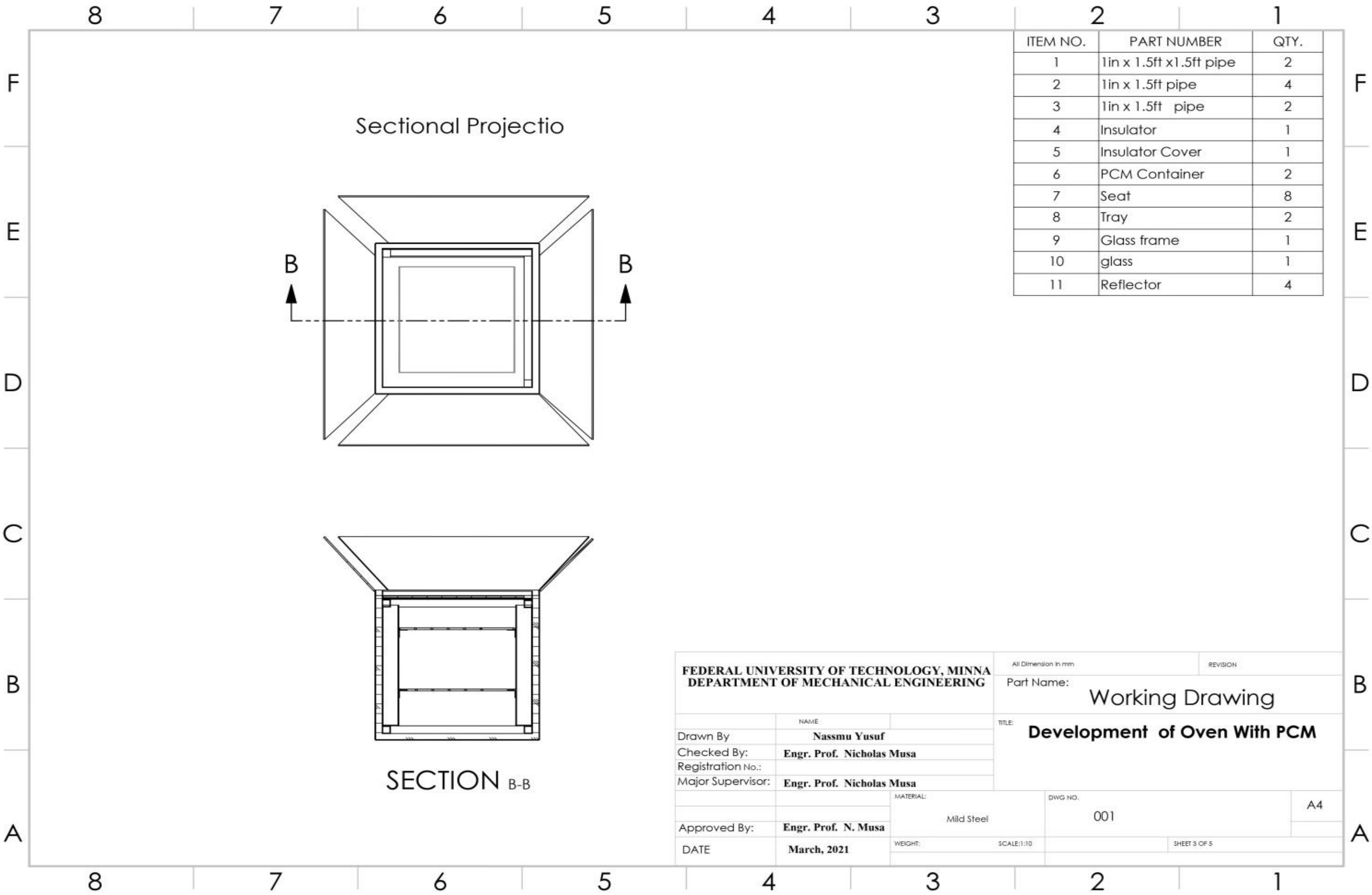
Working Drawing



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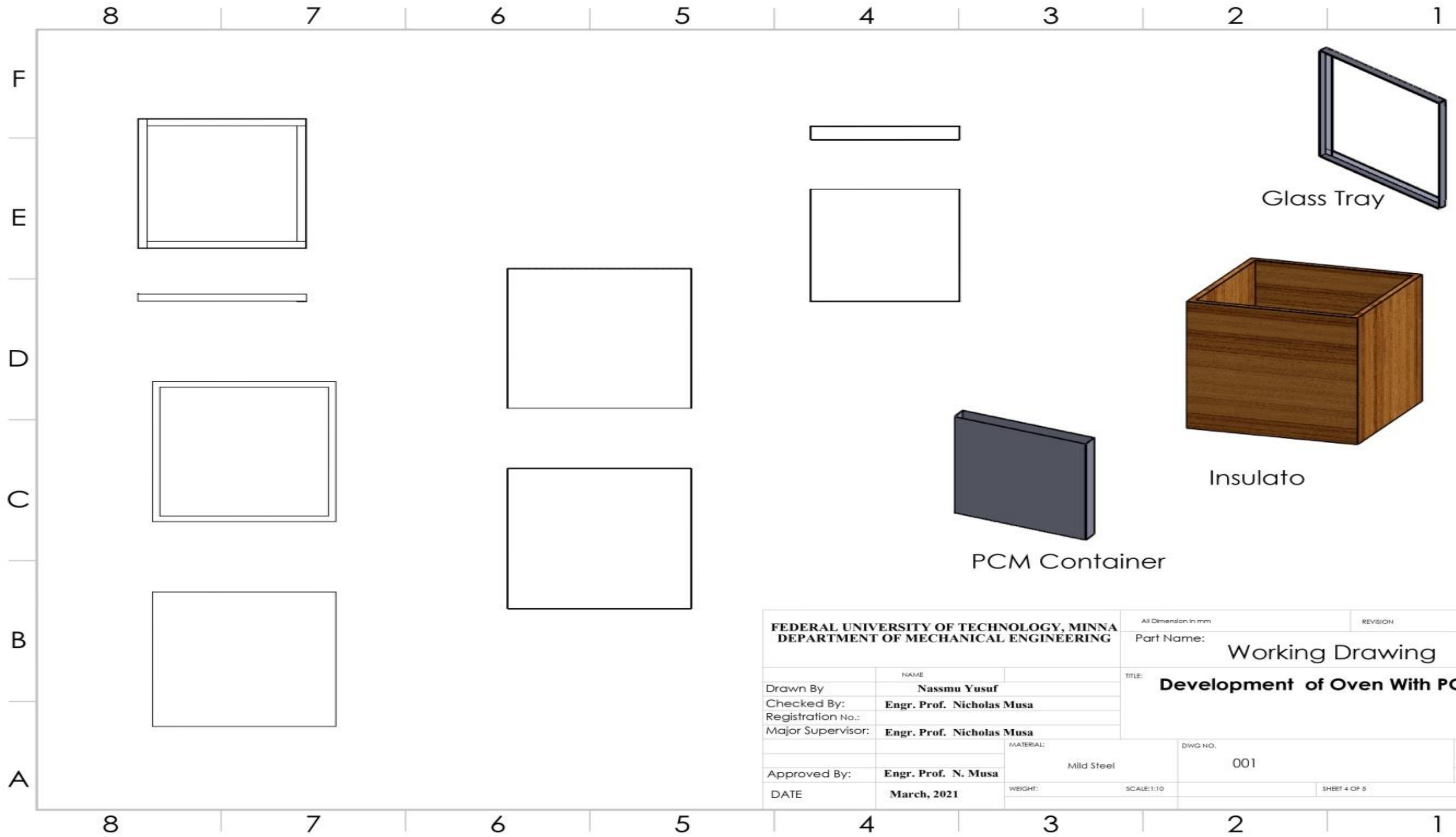

Orthographic Drawing