**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI**

**DEPARTMENT OF MECHANICAL ENGINEERING**

# SOLAR CROP DRYER WITH THERMAL ENERGY STORAGE AS BACKUP HEATER

By

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# DECLARATION

I hereby declare that this submission is my own work towards MPhil. in Mechanical Engineering at the department of mechanical engineering, KNUST, and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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I certify that this thesis has been assessed and all corrections have been made in accordance with the comments made by the examiners.

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Prof. George Yaw Obeng Date

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# DEDICATION

I dedicate this project to my families, lecturers, and colleagues, who through diverse ways financed, encouraged, assisted and motivated me to pursue this program.

## ACKNOWLEDGEMENT

I wish to express my sincere gratitude to the Almighty God for seeing me through successfully. I also express my profound gratitude to my supervisor, Dr Richard Opoku for his comments, suggestions and guidance during the entire duration of the project. I also express appreciation to the head of Department, Prof. George Yaw Obeng and all the lecturers of Mechanical Engineering

Department. I would also like to register my profound gratitude to all those who in one way or another provided a helping hand in this work. I am most grateful to various individuals for their moral support.



## ABSTRACT

In this work, solar crop dryer with thermal energy storage device is designed and constructed from locally available materials for drying sorghum.

Thermal energy storage (TES) systems provide several alternatives for efficient energy use and conservation. The thermal energy storage (TES) design incorporated in the solar crop dryer is used to store thermal energy from the sun during the day and dissipated in the night for drying when there is no sun.

The use of thermal energy storage (TES) is an effective way of storing thermal energy and has the advantage of high-energy storage density. In this study, flake salt was used as the storage medium to help store the heat energy in copper pipes.

From the experiment conducted on the thermal energy storage (TES) system, the results show that the dryer reduced the moisture content from about 30% to 11% wet basis in 6 hours. Also, 21% to 13% in solar drying with backup heating mode in 4 hours. The temperature of the absorber chamber with the thermal energy storage system was found to be between 89.8 $^0$C and 72.2 $^0$C which was

higher than the temperature without thermal energy storage (40.8 $^{0}$C to 46.5 $^{0}$C) for a 24-hour period.



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# CHAPTER ONE

# INTRODUCTION

## 1.1 Background of the Study

Agricultural produce such as sorghum, rice, nuts, and millet, in most cases required drying to avoid post harvest losses. The drying is done through a sustained effort of relatively low heat. Conventionally, crop drying is by burning wood and fossil fuels in ovens or open air drying under sunlight. Burning of wood / fossil fuel for crop drying is expensive and has negative effects on the environment. For open sun drying the crops are susceptible to unpredictability of the weather.

For solar crop dryers, the absence of the sun in the night makes it difficult for 24-hour crop drying to ensure good product quality. Modern solar crop drying system does not entirely depend on solar energy to function but it combines fuel burning or other techniques to supplement the energy of the sun during night times.

Methods and techniques including biomass back-up heater for providing heat to solar crop dryers in the night-time have been explored by some research works.

In the present work, a thermal energy storage device is used to store heat from the sun during the day and used in the night for drying when there is no sun. The thermal energy storage (TES) medium used was flake salt.

## 1.2 Problem Statement

One major problem associated with solar powered crop drying system is the fact that in the night there is no sun to provide the necessary heat for drying the crops.

The aim of this project is therefore to determine the feasibility of using a thermal energy storage device to store solar thermal energy in daytime for drying crops in the night.

## 1.3 Specific objectives

The overall goal of this project is to construct a thermal energy storage (TES) device for a solar crop dryer for the purpose of food preservation. The specific objectives which have been developed after a thorough literature review are presented as follows:

1. To design a solar crop dryer with thermal energy storage (TES) devices that is able to store heat during daytime and dissipate it in the night for drying crops.

2. To determine the hold over time for the thermal energy storage device that is developed.

3. To determine the performance of solar crop cabinet dryer integrated with the thermal energy storage device.

## 1.4 Benefits of the Project / Rationale for Project

Brewing companies, for instance Guinness Ghana Company Limited spend a lot of money in drying sorghum using electric heaters.

Economic benefit of solar crop dryer is that when solar energy is used rather than conventional fuels to dry products, it can have a significant saving cost. Solar crop drying lowers the drying costs, minimize losses due to spoilage and improves the quality of products. Drying foods at most desirable temperatures and in less time enables the crop to retain more of their nutritional value especially vitamin C. The advantage of this is that foods tastes good, which improve their marketability.

## 1.5 Organization of Report

This thesis is organized in five chapters: Chapter one, the introduction, presents the background of the work. It also presents the overall goal and specific objectives of this work. The different types of constructions of solar crop dryers and performance evaluation and the solar radiation levels/data that have been published for Ghana are presented in chapter two. The on-going research on different advancements in solar crop drying and the relevant equations to determine their performance are also discussed. Chapter three presents the detailed problem formulation, technical and economic aspects of instruments used and how data collection is analyzed. Again, design conceptualization, evaluation and selected design are describe in this chapter. In chapter four, the results are presented and discussed. Chapter five presents the conclusions and recommendations made from this study.

# CHAPTER TWO
# LITERATURE REVIEW

This chapter presents previous work on solar crop drying of agricultural produce. The various types and crop drying methods like sun drying, electric drying, solar tent dryers, solar tunnel dryers, and solar cabinet dryer are reviewed. Also, modern techniques in crop drying using biomass as back up heaters, V-groove collector for solar crop drying, conditions for drying sorghum and review on thermal heat storage devices and their importance are discussed.

## 2.1 Methods of Crop Drying

### *2.1.1 Sun drying*

The sun drying is the system storing grains, vegetables, fruits, meat and agriculture produce. Sun drying system is time wasting in that crops have to be always overlaid at night and in a situation where the weather is not good needs to be saved from animals.

The improvement of open sun drying is using the solar drying technology in that crops are dried in close system when the inlet temperature is maximum (Tiwari, 2016). The advantages of sun drying system are preservation from pests, rain and insects. Sun drying method of food preservation in Ghana is well known because of solar irradiance being good for the seasons.

### *2.1.2 Solar - Electric drying*

In solar-electric drying, an extra source of heating air is rendered along with solar collector so that the overall temperature of the drying air can be increased. It is made up of a solar thermal collector, resistant heater, controller and chamber for drying. The drying cabinet constructed with a galvanized iron box and insulated polystyrene walls containing six product trays; each tray has an area of 0.4 $m^2$ (Tiwari, 2016). Figure 2.1 shows solar drying system with indirect heating.

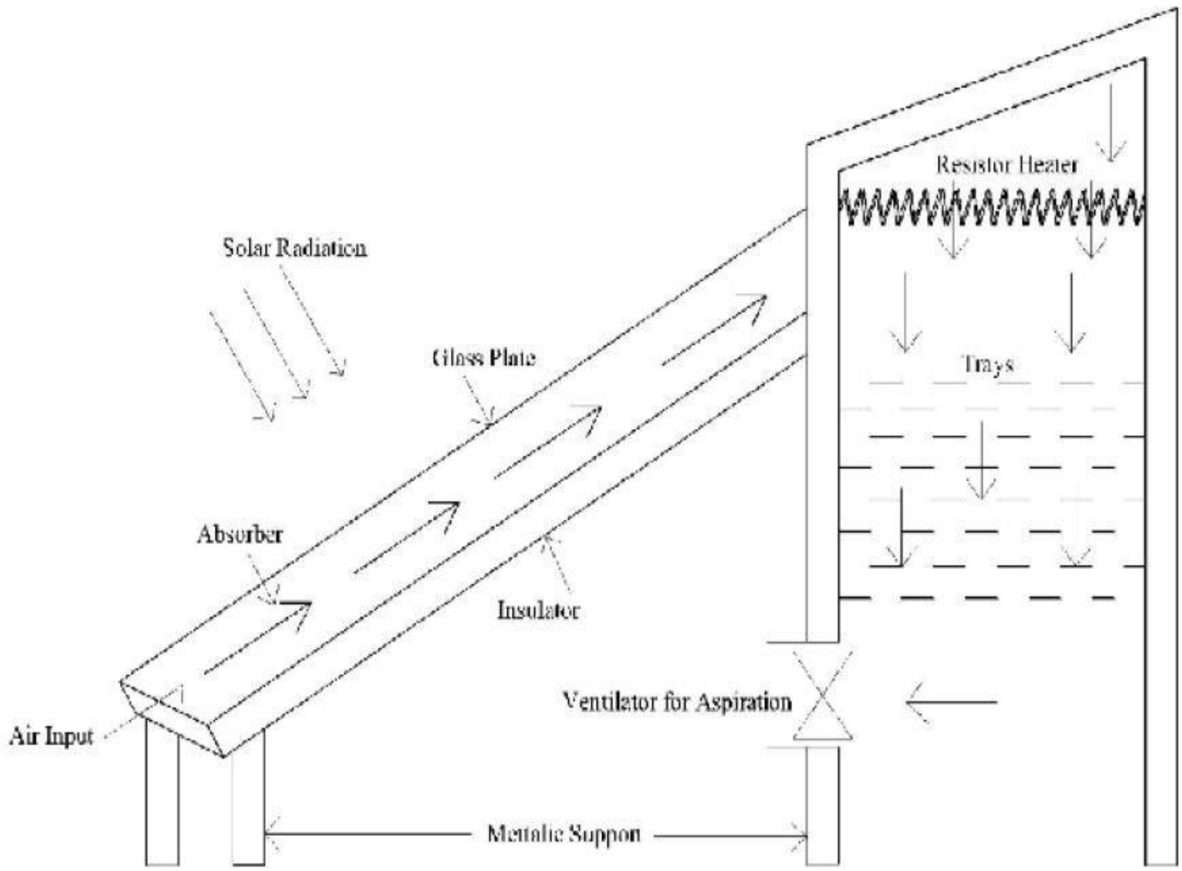


***Figure 2. 1 solar-electric drying with indirect heating***

### *2.1.3 Tent dryers*

According to Tiwari (2016) tent dryers are mostly constructed of wooden frames with plastic sheets serving as outer covering. The product to be dried is placed on a support above the ground. Tent driers have the advantage of offering protection from pests, predators, dust and are mainly used for drying fish and fruits. The main disadvantages is that it can be easily destroyed by heavy wind. The differences between the tent and cabinet driers is that the collector and the drying chamber are put together (Tiwari, 2016). The figure 2.2 shows a tent solar dryer.

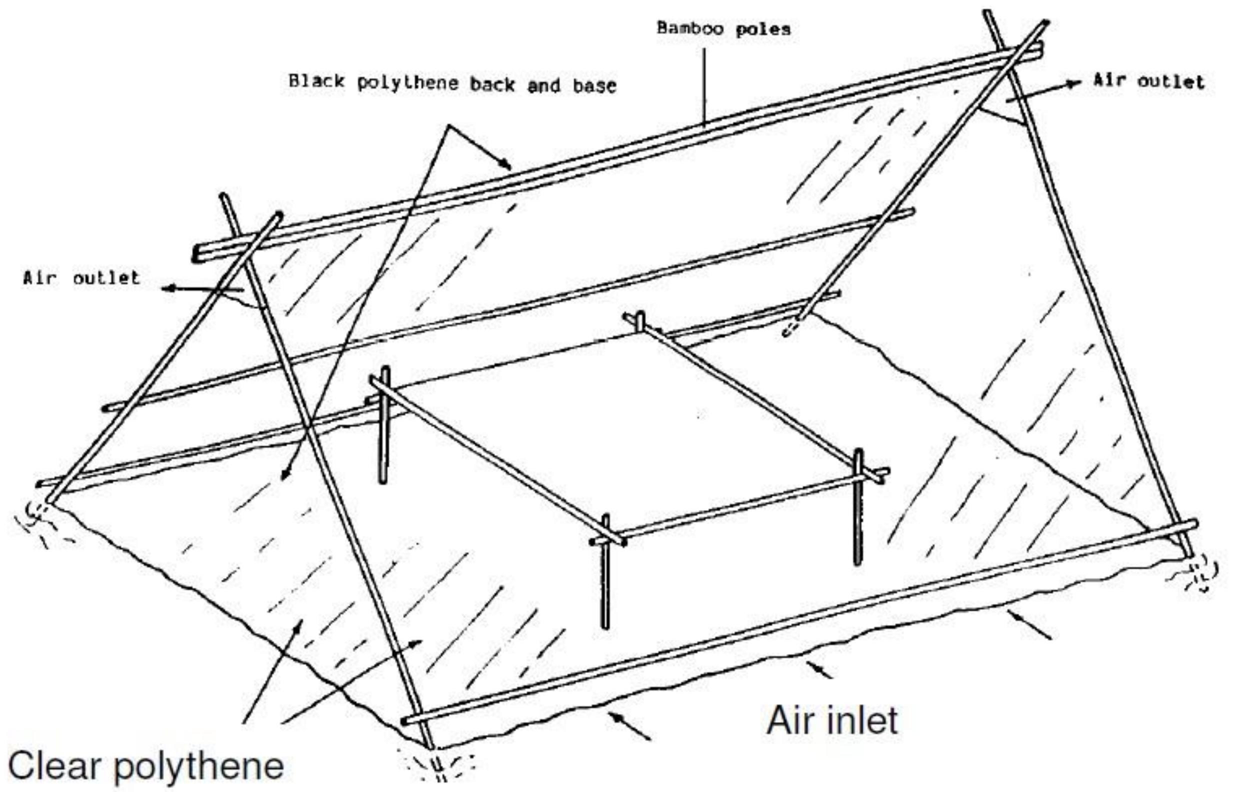


*Figure 2. 2 Tent Dryer*

A much smaller and larger tent dryer is shown in figure 2.3 and almost the same as a cabinet dryer.

***Figure 2. 3 Small and large solar crop tent drying sytem***

## *2.1.4 Solar tunnel dryer*

Solar tunnel dryer is an indirect forced convection solar dryer with a solar thermal collector, a solar photovoltaic panel and a drying tunnel. The photovoltaic system powers fans to increase air flow in order to maximize drying. The diagram in figure 2.4 shows the features of the dryer and figure 2.5 shows the pictorial view inside a Hohenheim solar tunnel dryer.

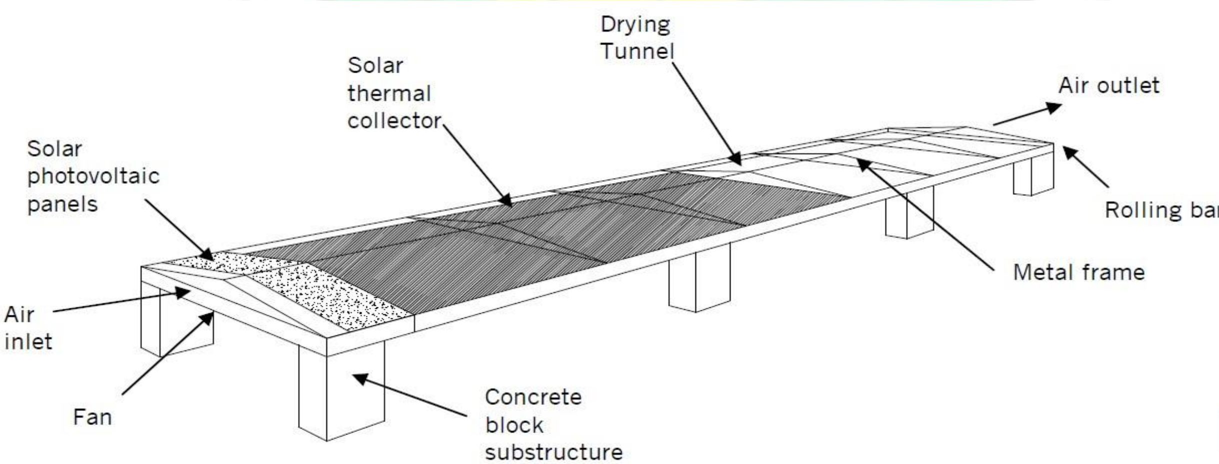

*Figure 2. 4 Solar tunnel dryer layout*

*Figure 2. 5 Pictorial view inside a Hohenheim solar tunnel dryer*

### 2.1.5 Solar cabinet dryer

The solar cabinet is made of drying cabinet, sun beans, plastic sheet and insulators. In operation, air enters the air ducts and flows through the cabinet where the drying trays are placed. After picking moisture from the products, the wet air flows through a chimney which is located at the upper side of the cabinet in order to enhance thermal buoyancy. The advantages of cabinet dryer using solar is that the design is relatively simple, offers relatively lower labour cost and convenient loading and unloading mechanism. The only limitation is that the system performance is low (Mircea Enachescu Dauthy, 1995).

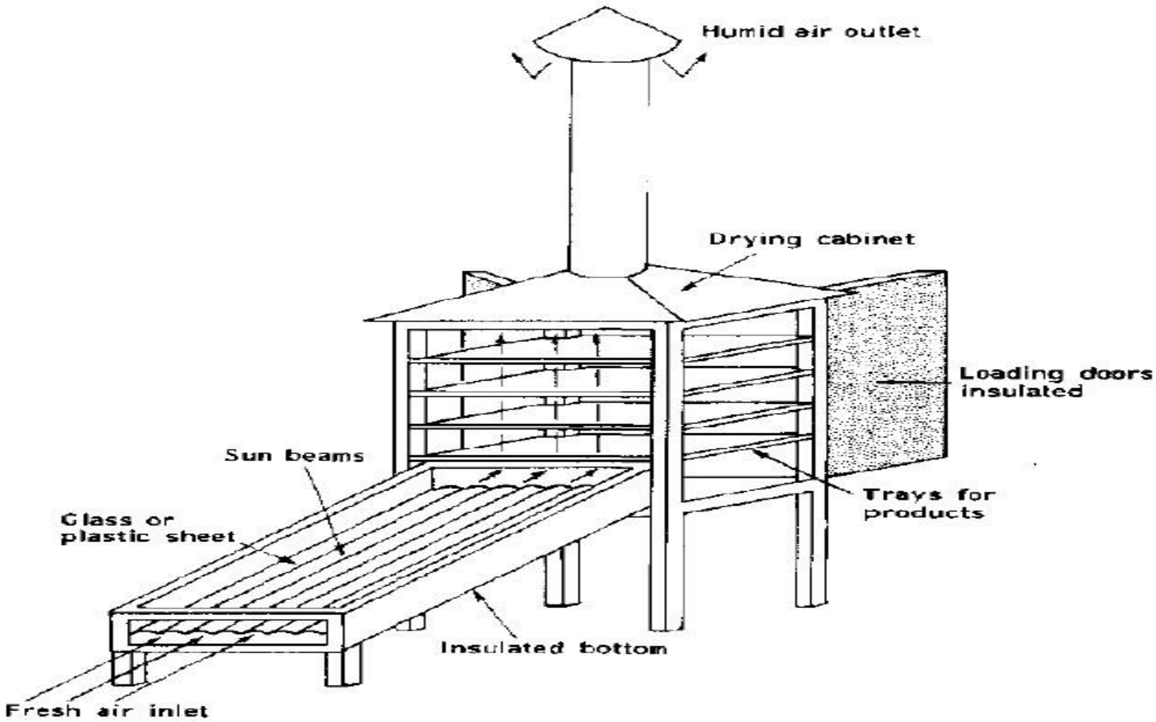


*Figure 2. 6 Solar cabinet dryer layout*

## 2.2 Modern Techniques in Crop Drying

### *2.2.1 Solar crop dryer using biomass as back up heater*

Sekyere et al. (2016) investigated the drying characteristic of a mixed mode natural convection solar crop using biomass as a backup heater. The laboratory model as shown in figure 2.7 was made up of plenum glass cover, drying chamber and supporting rails. The result shows that the model was possible to dry a batch of pineapples (weighing 2262 g) in each mode of operation. The dryer reduced the moisture content of pineapple slices from about 1049% to 144% (db) in 23 h in the solar mode of operation. Also, in solar drying with back up heating mode in 19 h, the dryer reduced the moisture content of pineapple slices from about 924% - 106%.

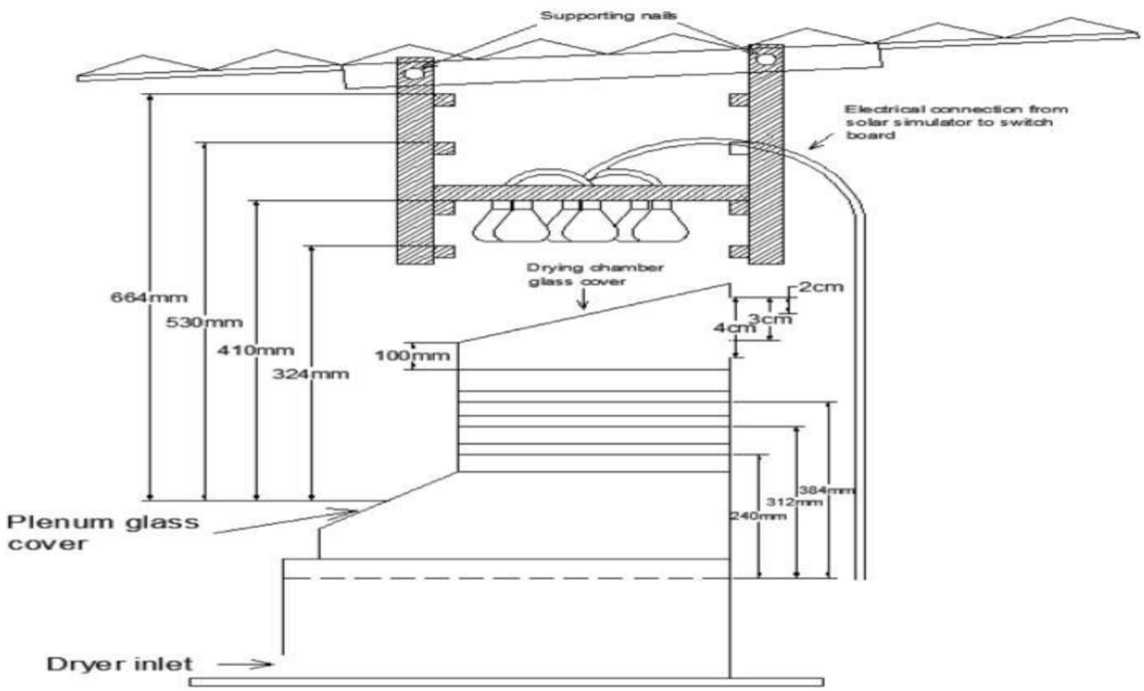


***Figure 2. 7 Laboratory model of solar crop dryer using biomass as backup heater***

## *2.2.2 V-groove collector for solar crop drying*

Fudholi et al. (2011) reported that for an average solar radiation of 700 W/m$^2$, a V-groove type collector with a collector area of 15 m$^2$ could produce an average air temperature of 50°C and a corresponding airflow rate of 15.1 m$^3$/min. The design of a V-groove solar collector type dryer (see figure 2.8) is made of drying chamber, glass cover, V-gloove collector and an air vent. In the operation, hot air is discharged into the drying chamber from outlet duct, which is located for optimum performance. A 10 kW auxiliary heat source is used for continuous operation and more effective temperature control. The design is used to produce noodles, herbal tea, and chilies due to their specification requirement. The moisture content reported ranges from 55% to 87% (wb).

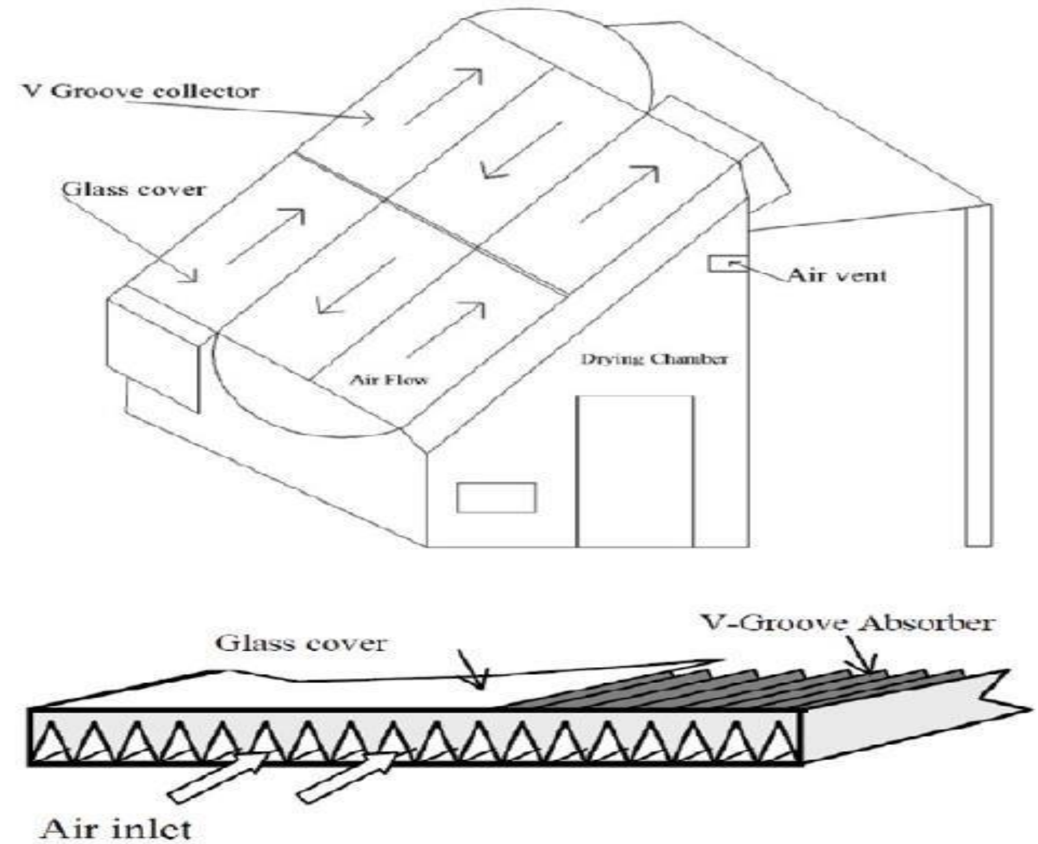


***Figure 2. 8 V-groove collector for solar crop drying***

## 2.3 Climate Conditions of Ghana

Ghana is located in the tropics at latitudes 5°N and 11°N and longitudes 3°W. Table 2.1 shows average relative humidity and dry bulb temperatures for Kumasi for the years 1976 – 1984 and 2012 – 2016. Figure 2.9 shows the monthly mean daily solar irradiation in Kumasi. It was noticed that the mean monthly solar irradiation ranged between 3.4 and 4.8 $kWhm^{-2}$ and the month of August recorded the lowest. The recorded maximum solar irradiation occurred in the month of

April.

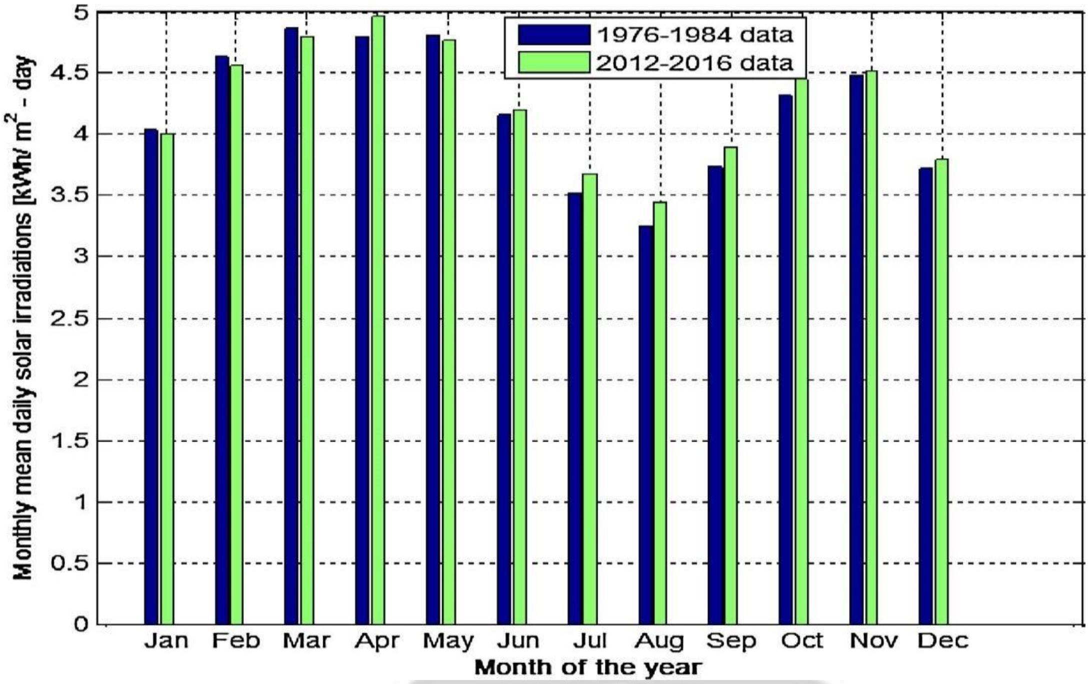


***Figure 2. 9 Monthly mean daily solar irradiation for Kumasi city, Ghana.***

***Table 2. 1 Dry bulb temperature and relative humidity average for Kumasi.***

| Period | 1976 – 1984 | | 2012 – 2016 | |
|---|---|---|---|---|
| Month | RH (%) | $T_{db}$ (°C) | RH (%) | $T_{db}$(°C) |
| Jan | 72.0 | 26.6 | 70.2 | 27.8 |
| Feb | 68.5 | 28.4 | 66.0 | 29.5 |
| Mar | 71.5 | 28.1 | 70.3 | 29.0 |
| Apr | 74.5 | 27.6 | 75.0 | 28.9 |

| | | | | |
|---|---|---|---|---|
| May | 78.5 | 26.9 | 78.0 | 28.0 |
| Jun | 82.5 | 25.6 | 80.1 | 26.5 |
| Jul | 82.5 | 24.5 | 82.1 | 25.9 |
| Aug | 82.5 | 23.9 | 84.0 | 25.0 |
| Sep | 82.0 | 25.1 | 81.2 | 26.1 |
| Oct | 81.0 | 25.9 | 78.5 | 27.0 |
| Nov | 76.5 | 26.4 | 76.1 | 28.1 |
| Dec | 73.5 | 25.8 | 70.3 | 27.5 |
| Annual | 77.1 | 26.2 | 76.0 | 27.4 |

Source: Opoku et al. (2018)

## 2.4 Conditions for Drying of Sorghum

Sadaka et al. (2015) conducted an experiment and reported that sorghum when properly dried retains a moisture content of about 12% on wet basis. Figure 2.10 shows freshly harvested grain sorghum. The recommended temperature range for drying sorghum is reported to be from 40 $^{0}$C to 60 $^{0}$C (Mejia, 1999). The relative humidity of air for drying sorghum should be between 50% and 70 % (Mejia, 1999).

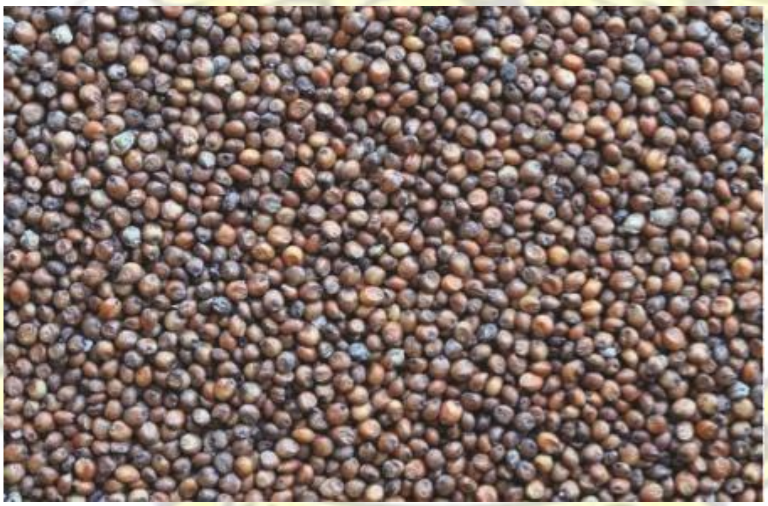

***Figure 2. 10 Freshly harvested grain sorghum***

### *2.4.1 Temperature and relative humidity*

The temperature and relative humidity determines the amount of moisture content of air. Drying temperature is a major deciding factor, which mainly determines the quality of the dried product. The relative humidity of air is relevant factor same as that of temperature because humidity gradient between air and the product will be a major driving force in a natural convection system. Also, lower relative humidity of the air can increase the drying rate and help in reducing drying time. Temperature and relative humidity is measured using thermocouple and RH-meter. The table 2.2 shows drying of sorghum with heated and unheated air forced into the bin.

***Table 2. 2 The drying of sorghum with heated and unheated air forced into the bin***

| **Unheated air drying force** | **Subsidiary Heat of air drying** | **Heated drying of air** |
|---|---|---|
| Lowest investment Simple to operate.<br>Relatively ineffective in wet condition of weather<br>Recommended airflow rates is 0.03 cu.m/sec sorghum at moisture content from 30% to 12% wet basis help economic drying. | During extended weather heat dissipated from electric or gas heaters Temperatures must not be more than 60 $^0$C.<br>Drying times shorter than unheated air reducing risk of mould growth. | Batch or continuous systems using constantly heated air.<br>Heated drying of air is simple in terms of cost.<br>Airflows intervals is from 0.51.5 cu.m/sec<br>The time for drying is very short |

### *2.4.2 Moisture content of grain sorghum*

The moisture content of grain sorghum is define as the amount of water in the grain. Manitoba (1990) reported that products with higher moisture content are found to have lesser drying time than those having very lesser moisture content. It is because the higher moisture content product may have better mass flow of the moisture from the interior of the product to the surface whereas the one with lower moisture content may have a thick outer skin. The equilibrium moisture content of grain sorghum is shown in table 2.3.

***Table 2. 3 Equilibrium moisture content of grain sorghum***

| **Temperature(°F)** | **Relative Humidity (%)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| **40** | 9.6 | 10.8 | 11.9 | 13.1 | 14.5 | 16.1 | 18.4 |
| **50** | 9.4 | 10.6 | 11.7 | 12.9 | 14.3 | 15.9 | 18.2 |
| **60** | 9.2 | 10.4 | 11.5 | 12.7 | **14.1** | 15.7 | 18.0 |
| **70** | 9.0 | 10.2 | 11.4 | 12.6 | 13.9 | 15.5 | 17.8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **80** | 8.9 | 10.1 | 11.2 | 12.4 | 13.7 | 15.3 | 17.6 |
| | **90** | 8.7 | 9.9 | 11.0 | 12.2 | 13.5 | 15.1 | 17.4 |
| | **120** | 8.6 | 9.8 | 10.9 | 12.1 | 13.4 | 14.9 | 17.2 |

## 2.5 Review on Thermal Energy Storage Systems (TES)

Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat or thermochemical or combination of these. Sensible heat storage is due to temperature change of material while latent heat storage is due to the phase transformation. Figure 2.11 and 2.12 show the stages and plotted graph of temperature against time for thermal energy storage systems. Different types of thermal energy storage of solar energy are shown in figure 2.13, and the classification is shown in figure 2.14 (Cabeza and Mehling, 2003).

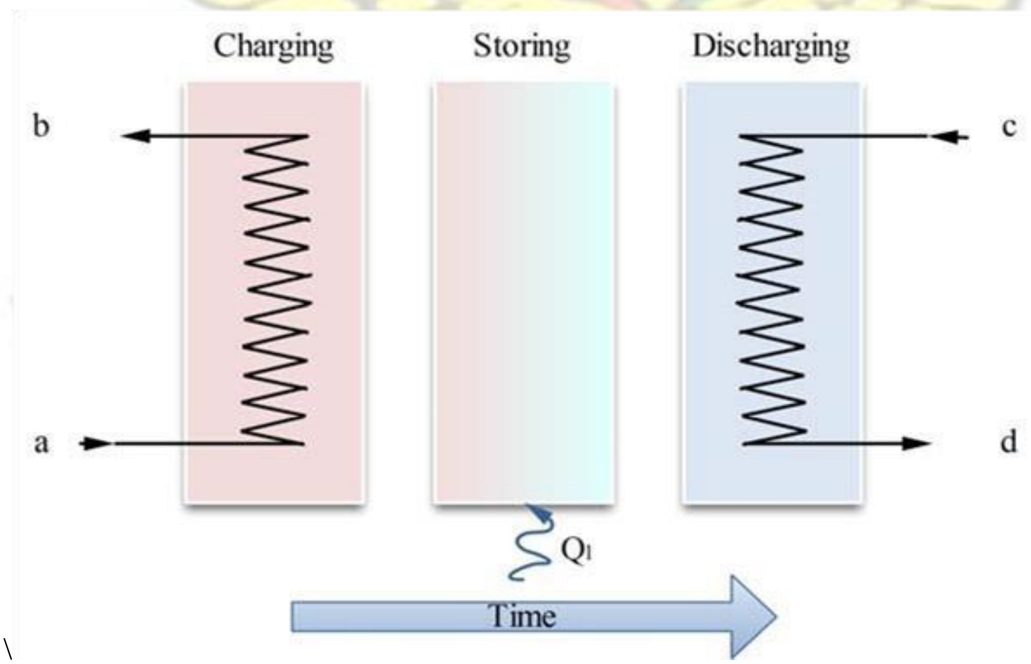


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*Figure 2. 11 Stages in thermal energy storage system*

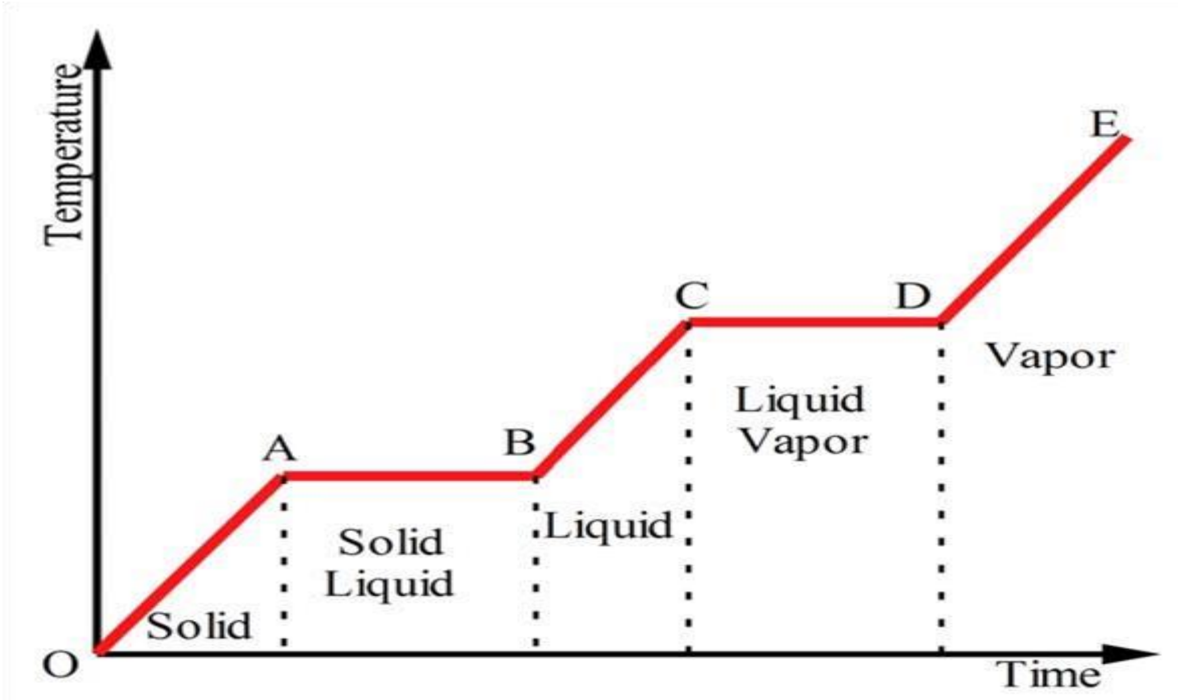


*Figure 2. 12 Graph of temperature against time of thermal energy storage*

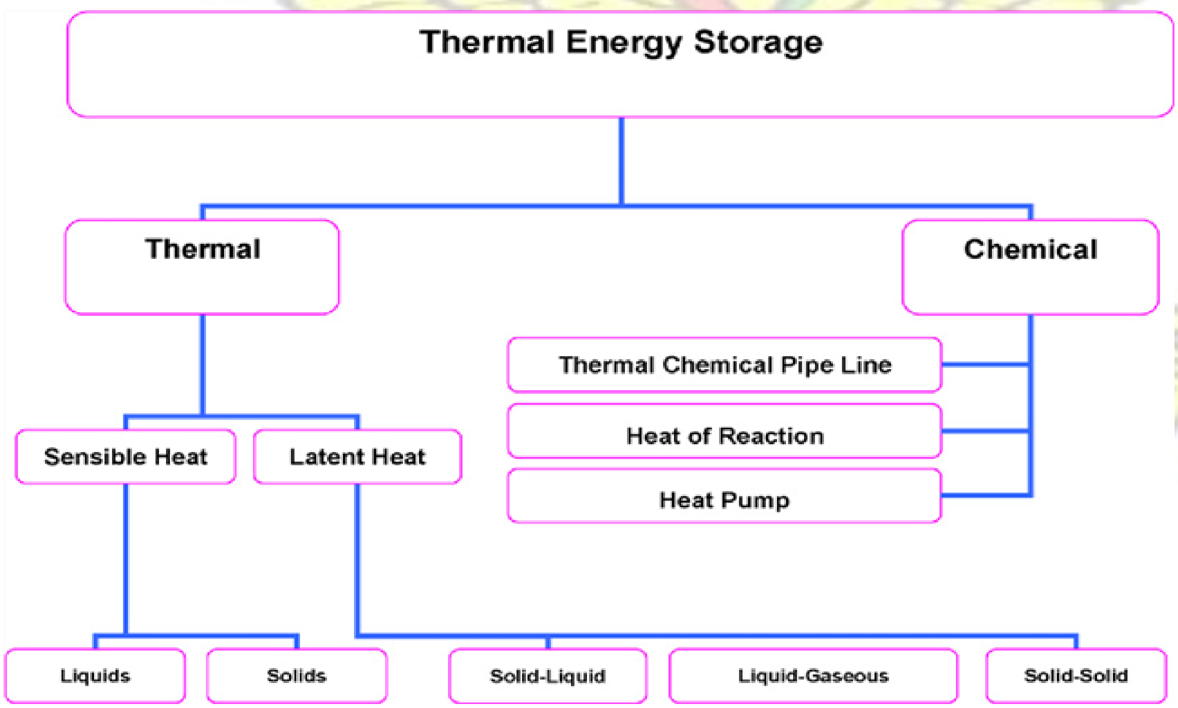

*Figure 2. 13 Kinds of storage devices using thermal energy*

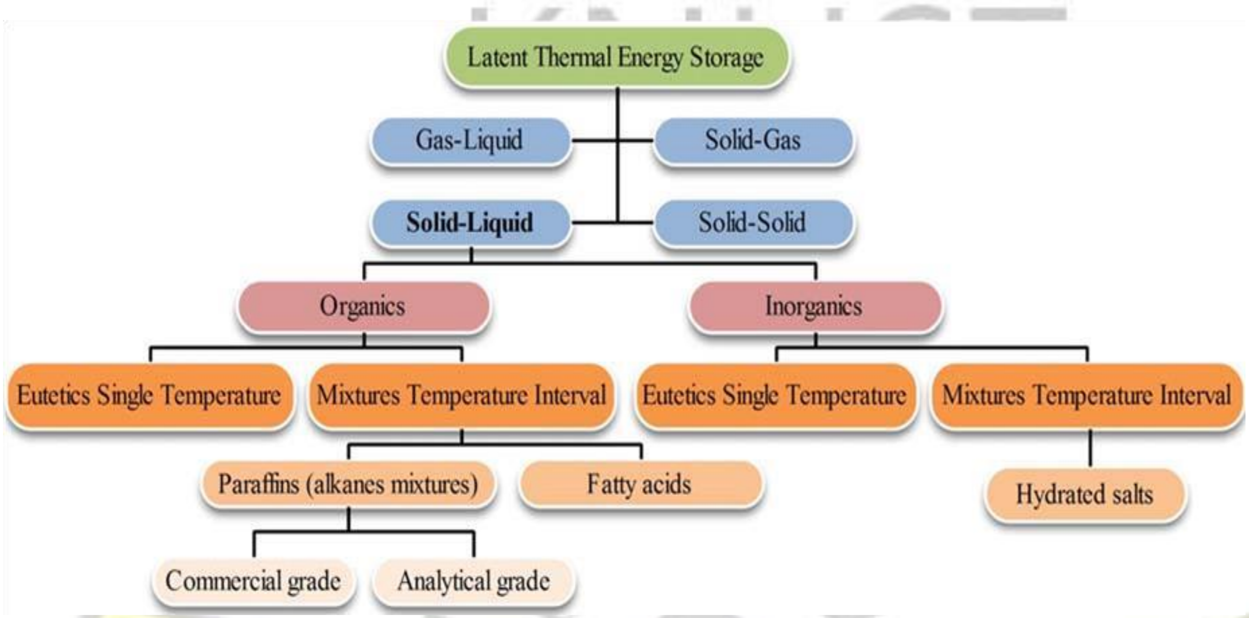


*Figure 2. 14 Classification of thermal energy storage*

### 2.5.1 Latent heat storage

In latent heat thermal energy storage, energy is stored in the phase change materials through the change of a substance from one phase to another. As the temperature increases, the material transforms from solid to liquid phase and absorbs heat in the endothermic process. When temperature is reduced, the material undergoes phase change from liquid to solid and releases heat.

Sharma et al. (2012) added that, the energy storage has to go through several phase transitions: solid-solid, solid–liquid, solid–gas and liquid–gas. In solid-solid transition, energy is stored by the crystalline transformation of the material. This transition contains much smaller latent heat and minor volume changes and have the benefit of less strict container requirements that allow greater design flexibility. Again, solid-liquid transformation provides a high energy storage density and has much higher latent heat of fusion. In contrast to solid-solid and solid-liquid phase transitions, solid-gas and liquid-gas transitions have the benefit of higher latent heat of fusion, but their large volume change during the phase change process increases the complexity and difficulty of the storage system.

### *2.5.2 Sensible heat storage*

Sensible heat storage devices store thermal energy by cooling or heating the storage material through heat transfer. Sensible heat thermal energy devices take benefit of the heat capacity and the change in temperature of the material during the charging and discharging processes. Also, the amount of energy stored in a sensible thermal energy storage depends on the mass, the specific heat of the storage medium, and the temperature difference of the storage medium between its initial and final states (Jesumathy et al. 2012). The table 2.4 shows the solid to liquid medium for sensible energy storage.

***Table 2. 4 Types of solid to liquid mediums for sensible heat storage type***

| **Medium** | **Type of fluid** | **Temperature range ($^0C$)** | **Density ($kg/m^3$)** | **Specific heat capacity (J/kg K)** |
|---|---|---|---|---|
| Rock | | 20 | 2560 | 879 |
| Brick | | 20 | 1600 | 840 |
| Concrete | | 20 | 1900–2300 | 880 |
| Water | | 0–100 | 1000 | 2400 |
| Engine oil | Oil | Up to 160 | 888 | 1880 |
| Ethanol | Organic liquid | Up to 78 | 790 | 2400 |
| Proponal | Organic liquid | Up to 97 | 800 | 2500 |
| Isopentanol | Organic liquid | Up to 148 | 831 | 2200 |
| Octane | Organic liquid | Up to 126 | 704 | 2400 |

Source: Sharma et al. (2009)

## 2.6 Thermophysical Properties of Energy Storage Unit

Themophysical properties of energy storage unit shown in table 2.5 are temperature, density and specific heat capacity. Selecting thermal energy storage device for a required job, the temperature required for cooling or heating should operate to provide the change over temperature of thermal energy storage.

***Table 2. 5 Thermophysical properties of energy storage system***

| **Material** | **Temperature range ($^0C$)** | **Density ($kg/m^3$)** | **Specific heat (J/kg K)** |
|---|---|---|---|
| Rock | 20 | 2560 | 879 |
| Brick | 20 | 1600 | 840 |
| Concrete | 20 | 1900–2300 | 880 |
| Water | 0–100 | 1000 | 2400 |
| Engine oil | Up to 160 | 888 | 1880 |

Source: Sharma et al. (2009)

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Problem Formulation

One major problem associated with solar powered crop drying system is the fact that in the night there is no sun to provide the necessary heat for drying the crops.

Open sun drying has been used to dry agricultural produce for many years and it is still the most widely used energy source particularly in Africa. Literature sufficiently proves that open sun drying is labour intensive and unhygienic.

Moreover, the open sun drying method is unsafe due to exposure to insects, rodents, wind and other problems. The direct exposure to sun increase temperature and can cause case hardening of the agricultural produce.

The goal of this thesis is to design a thermal energy storage device using solar crop dryer for the purpose of food preservation.

## 3.2 Description of the Proposed Dryer with TES

It is proposed to use the dryer depicted in figure 3.1. The dryer consist of drying shelves, heat absorber sheet, glass sheet and a thermal energy storage. The heat absorber is a metal plate painted black and set beneath the cover to absorbed radiant energy. The material used for absorber plate is aluminium, which has a fast response in absorbing solar energy. The thermal energy storage (TES) design incorporated in the solar crop dryer is used to store thermal energy from the sun during the day and dissipated in the night for drying when there is no sun. In this study, flake salt is used as the storage medium to help store the heat energy in aluminium pipes.

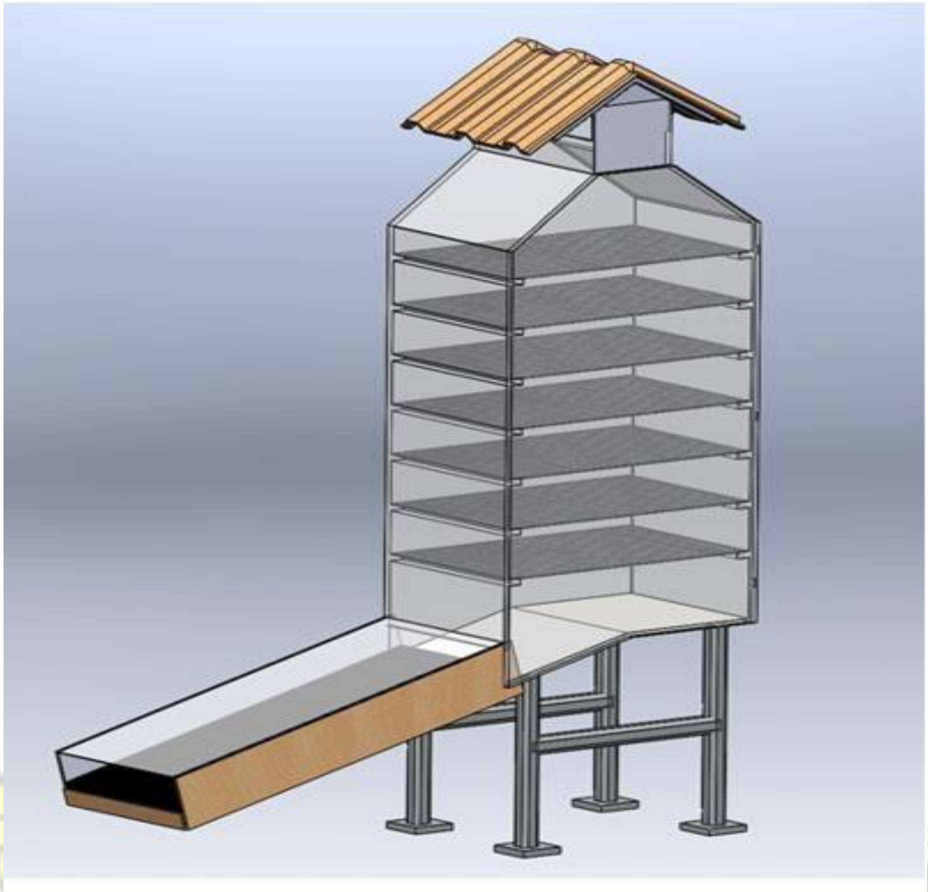

***Figure 3. 1: A 3D AutoCAD drawing of proposed Dryer***

## 3.3 Design of the Solar Crop Dryer with TES

### *3.3.1 Design requirement*

The amount of moisture content of fresh agricultural products is expressed on wet basis during analysis of drying results. Equation (3.1) gives the moisture content on wet basis as

$$M = \frac{100\ W_m}{W_m + W_{dm}} \tag{3.1}$$

Where:

M = Moisture content

$W_m$ = mass of moisture

$W_{dm}$ = mass of bone dry material

Also, the moisture content of a product expressed as a percentage dry basis is the ratio of the amount of water in the product at any time compared to the amount of dry matter in the product and is calculated using equation (3.2).

$$M = \frac{100\ W_m}{W_{dm}} \quad \ldots \ldots \ldots \quad (3.2)$$

Where:

M = Moisture content

$W_m$ = mass of moisture

$W_{dm}$ = mass of bone dry materia

***Table 3. 1: Initial and safe moisture content of selected crop***

| **Grain** | **Initial Moisture Content (%wb) of crop** | **Final Moisture Content (%wb)** |
|---|---|---|
| Sorghum | 30 | 11 |
| Carrots | 70 | 5 |
| Bananas | 80 | 15 |
| Potatoes | 75 | 13 |
| Grapes | 80 | 15-20 |

Source: Bansal and Misra (1988)

Equilibrium relative humidity of slightly wet air at the exit of drying chamber is computed using equation 3.3.

$a_w = 1 - \exp\,[(-\exp\,(0.914 + 8.569 lnM)]$ ....................................... (3.3) Where:

$a_w = water\ activity$

M = mass on dry basis

$$M = \frac{M_f}{(180 - M_f)} \quad \ldots \quad (3.4)$$

Where:

M = mass on dry basis

$M_f$ = Final mass of dry basis

$ERH = 100\ a_w$ ...................................................................... (3.5)

Where:

ERH = equilibrium relative humidity

$a_w = water\ activity$

### *3.3.2 Design of absorber plate*

The absorber plate is a metal plate painted black and set beneath the cover to absorbed the radiant energy. The material used for absorber plate is aluminium, which has a fast response in absorbing solar energy. The absorber surface area Aab is almost the same as collector surface area, Ac is computed using equation 3.6.

$A_{ab} = A_c = L_c \times W$ ................................................................................ (3.6)

Where:

Aab = Absorber surface area

Ac = Collector surface area

Lc = Length of the solar collector

W = Width of the solar collector

### *3.3.2 Design of collector*

The collector has three major components namely plate absorber, insulation and transparent cover. The cover is made of a glass and a sheet of aluminum of thickness 2 mm was used as heat absorber. The insulator is mainly to minimize heat loss from the system.

Fudholi et al. (2011) defined thermal efficiency of a solar collector as the ratio of useful heat energy to the solar radiant energy incident on the collector.

$$\eta_c = \frac{\dot{m}\, C(T_o - T_i)}{A_c I} \times 100\% \quad (3.7)$$

Where: $\eta_c$ = Solar collector for thermal efficiency $\dot{m}$ = mass of air flow( kg/s)

C = specific heat capacity of air (KJ $kg^{-1}°C^{-1}$)

$A_c$ = Area of a collector ($m^2$)

$T_i$ = initial temperature of the collector (°C)

$T_o$ = final temperature of the collector (°C)

I = Intensity of solar radiation ($W/m^2$)

Also, volume flow rate of air Va ($m^3/hr$) is calculated as shown below:

$$V_a = \frac{W_a}{t_d} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \quad (3.8)$$

Where:

Wa = quantity of air required in $m^3$ $t_d$

= Final drying time in hours

$V_a$ = volume flow rate of air

Also mass flow rate of air $m_a$ is calculated as:

$$m_a = \rho_a \times V_a \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. \quad (3.9)$$

Where:

$\rho_a$ = density of drying air ($kg/m^3$) = $1.2 kg/m^3$

$V_a$ = volumetric flow rate of air

### *3.3.3 Drying chamber*

The drying chamber was made from galvanized steel wrapped with aluminum foil. It consisted of four trays, each with size of 50 x 40 mm, for the produce to be dried. The trays were made from perforated galvanized steel wrapped with aluminum foil. Galvanized steel was chosen to avoid rusting due to high initial moisture content. The back of the drying chamber has a door that provides a means for loading and removing the material to be dried.

### *3.3.4. Sizing the collector*

The daily average insolation in Kumasi is taken to be 15.48 $MJ/m^2$/day. Struckmann (2008) gives a typical flat-plate collector efficiency (at ambient temperature of 25 $^0$C and I = 400 $W/m^2$) to be between 25% and 45%. The collector efficiency is influenced by factors such as temperature, airflow rate, insolation, type of transparent material, absorber plate and insulation used (Struckmann, 2008). The optimum design value of collector efficiency of 35% was considered as a design parameter. Also, typical values for daily global solar exposure range from 1 to 35 $MJ/m^2$ and 10.84 was considered as a design parameter. As a result,

daily expected energy production by the collector = 15.48 $MJ/m^2$/day x 0.35

= 5.42 $MJ/m^2$/day

$$\text{Collector Area} = \frac{10.84\,MJ}{5.42\,MJ/m^2} = 0.5\ m^2$$

Hence, the area of the collector was approximated to 0.5 $m^2$. Tibebu & Nkrumah (2015) suggested the length-to-width ratio of a solar collector to be 1 – 2. Considering the ratio to be 2 for this design, the length and width of the collector were 1.1 m and 0.6 m, respectively.

### *3.3.5 Thermal energy storage device*

The backup heater used thermal energy storage as a source of energy. A “flake salt” and copper pipe was used to construct thermal energy storage. For this project, the medium type of copper pipe was used. In the daytime, the thermal energy device stored heat and dissipated it in the night for drying crops.

### *3.3.6 Design calculation*

Table 3.2 presents the calculated results.

***Table 3. 2 Design parameters***

| **No.** | **Parameters** | **Units** | **Actual dryer dimensions** |
|---|---|---|---|
| 1 | Solar collector | | |
| | Collector area | $m^2$ | 0.5 |
| | Length, Lc | m | 1.1 |
| | Width, Wc | m | 0.6 |
| 2 | Solar crop dryer | | |
| | Length, $L_d$ | m | 5.348 |
| | Width, $W_d$ | m | 2.849 |
| 3 | Absorber surface area, $A_{ab}$ | $m^2$ | 0.66 |
| 4 | The quantity of moisture content removed | kg | 9.2 |
| 5 | Final / equilibrium relative humidity | % | 57 |

The figure 3.2 displays an exploded view of thermal energy storage of a solar crop dryer with part list.

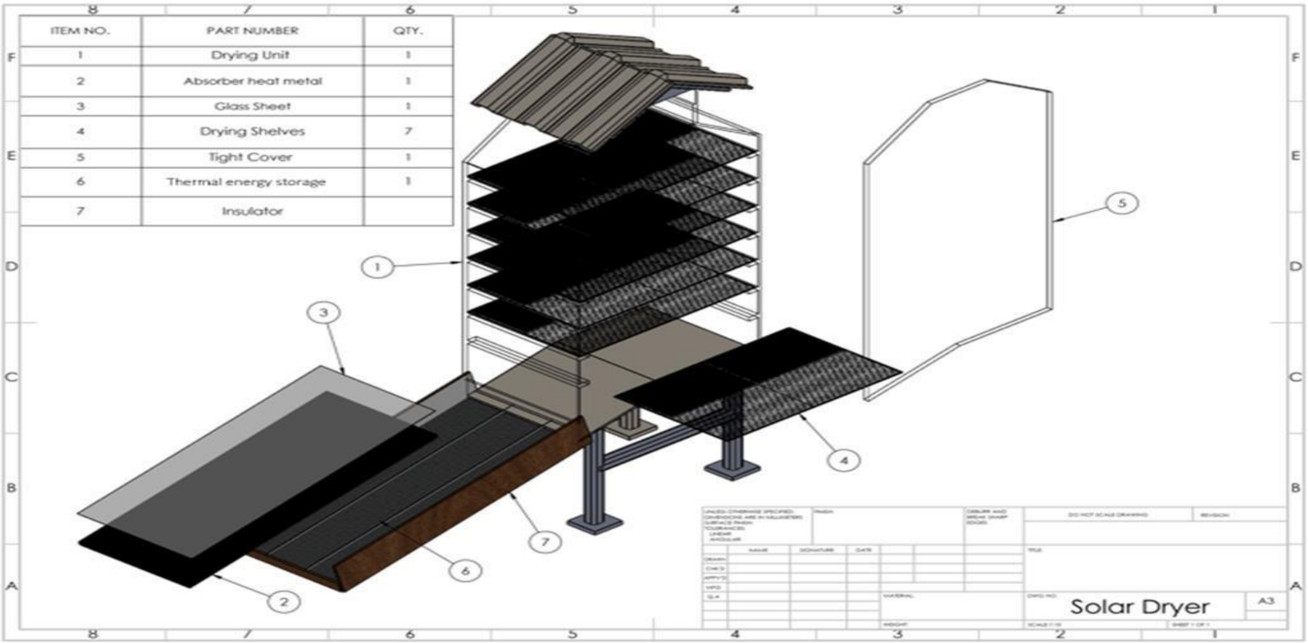


***Figure 3. 2: Displays of an exploded view of thermal energy storage of a solar crop dryer.***

Figure 3.3 shows 3rd Angle Orthographic projection of solar crop dryer using thermal energy storage

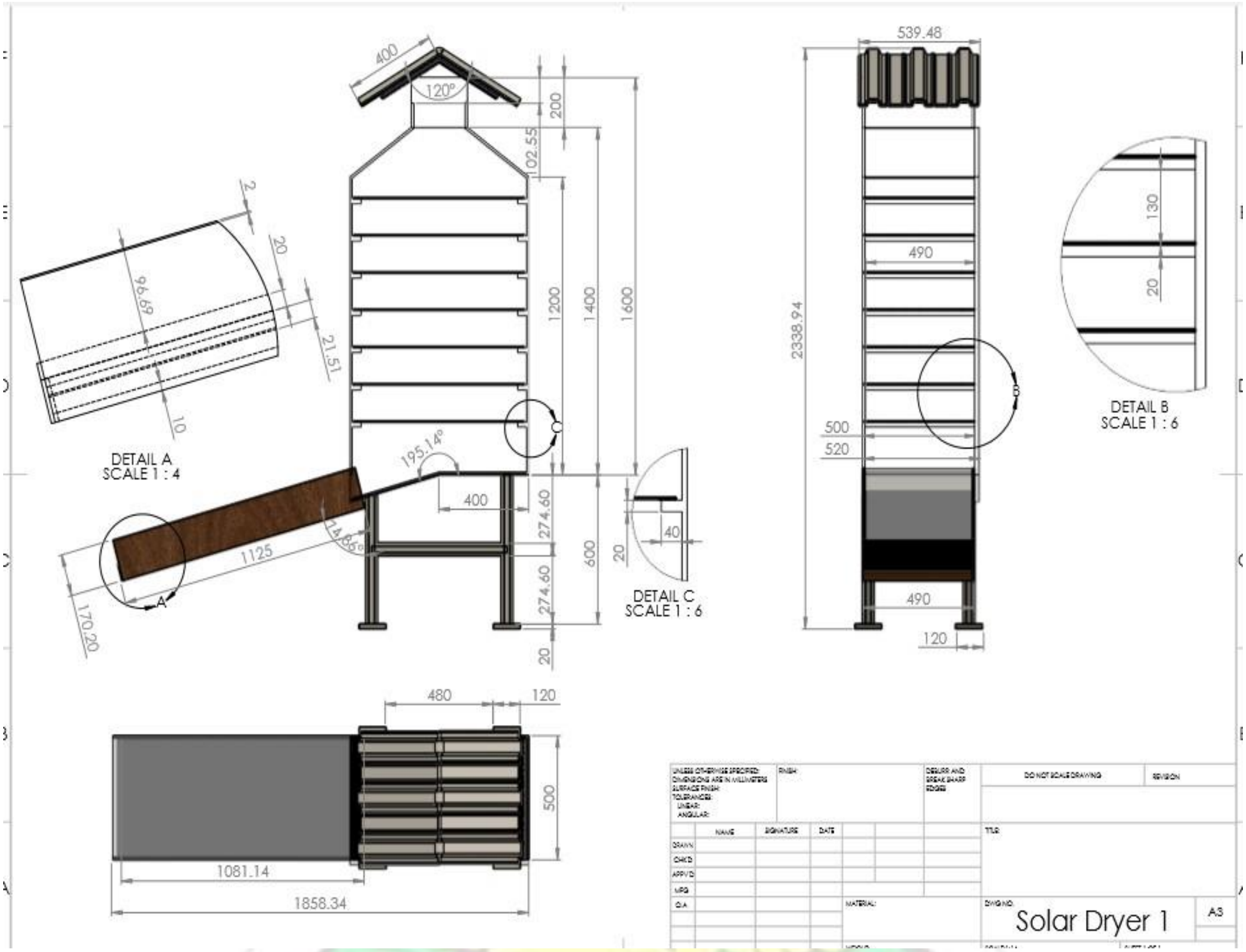


*Figure 3. 3: 3rd Angle Orthographic projection of solar crop dryer using TES*

Figure 3.4 shows solar heat collector of solar crop dryer and figure 3.5 shows isometric drawing of thermal energy storage device, which comprises of the aluminum pipes, insulators and thermal energy storage material (flake salt). The pictorial drawing is displayed in figure 3.6.

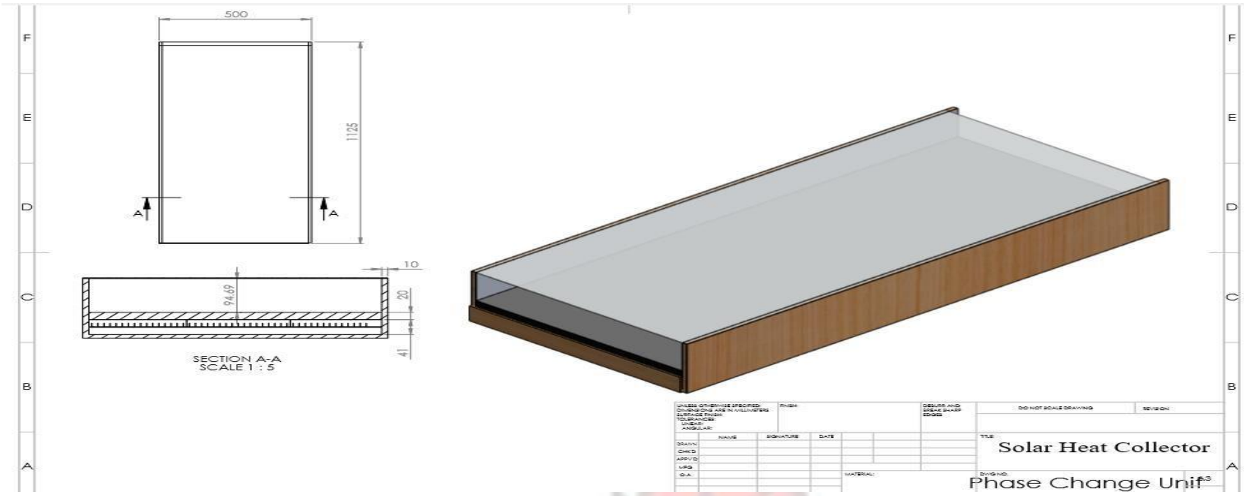


*Figure 3. 4 Heat collector of solar crop dryer using TES*

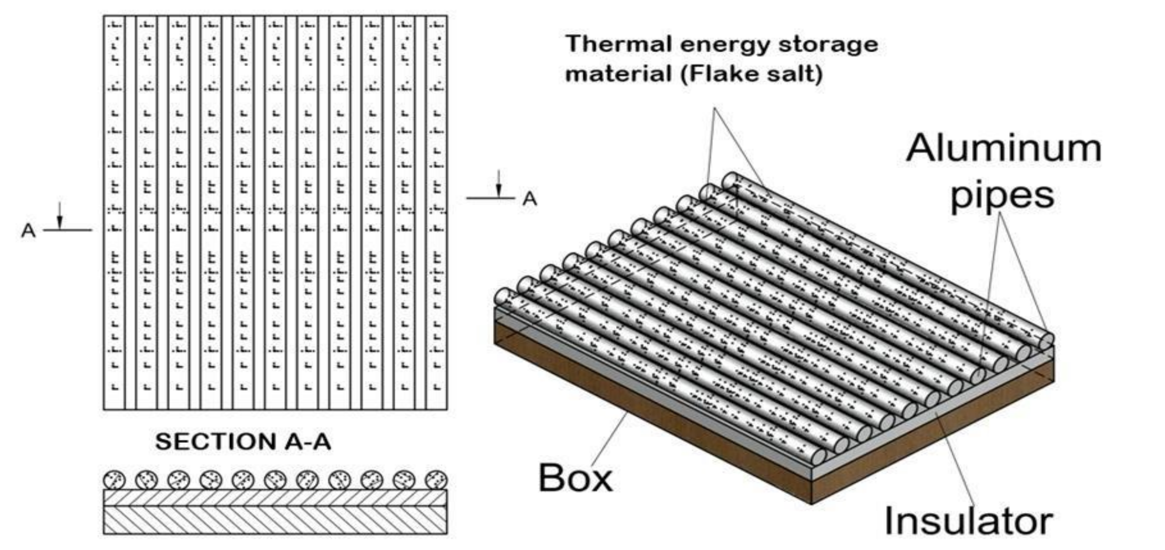


*Figure 3. 5 Isometric drawing of thermal energy storage device*

### *3.3.6 Fabrication of the thermal energy storage system*

***Figure 3. 6 Pictorial drawing of thermal energy storage device***

**Procedure for thermal energy storage**

The aluminium pipes were removed and filled with flake salt as shown in figure 3.7, afterwards the pipes were fixed permanently in their housing.

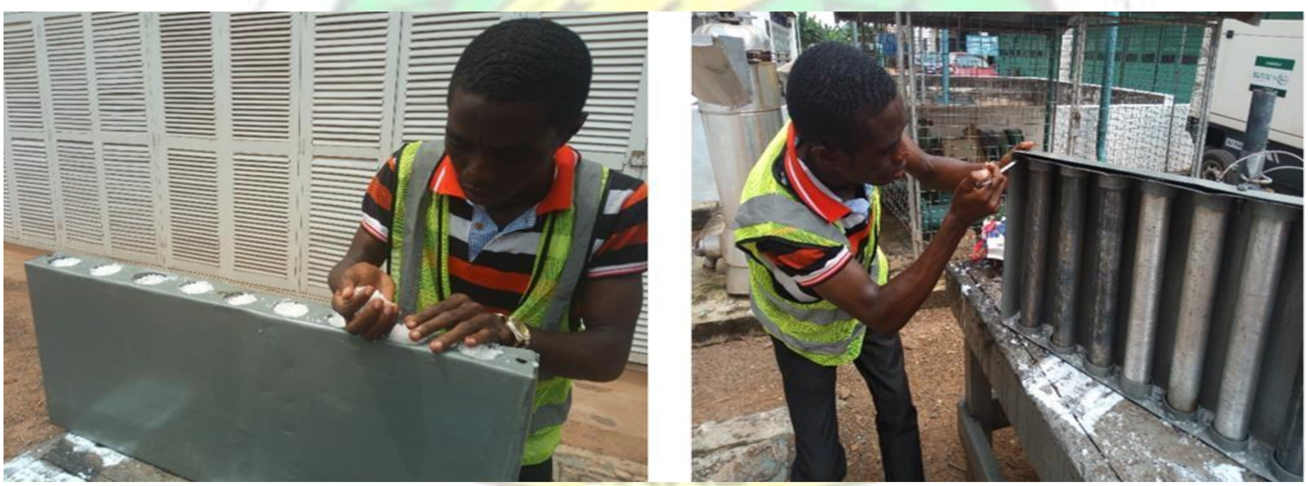

*Figure 3. 7 Pictorial view of copper pipes filled with flake salt and sealed*

The thermal energy storage which comprises of aluminum pipe and flake salt were then place inside the collector and a black polythene was used to cover the surface of the collector as shown in figure 3.8. The next step was to use a glass to cover the thermal energy heat storage.

***Figure 3. 8 Pictorial view of a black polythene used to cover the surface of the aluminium pipes and inserted into the crop dryer coved with glass***

## 3.4 Experimental Setup for initial moisture content determination

The experimental determination of sorghum initial moisture content was done at the Micro laboratory, Accra brewery industry, in May 2018.


***Figure 3. 9 Pictorial view of oven  instrument***

## Measurement of moisture content

Analysis of wet sample of sorghum from the farm is presented as follows:

An empty dish was measured and a sample of sorghum was put in the dish. The sample of sorghum from the farm was put in an oven at a temperature of 105 degrees and left for 4 hrs. The sample was then taken out of the oven and left to cool for 10 minutes. The start time was 8:00 am to 12:00 pm.

The initial moisture content was then calculated as

$$\text{Moisture content} = \frac{\text{total sample mass before heating in a dish} - \text{total sample mass after heating}}{\text{Sample mass only} \times 100}$$

Using sample 1

$$M_c = \frac{80 - 77}{10} \times 100$$

Mc = 30

Table 3.3 shows the average moisture contents of three different samples of sorghum dehydrated at a constant temperature of 105 $^0$C in the oven at the micro laboratory. ***Table 3. 3 Moisture content of sample of sorghum of day 1 analysis***

| **Sample** | **Moisture content (%)** |
|---|---|
| Sample 1 | 30 |
| Sample 2 | 29 |
| Sample 3 | 28 |
| Average | 29 |

## 3.5 Drying experiments conducted using the designed dryer

### *3.5.1 Instrumentation*

Temperature and relative humidity were measured using thermocouple and RH-meter as shown in figures 3.10 and 3.11.


**(a) Thermocouple omega engineering** **(b) Thermocouple instrument**

***Figure 3. 10 Pictorial view of thermocouple instruments for temperature measurement***


***Figure 3. 11 Pictorial view of relative humidity and temperature instruments for measurement***

**(a) Vaisala Humidity & Temperature meter** **(b) Sper Scientific Humidity & Temperature device**

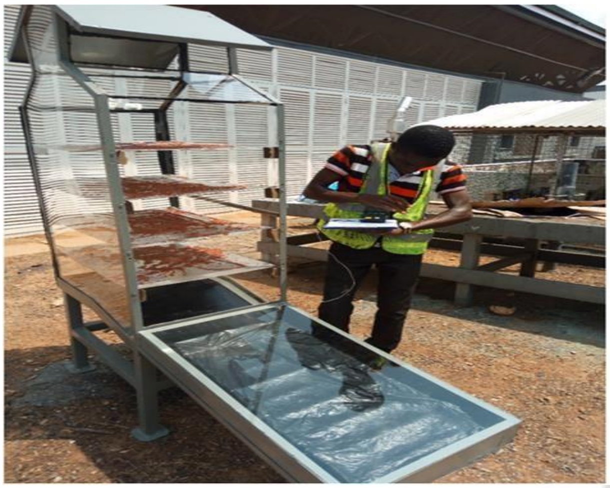

***Figure 3. 12 Pictorial view of using thermocouple omega engineering instrument for temperature measurement and recording the temperatures at every hour***

### *3.5.2 The Drying Test of Solar Crop Dryer with TES*

The drying test of solar crop dryer with thermal energy storage was done by continously monitoring the mass of the sorghum and the temperature of the thermal energy storage unit. Mass of product, dryer inlet and outlet temperatures as well as relative humidities of air were measured at intervals of 1 hour from 7:00 am to 12:00 am. The night time drying (ie. From 6:00 pm to 12:00 am) was done in order to determine the effectiveness of the thermal energy storage unit.

*Table 3. 4 Drying test results*

| Time/hr | Mass (kg) of Tray 1 (Bottom) | Mass (kg) of Tray 2 (Middle) | Mass (kg) of Tray 3 (Top) |
|---|---|---|---|
| 10:00 | 20.03 | 20.03 | 20.03 |
| 11:00 | 18.00 | 18.01 | 18.02 |
| 12:00 | 17.84 | 17.86 | 17.83 |
| 13:00 | 15.80 | 15.82 | 15.85 |
| 14:00 | 14.78 | 14.80 | 14.81 |
| 15:00 | 12.70 | 12.75 | 12.78 |
| 16:00 | 11.66 | 11.71 | 11.73 |
| 17:00 | 10.00 | 10.65 | 10.70 |
| 18:00 | 9.50 | 9.54 | 9.60 |
| 19:00 | 20.03 | 20.03 | 20.03 |
| 20:00 | 19.01 | 19.03 | 19.04 |
| 21:00 | 18.89 | 18.90 | 18.98 |
| 22:00 | 18.02 | 18.50 | 18.80 |
| 23:00 | 17.50 | 17.48 | 18.00 |
| 0:00 | 17.00 | 17.30 | 17.80 |
| 1:00 | 16.58 | 17.00 | 17.50 |
| 2:00 | 15.00 | 16.50 | 17.00 |
| 3:00 | 14.52 | 15.00 | 16.68 |
| 4:00 | 14.00 | 14.58 | 15.40 |
| 5:00 | 13.00 | 13.58 | 14.00 |
| 6:00 | 12.50 | 12.80 | 13.02 |
| 7:00 | 11.00 | 12.00 | 12.50 |
| 8:00 | 10.02 | 11.50 | 11.58 |
| 9:00 | 9.00 | 10.02 | 10.50 |

## 3.5 Performance Evaluation of Solar Crop Dryer with TES

### *3.5.1 Collector efficiency*

Struckmann (2008) calculated the performance of collector efficiency in equation 3.10. Once the collector absorbs heat and as a result, temperature gets higher than the surrounding, there is also losses of energy to the atmosphere by radiation and convection.

$$\text{Collector Efficiency, } \eta_c = \frac{\dot{Q}}{I_c A_c} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3.10$$

where:

$\dot{Q}$ = the heat transfer rate of the collector, W

$I_c$ = insolation on collector surface, $W/m^2$ = 400 $W/m^2$

$A_c$ = collector area, $m^2$ = 0.5 $m^2$

$\dot{Q} = \dot{m}\, C_p \Delta T$

Where

$\dot{m}$ = mass flow rate of air, kg/s

$C_p$ – air specific heat capacity, kJ/kg°C = 1.00 kJ/kg°C

$\Delta T$ = temperature change of the collector, °C

$T_{ca}$ = Cabinet temperature (°C) = 33.6 °C

$T_{amb}$ = Ambient temperature (°C) = 28.2 °C

$\dot{m} = A_c \times v \times \rho$ $\dot{m} = 0.102 \times 0.7 \times 1.2$

$\dot{m} = 0.0857\ kg/s$

Hence, from excel computation the collector efficiency, $\eta_c = 0.20$ %

### *3.5.2 Efficiency of solar crop dryer*

The drying efficiency in equation 3.11 is used to measure the total effectiveness of a drying in the cabinet.

$$\text{Drying Efficiency, } \eta_d = \frac{M_w L}{I_c A_c t} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . 3.11$$

$M_w$ = moisture evaporated from product, kg = 14.85 kg

L = Latent heat of vaporization (kJ/kg) 245 kJ/kg

$I_c$ = insolation on collector surface, W/m$^2$ = 400 W/m$^2$

$A_c$ = effective collector surface area, m$^2$ = 0.5 m$^2$ t

= drying time = 24 hrs

$$\eta_d = \frac{14.85 \times 245 \times 1000}{400 \times 0.5 \times 24 \times 3600} \times 100$$

$\eta_d = 21.1$ %

### *3.5.3 Drying rate*

(Tibebu & Nkrumah, 2015) define the drying rate as the amount of evaporated moisture content ended with time.

$$\text{Drying rate} = \frac{m_i - m_d}{t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . 3.12$$

Where:

$m_i$ = Initial drying of sample of mass

Md = After drying of sample of mass t

= drying time

The figure 3.14 displays the pictorial view of the constructed dryer

***Figure 3. 13 Pictorial view of the constructed dryer***

# CHAPTER FOUR

# RESULTS AND DISCUSSION

## 4.1 Moisture Content of sorghum

The table in Appendix 1 shows drying test results obtained using solar crop dryer with thermal energy storage (TES) device and the results are plotted in figure 4.1.

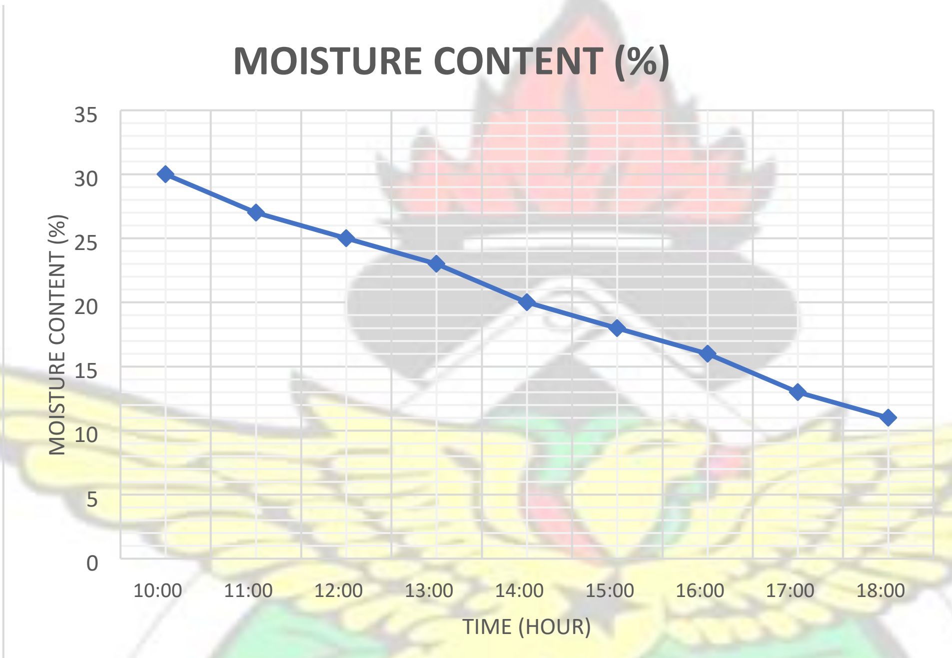

***Figure 4. 1 Moisture Content (%) of Sorghum (From 10 am to 6 pm) on July 2018***

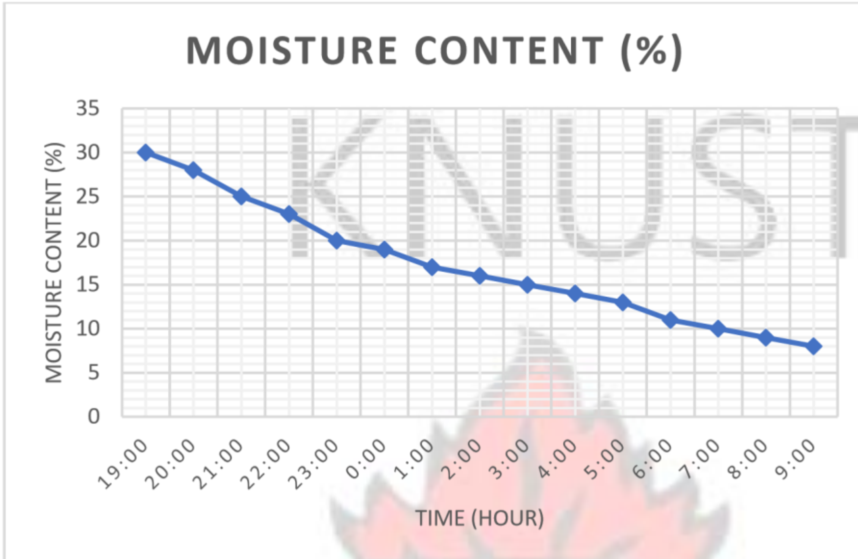


***Figure 4. 2 Moisture Content (%) of Sorghum (From 7 pm to 9 am) on July 2018***

From figure 4.1 and 4.2 the following observations were made.

1. From 10 AM to 6 PM the moisture content of sorghum is reduce from 30% to 11% on wet basis using the constructed solar crop dryer.

2. With thermal energy storage (TES) system, from (7:00 PM till the next morning 9:00 AM), the moisture content of sorghum is reduce from 30% to 8% using the constructed solar crop dryer.

Again, figure 4.3 and 4.4 shows how the mass is changing with respect to time.

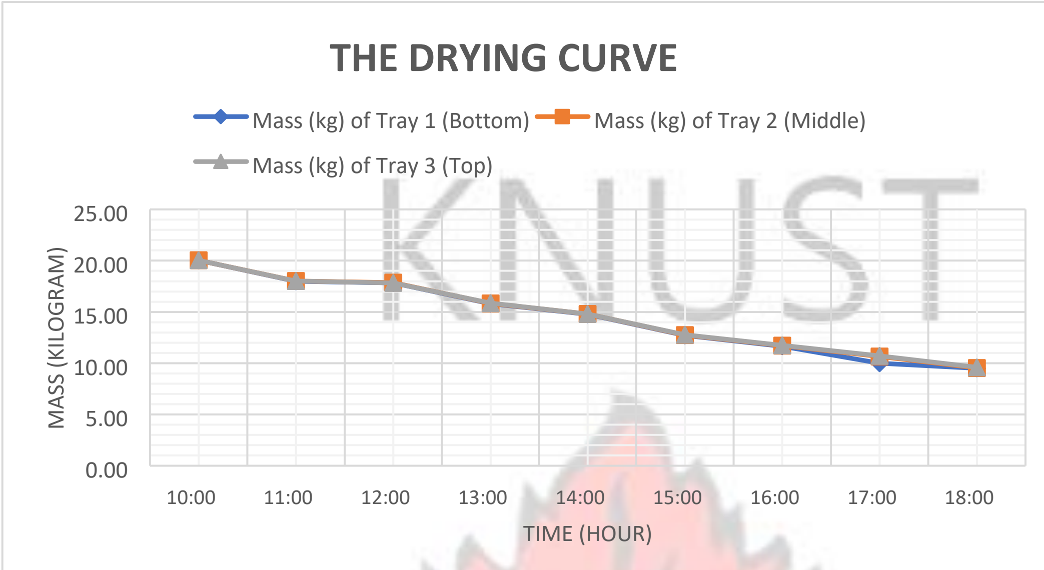


***Figure 4. 3 Graph of moisture verses time***

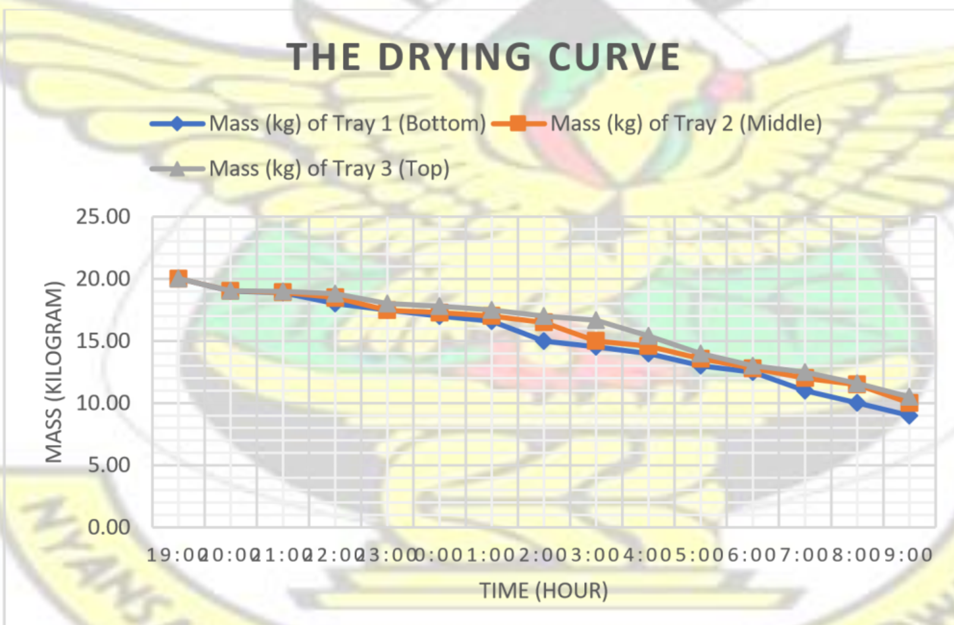


***Figure 4. 4 Graph of moisture variation verses time***

From figure 4.2 and 4.3 the observation made is that as the product loses moisture, the mass changes.

## 4.2 Temperature of the Solar Crop Dryer with / without Thermal energy storage

Figures 4.5 to 4.10 show the variation of ambient temperature and inside cabinet temperature for cabinet dryer using thermal energy storage and without thermal energy storage.

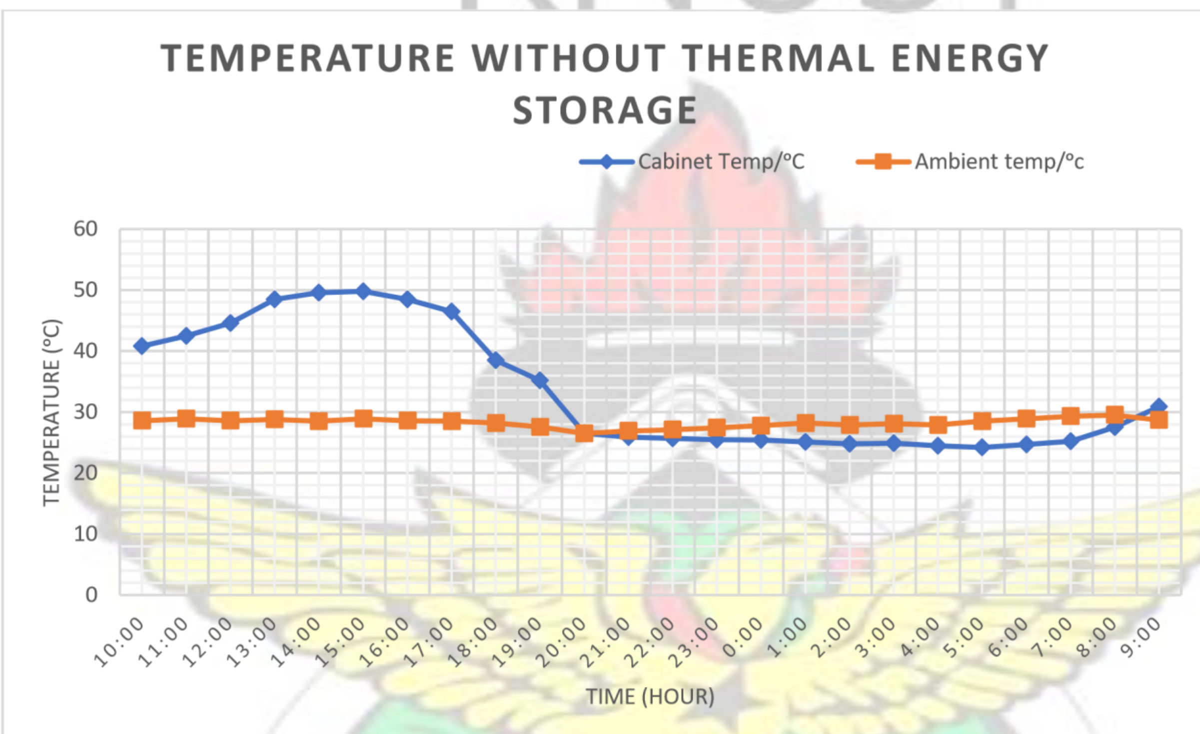


***Figure 4. 5 Temperature variation with time without thermal energy storage (TES) device***

From figure 4.5 three observation (without TES) were made

1. From 10 AM to 5 PM the temperature recorded (40.8 $^{0}$C to 46.5 $^{0}$C) was enough for drying sorghum

2. From 6 PM till the next morning 9 AM, the cabinet temperature recorded decreases because there is no thermal energy storage system to store heat for drying.

3. Again, after 6 pm or 7 pm the cabinet temperature without thermal energy storage decreases.

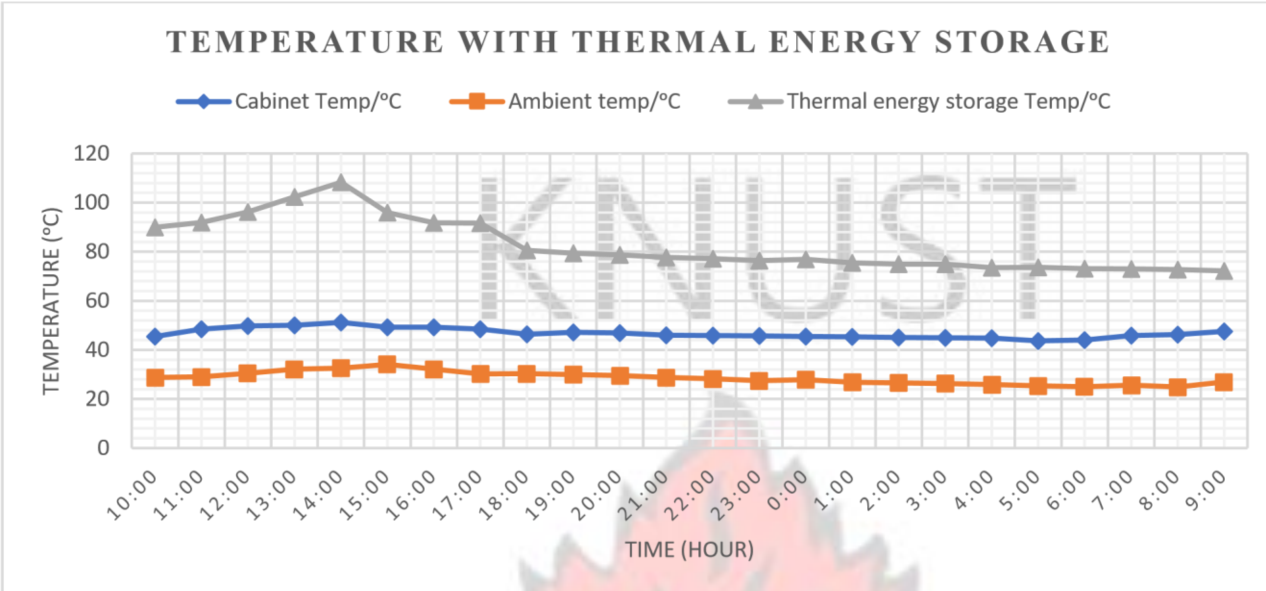


***Figure 4. 6 Temperature variation with time with thermal energy storage (TES) device***

From figure 4.6 three observation with thermal energy storage (TES) were made:

1. From 10 AM till the next morning 9 AM, the temperature recorded (45.5 $^0$C to 47.5 $^0$C) for drying of sorghum was enough because there is thermal energy storage system to store heat for drying.

2. The thermal energy storage temperature was at a maximum of (89.8 $^0$C) till the next morning (72.2 $^0$C) to store energy and distribute the energy to the system in order to dry the sorghum.

3. The thermal energy storage temperature recorded (ie. 89.8 $^0$C to 72.2 $^0$C) and the average product drying temperature (ie. 45.5 $^0$C to 47.5 $^0$C) were comparatively higher than the recorded ambient temperature for the scenario involving drying without thermal energy storage.

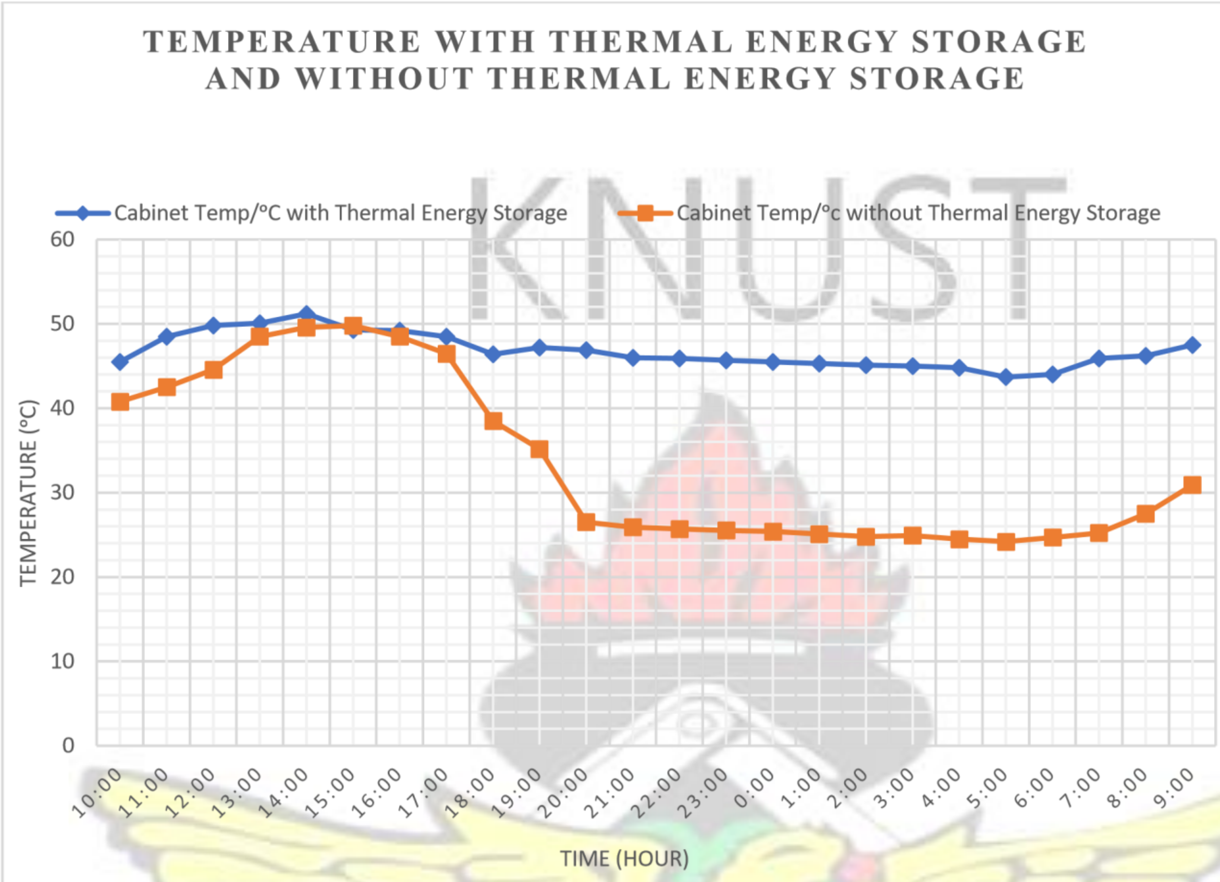


*Figure 4. 7 Temperature variation with time with and without thermal storage heat*

From figure 4.7 four observation with thermal storage and without thermal storage temperatures were made.

1. The temperature of thermal energy storage system (89.8 $^0$C to 72.2 $^0$C) was higher than the temperature without thermal energy storage system (40.8 $^0$C to 46.5 $^0$C) for 24 hours.

2. As at 8:00 PM, the temperatures almost remain constant for both TES and without TES as shown in figure 4.3.

3. The highest temperature occurred from 11:00 AM to 3 PM within the period.

4. The temperature without thermal energy storage system decreases from (46.5 $^{0}$C to 30.9 $^{0}$C) at 5 PM till the next morning because there was no thermal energy storage to store heat for drying.

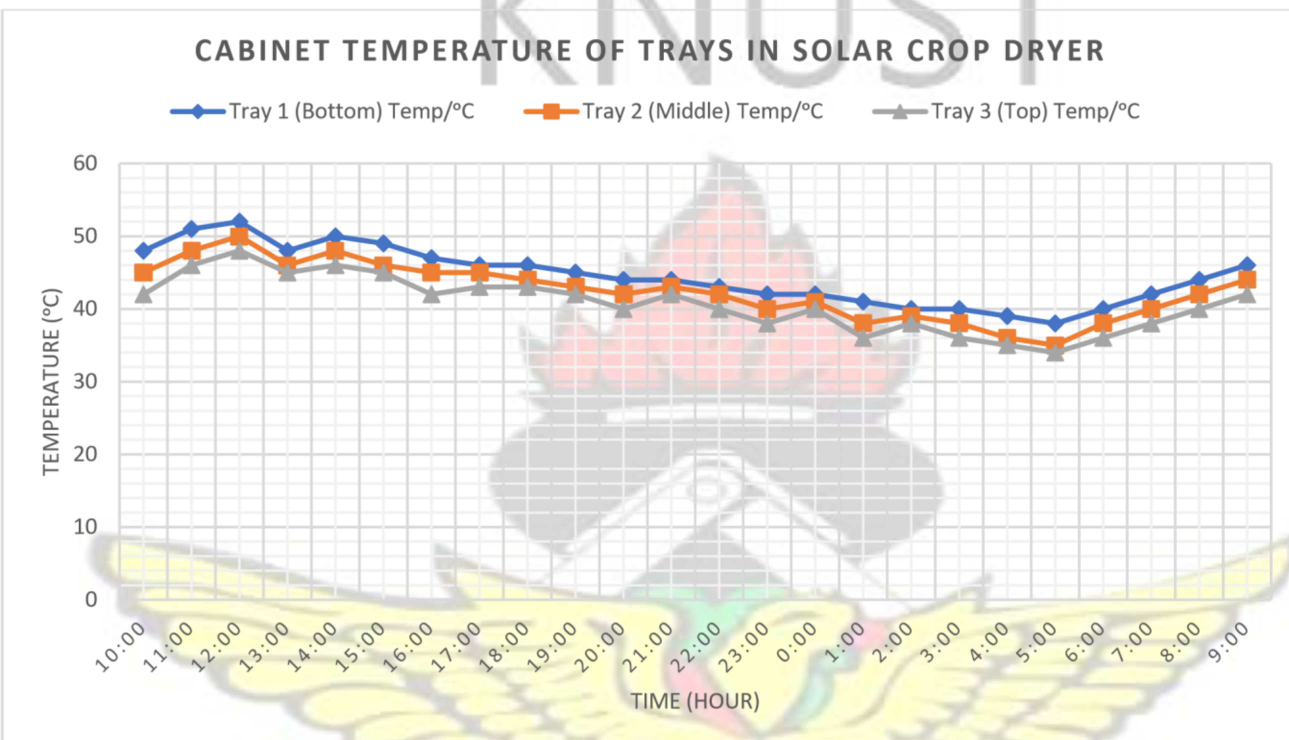


***Figure 4. 8 Cabinet temperature variation with time with TES of solar crop dryer***

From figure 4.8 the following observations with thermal energy storage cabinet temperatures were made:

1. The highest temperature of 52 $^{0}$C occurred at tray 1

2. From 2:00 PM to 5:00 PM, the temperatures almost remain constant with thermal energy storage for all trials in the cabinet.

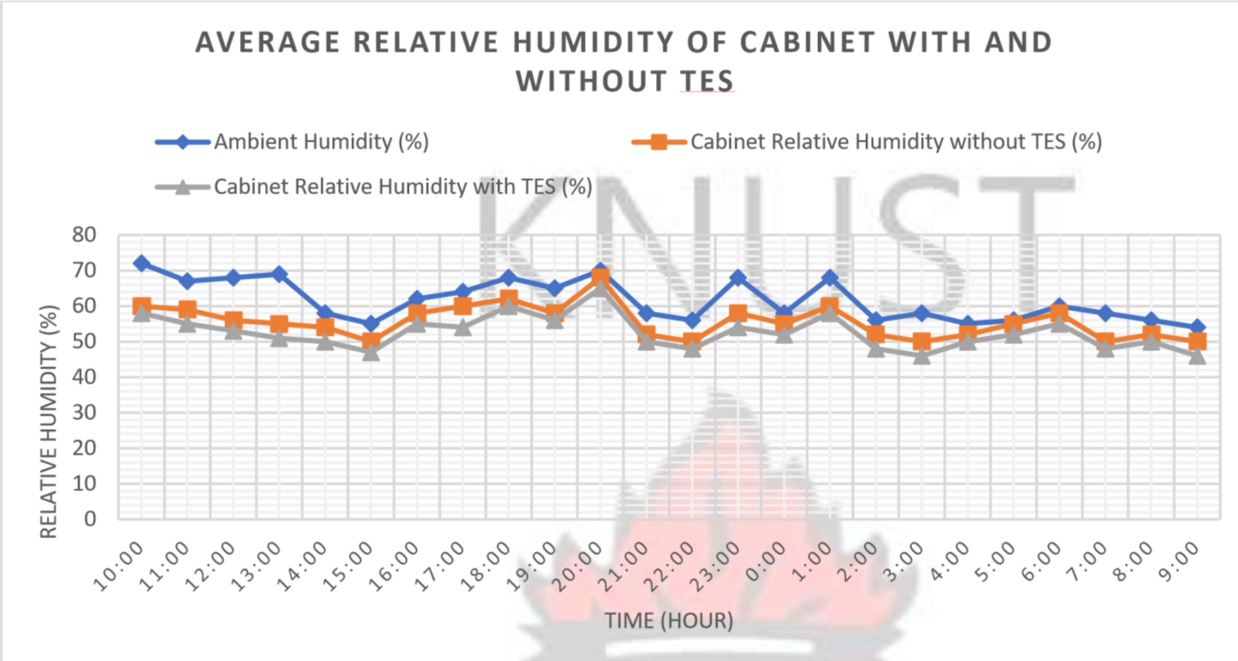


***Figure 4. 9 Relative humidity of cabinet with and without thermal storage heat***

From figure 4.9 the following observations of relative humidity of cabinet with and without thermal storage were made:

1. The ambient relative humidity is lower than the humidity of cabinet with and without thermal storage.

2. The highest ambient relative humidity recorded was 72 % at 10:00 AM and the lowest, 54 % at 3:00 AM on day one.

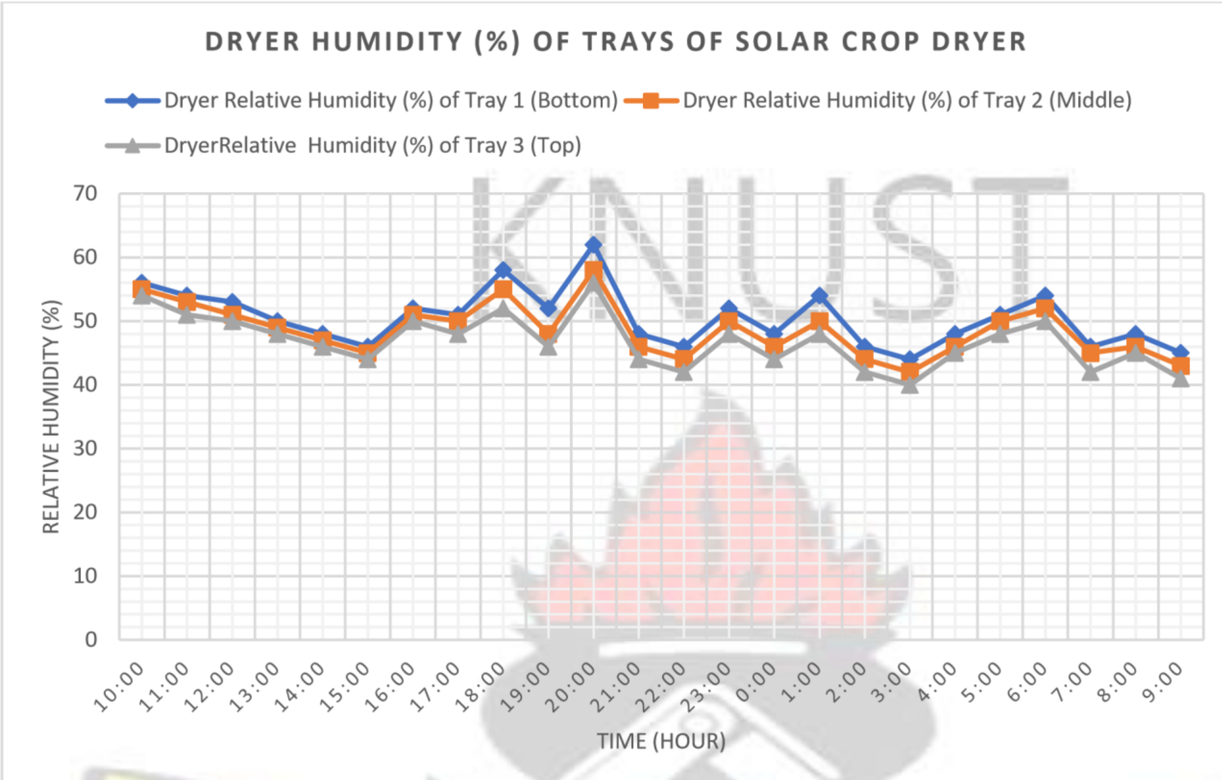


***Figure 4. 10 Dryer relative humidity (%) of trays of solar crop dryer with TES***

From figure 4.10 the following observations were made.

1. The highest relative humidity of 62 % occurred at tray 1 of solar crop dryer with thermal energy storage as compared with trays 2 and 3.

2. From 10:00 AM to 3:00 PM, the temperatures almost remain constant for all trays with thermal energy storage in the cabinet.

3. The relative humidity of air in drying of sorghum was reduced from 56 % to 46 % from 10:00 AM to 3:00 PM for 24-hour period on day one.

## 4.3 Performance of the Solar Crop Dryer with TES

The efficiency of drying sorghum using the constructed solar crop dryer was 21.1 %. This value is within the range stated in Cherotich and Simate (2017) which suggested that typical values of drying efficiency should be between 10 - 15 % for natural convection solar dryers. Hii et al. (2012) also reported efficiency values between 8.6% - 22.6 % for direct convection solar dryers.

The highest ambient relative humidity of 72% was recorded at 10:00 AM and the lowest is 52 % at 3:00 AM. These results are in close conformity with the observation of Mejia (1999).

The dryer also reduced the moisture content of freshly harvested sorghum from 30% to 11% wet basis in 6 hours per batch.

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

A solar crop dryer with thermal energy storage device (TES) was designed and constructed from locally available materials and used to dry sorghum. Experiments were conducted and moisture content of sorghum was reduced from 30% to 13% wet basis in 4 hours using the constructed solar crop dryer. In solar crop drying with thermal energy storage device, results show that the thermal mass was capable of storing part of the absorbed solar energy in daytime and the amount of heat stored was sufficient to sustain drying in the night. The collector efficiency calculated using thermal energy storage was found to be 11.2 % and the efficiency of drying sorghum using the constructed solar crop dryer was 12.5 %.

## 5.2 Recommendation

It is recommended that, further testing should be done to determine the full characteristics of the dryer.

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## APPENDIX 1: Moisture content of sorghum in solar crop dryer with TES

| Time/hr | Moisture Content (%) |
|---|---|
| 10:00 | 30 |
| 11:00 | 27 |
| 12:00 | 25 |
| 13:00 | 23 |

| | |
|---|---|
| 14:00 | 20 |
| 15:00 | 18 |
| 16:00 | 16 |
| 17:00 | 13 |
| 18:00 | 11 |
| 19:00 | 30 |
| 20:00 | 28 |
| 21:00 | 25 |
| 22:00 | 23 |
| 23:00 | 20 |
| 0:00 | 19 |
| 1:00 | 17 |
| 2:00 | 16 |
| 3:00 | 15 |
| 4:00 | 14 |
| 5:00 | 13 |
| 6:00 | 11 |
| 7:00 | 10 |
| 8:00 | 9 |
| 9:00 | 8 |



**APPENDIX 2: How mass is changing with respect to time**

| Time/hr | Mass (kg) of Tray 1 (Bottom) | Mass (kg) of Tray 2 (Middle) | Mass (kg) of Tray 3 (Top) |
|---|---|---|---|
| 10:00 | 20.03 | 20.03 | 20.03 |
| 11:00 | 18.00 | 18.01 | 18.02 |
| 12:00 | 17.84 | 17.86 | 17.83 |

| | | | |
|---|---|---|---|
| 13:00 | 15.80 | 15.82 | 15.85 |
| 14:00 | 14.78 | 14.80 | 14.81 |
| 15:00 | 12.70 | 12.75 | 12.78 |
| 16:00 | 11.66 | 11.71 | 11.73 |
| 17:00 | 10.00 | 10.65 | 10.70 |
| 18:00 | 9.50 | 9.54 | 9.60 |
| 19:00 | 20.03 | 20.03 | 20.03 |
| 20:00 | 19.01 | 19.03 | 19.04 |
| 21:00 | 18.89 | 18.90 | 18.98 |
| 22:00 | 18.02 | 18.50 | 18.80 |
| 23:00 | 17.50 | 17.48 | 18.00 |
| 0:00 | 17.00 | 17.30 | 17.80 |
| 1:00 | 16.58 | 17.00 | 17.50 |
| 2:00 | 15.00 | 16.50 | 17.00 |
| 3:00 | 14.52 | 15.00 | 16.68 |
| 4:00 | 14.00 | 14.58 | 15.40 |
| 5:00 | 13.00 | 13.58 | 14.00 |
| 6:00 | 12.50 | 12.80 | 13.02 |
| 7:00 | 11.00 | 12.00 | 12.50 |
| 8:00 | 10.02 | 11.50 | 11.58 |
| 9:00 | 9.00 | 10.02 | 10.50 |

## APPENDIX 3: Temperature recorded without thermal energy storage (TES) device

| Time/hr | Cabinet Temp/°C | Ambient temp/°C |
|---|---|---|
| 10:00 | 40.8 | 28.6 |
| 11:00 | 42.5 | 28.9 |
| 12:00 | 44.6 | 28.6 |
| 13:00 | 48.5 | 28.8 |
| 14:00 | 49.6 | 28.5 |
| 15:00 | 49.8 | 28.9 |
| 16:00 | 48.5 | 28.6 |
| 17:00 | 46.5 | 28.5 |
| 18:00 | 38.5 | 28.2 |
| 19:00 | 35.2 | 27.6 |
| 20:00 | 26.5 | 26.5 |
| 21:00 | 25.9 | 26.9 |
| 22:00 | 25.7 | 27.1 |
| 23:00 | 25.5 | 27.4 |
| 0:00 | 25.4 | 27.8 |
| 1:00 | 25.1 | 28.2 |
| 2:00 | 24.8 | 27.9 |
| 3:00 | 24.9 | 28.1 |
| 4:00 | 24.5 | 27.9 |
| 5:00 | 24.2 | 28.5 |
| 6:00 | 24.7 | 28.9 |
| 7:00 | 25.2 | 29.3 |
| 8:00 | 27.5 | 29.5 |
| 9:00 | 30.9 | 28.7 |

## APPENDIX 4: Temperature recorded with thermal energy storage device

| Time/hr | Cabinet Temp/°C | Ambient temp/°C | Thermal energy storage Temp/°C |
|---|---|---|---|
| 10:00 | 45.5 | 28.8 | 89.9 |
| 11:00 | 48.5 | 29 | 91.9 |
| 12:00 | 49.8 | 30.5 | 96.2 |
| 13:00 | 50.1 | 32.2 | 102.3 |
| 14:00 | 51.2 | 32.5 | 108.3 |
| 15:00 | 49.3 | 34.1 | 95.9 |
| 16:00 | 49.2 | 32.2 | 91.8 |
| 17:00 | 48.5 | 30.2 | 91.7 |
| 18:00 | 46.4 | 30.4 | 80.5 |
| 19:00 | 47.2 | 29.9 | 79.4 |
| 20:00 | 46.9 | 29.5 | 78.8 |
| 21:00 | 46 | 28.8 | 77.7 |
| 22:00 | 45.9 | 28.2 | 77.2 |
| 23:00 | 45.7 | 27.5 | 76.4 |
| 0:00 | 45.5 | 27.9 | 76.9 |
| 1:00 | 45.3 | 26.8 | 75.5 |
| 2:00 | 45.1 | 26.5 | 75 |
| 3:00 | 45 | 26.3 | 74.9 |
| 4:00 | 44.8 | 25.9 | 73.5 |
| 5:00 | 43.7 | 25.4 | 73.6 |
| 6:00 | 44 | 25 | 73.1 |
| 7:00 | 45.9 | 25.7 | 73 |
| 8:00 | 46.2 | 24.9 | 72.7 |
| 9:00 | 47.5 | 26.9 | 72.2 |

## APPENDIX 5: Temperature recorded with and without thermal energy storage

| Time/hr | Cabinet Temp/°C with Thermal Energy Storage | Cabinet Temp/°c without Thermal Energy Storage |
|---|---|---|
| 10:00 | 45.5 | 40.8 |
| 11:00 | 48.5 | 42.5 |
| 12:00 | 49.8 | 44.6 |
| 13:00 | 50.1 | 48.5 |
| 14:00 | 51.2 | 49.6 |
| 15:00 | 49.3 | 49.8 |
| 16:00 | 49.2 | 48.5 |
| 17:00 | 48.5 | 46.5 |
| 18:00 | 46.4 | 38.5 |
| 19:00 | 47.2 | 35.2 |
| 20:00 | 46.9 | 26.5 |
| 21:00 | 46 | 25.9 |
| 22:00 | 45.9 | 25.7 |
| 23:00 | 45.7 | 25.5 |
| 0:00 | 45.5 | 25.4 |
| 1:00 | 45.3 | 25.1 |
| 2:00 | 45.1 | 24.8 |
| 3:00 | 45 | 24.9 |
| 4:00 | 44.8 | 24.5 |
| 5:00 | 43.7 | 24.2 |
| 6:00 | 44 | 24.7 |
| 7:00 | 45.9 | 25.2 |
| 8:00 | 46.2 | 27.5 |
| 9:00 | 47.5 | 30.9 |

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## APPENDIX 6 Cabinet Temperature of Trays in Solar Crop Dryer

| Time/hr | Tray 1 (Bottom) Temp/°C | Tray 2 (Middle) Temp/°C | Tray 3 (Top) Temp/°C |
|---|---|---|---|
| 10:00 | 48 | 45 | 42 |
| 11:00 | 51 | 48 | 46 |
| 12:00 | 52 | 50 | 48 |
| 13:00 | 48 | 46 | 45 |
| 14:00 | 50 | 48 | 46 |
| 15:00 | 49 | 46 | 45 |
| 16:00 | 47 | 45 | 42 |
| 17:00 | 46 | 45 | 43 |
| 18:00 | 46 | 44 | 43 |
| 19:00 | 45 | 43 | 42 |
| 20:00 | 44 | 42 | 40 |
| 21:00 | 44 | 43 | 42 |
| 22:00 | 43 | 42 | 40 |
| 23:00 | 42 | 40 | 38 |
| 0:00 | 42 | 41 | 40 |
| 1:00 | 41 | 38 | 36 |
| 2:00 | 40 | 39 | 38 |
| 3:00 | 40 | 38 | 36 |
| 4:00 | 39 | 36 | 35 |
| 5:00 | 38 | 35 | 34 |
| 6:00 | 40 | 38 | 36 |
| 7:00 | 42 | 40 | 38 |
| 8:00 | 44 | 42 | 40 |
| 9:00 | 46 | 44 | 42 |

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**APPENDIX 7 Relative humidity of cabinet with and without TES**

| Time/hr | Ambient Humidity (%) | Cabinet Relative Humidity without TES (%) | Cabinet Relative Humidity with TES (%) |
|---|---|---|---|
| 10:00 | 72 | 60 | 58 |
| 11:00 | 67 | 59 | 55 |
| 12:00 | 68 | 56 | 53 |
| 13:00 | 69 | 55 | 51 |
| 14:00 | 58 | 54 | 50 |
| 15:00 | 55 | 50 | 47 |
| 16:00 | 62 | 58 | 55 |
| 17:00 | 64 | 60 | 54 |
| 18:00 | 68 | 62 | 60 |
| 19:00 | 65 | 58 | 56 |
| 20:00 | 70 | 68 | 65 |
| 21:00 | 58 | 52 | 50 |
| 22:00 | 56 | 50 | 48 |
| 23:00 | 68 | 58 | 54 |
| 0:00 | 58 | 55 | 52 |
| 1:00 | 68 | 60 | 58 |
| 2:00 | 56 | 52 | 48 |
| 3:00 | 58 | 50 | 46 |
| 4:00 | 55 | 52 | 50 |
| 5:00 | 56 | 55 | 52 |
| 6:00 | 60 | 58 | 55 |
| 7:00 | 58 | 50 | 48 |
| 8:00 | 56 | 52 | 50 |

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|---|---|---|---|
| 9:00 | 54 | 50 | 46 |



**APPENDIX 8 Dryer relative humidity (%) of trays of solar crop dryer**

| Time/hr | Dryer Relative Humidity (%) of Tray 1 (Bottom) | Dryer Relative Humidity (%) of Tray 2 (Middle) | DryerRelative Humidity (%) of Tray 3 (Top) |
|---|---|---|---|
| 10:00 | 56 | 55 | 54 |
| 11:00 | 54 | 53 | 51 |
| 12:00 | 53 | 51 | 50 |
| 13:00 | 50 | 49 | 48 |
| 14:00 | 48 | 47 | 46 |
| 15:00 | 46 | 45 | 44 |
| 16:00 | 52 | 51 | 50 |
| 17:00 | 51 | 50 | 48 |
| 18:00 | 58 | 55 | 52 |
| 19:00 | 52 | 48 | 46 |
| 20:00 | 62 | 58 | 56 |
| 21:00 | 48 | 46 | 44 |
| 22:00 | 46 | 44 | 42 |
| 23:00 | 52 | 50 | 48 |
| 0:00 | 48 | 46 | 44 |
| 1:00 | 54 | 50 | 48 |
| 2:00 | 46 | 44 | 42 |
| 3:00 | 44 | 42 | 40 |
| 4:00 | 48 | 46 | 45 |
| 5:00 | 51 | 50 | 48 |
| 6:00 | 54 | 52 | 50 |

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| | | | |
|---|---|---|---|
| 7:00 | 46 | 45 | 42 |
| 8:00 | 48 | 46 | 45 |
| 9:00 | 45 | 43 | 41 |



# APPENDIX 9 The Heat Transfer Rate and the Collector Efficiency

| Time/hr | Mass (kg) of Tray 1 (Bottom) | Mass (kg) of Tray 2 (Middle) | Mass (kg) of Tray 3 (Top) | $\Delta T$ | $\dot{Q} = \dot{m} C_p \Delta T$ | $\eta_c = \frac{Q}{I_c A_c} \times 100$ |
|---|---|---|---|---|---|---|
| 10:00 | 20.03 | 20.03 | 20.03 | 12.2 | 0.00 | 0.00 |
| 11:00 | 18.00 | 18.01 | 18.02 | 13.6 | 0.33 | 0.16 |
| 12:00 | 17.84 | 17.86 | 17.83 | 16 | 0.38 | 0.19 |
| 13:00 | 15.80 | 15.82 | 15.85 | 19.7 | 0.47 | 0.24 |
| 14:00 | 14.78 | 14.80 | 14.81 | 21.1 | 0.50 | 0.25 |
| 15:00 | 12.70 | 12.75 | 12.78 | 20.9 | 0.50 | 0.25 |
| 16:00 | 11.66 | 11.71 | 11.73 | 19.9 | 0.48 | 0.24 |
| 17:00 | 10.00 | 10.65 | 10.70 | 18.00 | 0.43 | 0.22 |
| 18:00 | 9.50 | 9.54 | 9.60 | 10.3 | 0.25 | 0.12 |
| 19:00 | 20.03 | 20.03 | 20.03 | 7.6 | 0.18 | 0.09 |
| 20:00 | 19.01 | 19.03 | 19.04 | 0 | 0.00 | 0.00 |
| 21:00 | 18.89 | 18.90 | 18.98 | -1 | -0.02 | -0.01 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 22:00 | 18.02 | 18.50 | 18.80 | -1.4 | -0.03 | -0.02 |
| 23:00 | 17.50 | 17.48 | 18.00 | -1.9 | -0.05 | -0.02 |
| 0:00 | 17.00 | 17.30 | 17.80 | -2.4 | -0.06 | -0.03 |
| 1:00 | 16.58 | 17.00 | 17.50 | -3.1 | -0.07 | -0.04 |
| 2:00 | 15.00 | 16.50 | 17.00 | -3.1 | -0.07 | -0.04 |
| 3:00 | 14.52 | 15.00 | 16.68 | -3.2 | -0.08 | -0.04 |
| 4:00 | 14.00 | 14.58 | 15.40 | -3.4 | -0.08 | -0.04 |
| 5:00 | 13.00 | 13.58 | 14.00 | -4.3 | -0.10 | -0.05 |
| 6:00 | 12.50 | 12.80 | 13.02 | -4.2 | -0.10 | -0.05 |
| 7:00 | 11.00 | 12.00 | 12.50 | -4.1 | -0.10 | -0.05 |
| 8:00 | 10.02 | 11.50 | 11.58 | -2 | -0.05 | -0.02 |
| 9:00 | 9.00 | 10.02 | 10.50 | 2.2 | 0.05 | 0.03 |
| | 356.38 | | | | 2.76 | 1.38 |
| **AVERAGE MASS** | **14.85** | | | | 0.11 | **0.06** |
| | | | | | | 0.20 |

## APPENDIX 10: The Change in Cabinet and Ambient Temperature

| Time/hr | Cabinet Temp/°C | Ambient temp/°c | $\Delta T = T_{ca} - T_{ar}$ |
|---|---|---|---|
| 10:00 | 40.8 | 28.6 | 12.2 |
| 11:00 | 42.5 | 28.9 | 13.6 |
| 12:00 | 44.6 | 28.6 | 16 |
| 13:00 | 48.5 | 28.8 | 19.7 |
| 14:00 | 49.6 | 28.5 | 21.1 |
| 15:00 | 49.8 | 28.9 | 20.9 |
| 16:00 | 48.5 | 28.6 | 19.9 |
| 17:00 | 46.5 | 28.5 | 18 |
| 18:00 | 38.5 | 28.2 | 10.3 |
| 19:00 | 35.2 | 27.6 | 7.6 |
| 20:00 | 26.5 | 26.5 | 0 |
| 21:00 | 25.9 | 26.9 | -1 |
| 22:00 | 25.7 | 27.1 | -1.4 |
| 23:00 | 25.5 | 27.4 | -1.9 |
| 0:00 | 25.4 | 27.8 | -2.4 |
| 1:00 | 25.1 | 28.2 | -3.1 |
| 2:00 | 24.8 | 27.9 | -3.1 |
| 3:00 | 24.9 | 28.1 | -3.2 |
| 4:00 | 24.5 | 27.9 | -3.4 |
| 5:00 | 24.2 | 28.5 | -4.3 |
| 6:00 | 24.7 | 28.9 | -4.2 |
| 7:00 | 25.2 | 29.3 | -4.1 |
| 8:00 | 27.5 | 29.5 | -2 |
| 9:00 | 30.9 | 28.7 | 2.2 |
| | 805.3 | 677.9 | 127.4 |
| | **33.6** | **28.2** | |
| **TOTAL AVERAGE CHANGE IN TEMPERATURE** | | | **5.3** |