DESIGN, SIMULATION, CONSTRUCTION AND PERFORMANCE COMPARISON OF MIXED-MODE SOLAR CROP DRYERS WITH AND WITHOUT THERMAL STORAGE

BY

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BY

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DEPARTMENT OF MECHANICAL ENGINEERING
FACULTY OF ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

APRIL, 2017

DECLARATION

I declare that the work in this Dissertation entitled '**Design**, **Simulation**, **ConstructionandPerformanceComparisonofMixed-ModeSolarCropDryerswithandwithoutThermalStorage'** has been carried out by me in the Department of Mechanical Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this Dissertation was previously presented for another degree or diploma to this or any other Institution.

Shitu ABUBAKAR _____

Name of student Signature and Date

CERTIFICATION

This dissertation entitled 'DESIGN, SIMULATION, CONSTRUCTION AND PERFORMANCE COMPARISON OF MIXED-MODE SOLAR CROP DRYERS WITH AND WITHOUT THERMAL STORAGE' by Shitu ABUBAKAR (P13EGME8001) meets the regulations governing the award of the degree of Master of Science in Mechanical Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This project work is dedicated to the founding father of my status; my parents.

ACKNOWLEDGEMENT

I thank the Almighty Allah, the Sovereign of the world, the Master of the day of resurrection; the Creator and the Sustainer for making this work a success.

This dissertation will be incomplete without thanking my amiable supervisors; Dr. F.O Anafi and Dr. S. Umaru. I appreciate your valuable guidance, constructive criticism, patience, words of wisdom and encouragement.

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My profound gratitude goes to my father, late Mallam Shitu Abubakar Bindawa, who was the founding father of my status, may Allah (SWT) grant him a niche in Aljannatul Firdaus.

Also to my beloved mother, MalamaRabiatuShituwhom I enjoy her motherly cares and support. Maryam Maude(Kusfa), Mal. Abdullahi Maude (Kusfa), Mal. Nura Shitu, Maimunatu Shitu, Maryam Shitu, Fateema Shitu, Zainab Shitu, Mal Sabi'u Shitu, and Tasi'u Shitu, thank you all for your prayers.

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For those who I unwillingly omitted, of which "thank you" is not enough for your huge contributions, may Allah bless you all and accept your sincere contributions.

ABSTRACT

Agricultural products upon harvesting have high moisture content which makes it unsafe for storage as the moisture in the crops attracts microorganisms which result in deterioration of the products. The major shortcoming of multiple trays drying is uneven drying of the products being dried on different trays.Solar dryers with and without thermal storage materials were developed, simulated and tested under the same meteorological conditions of Zaria and their performance evaluation were carried out. The average drying rates, collector efficiencies, and drying efficiencies of the solar crop dryers with and without thermal storage are 2.82×10^{-5} kg/s and 2.55×10^{-5} kg/s, 78.25% and 42.20%, 29.15 % and 25.35% respectively. During the experiment, the drying rates do not vary much with the coordinate positions of the trays. The performances of the solar dryers were simulated under varying meteorological conditions of Zaria. TRANSYS 16.0software was used to simulate the collectors' outlet air temperatures with and without thermal storage. Since a drying model is not available in the TRNSYS library, MATLAB code was written to computes the weight loss of the yam slices in the drying chamber. The computedNash-Sutcliffe Coefficient of Efficiency (NSE) values and its correspondingRoot Means Square Errors(RMSE) between the modeled collector air temperature, and the observed collector air temperature, with and without thermal storage confirms that the model formulation using TRANSYS 16 software used here for the performance simulation of the system is valid and realistic owing to the good quality of fit between the experimental and the simulated results. Similarly, the computed NSE values and its corresponding RMSE between the modeled weight loss of yam slices, and the observed weight loss of yam slices, with and without thermal storage follow the same trend

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NOMENCLATURE

A_c Collector area, m^2

C_p Specific heat capacity of air, kJ/kgK

F_R Heat removal factor, kJ/kg

g The gravitational acceleration in m/s^2

h_L Drying bed thickness, m

H Horizontal radiation, kJ/m^2hr

I_T Total solar radiation incident on the collector surface. W/m^2

L_d Length of dryer, m

L_T Length of tray, m

L_c Length of collector, m

L_v Latent heat of vaporization of water, kJ/kg

$\dot{m}$ Air mass flow rate, kg/s

M_w Mass of water to be evaporated from the yam slices, kg

M_1 Initial mass of the yam slices, kg

M_2 Final mass of the yam slices, kg

M_w Mass of water evaporated, kg

M_{we} Mass of the wet yam slices, kg

M_i, M_f Initial and final moisture contents on wet basis, %

ΔP_T The total pressure drop in the dryer, Pa

Pa Atmospheric pressure, Pa

P_a Partial pressure of dry air in the atmosphere, Pa

Q_s Energy stored, kJ/kg

Q_l Heat loss from the collector, W

Q_u Useful energy gained by the air, W

R The gas constant, kPa m^3/K

R Ratio of solar energy on tilted surface to that on the horizontal

t_d Drying time per day, hrs

T_f Temperature of air leaving the drying bed, ℃

T_o Temperature of air at the collector outlet, ℃

T_d Temperature of outgoing air from the drying chamber,℃

T_{dryer} The temperature of air in the dryer, K

T_{amb} The temperature of ambient air, K

u Superficial air velocity (m/s),

U_L Overall collector Loss Coefficient, W/m^2K

$\dot{V}_a$ Volume flow rate of the drying air, m^3/s

W_T Width of the tray which is equal to the width of the drying chamber, m

W_{we} Total mass of yam slices, kg

Y_l Thickness of the yam slices in the drying chamber, m

Greek Symbols

η_C Collector efficiency, %

ρ_b Bulk density of yam, kg/m^3

η_{dryer} Dryer efficiency, dimensionless

ε_p Absorber plate emittance,

α_p Absorptance of absorber plate

β Collector slope, degrees

ρ_a Density of air, kg/m^3

θ_z Zennit angle, degrees

δ Declination, degrees

∅Latitude of the location, degrees

ωSolar angle hour,degrees

ω_s Sunset hour angle,degrees

ε_g Emittance of glass (dimensionless)

ε_P Emittance of plate (dimensionless)

CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

Solar thermal technology is rapidly gaining acceptance as an energy saving measure in agricultural application. It is preferred to other alternative sources of energy because it is abundant, inexhaustible and non-polluting (Bukola and Ayoola, 2008).

In Nigeria, just like several other developing nations, agriculture is considered a factor for growth and development. The country is blessed with a landmass of 98.3 million hectares of which 72% is considered suitable for agricultural production(Aasa *et al.,* 2012). However, the rate of growth has been attributed to the level of agricultural preservation in the country. Her poor record of food preservation has led to improper management of agricultural produce and this impinged on the growth of food production (Aasa*et al.,* 2012).

After agricultural products are harvested, there is the need for proper storage for future use. The products upon harvesting have high moisture content which makes it unsafe for storage as the moisture in the crops attracts microorganisms which result in deterioration of the products. Among other reasons, crops are dried to improve shelf life, retain original flavor and reduce weight for easy transport and trade. Drying ensures water evaporation from agricultural products to the drying medium- usually hot air. Drying plays a vital role in the preservation of agricultural products (Amma, 2014).

Conservatively, many cereal crops, vegetables and fruits are dried by thinly spreading them on a prepared ground, mats, and paved ground in open sunlight. Large losses are generally incurred as a result of using this method. The losses are attributed to birds,

rodents, domestic animals and the wind blowing the product beyond recovery (Bolaji, 2005). High humidity levels associated with tropical environments has been contributing immensely to crop lost to fungal and microbial degradation (Drew, 2011). The further disadvantage of this open air sun drying technique is lack of control over the drying rate which results in under drying or over drying (Bolaji, 2005). Controlled Solar drying gives quality end product, rapid drying and more hygienic product.

Many dryer types have been in used in both domestic and industry sectors. The simplicity of design and economic consideration make cabinet dryer most extensively used. A cabinet dryer consists of several stacks of trays placed in an insulated chamber in which hot air is distributed by a fan or natural flow (Misha*et al.,* 2013). The major shortcoming of the cabinet dryer is uneven drying because of poor air flow distribution in the drying chamber. Good air flow distribution in the drying chamber will help in attaining uniform moisture contents of the products being dried on different a tray.

Solar energy application requires efficient thermal energy storage so that the excess heat collected during high insolation may be stored for later use during low insolation, cloud cover, rains and even in the night. Due to the intermittent nature of solar energy, an integration of energy storage material with the solar collectors is necessary in order to make the solar energy source more consistent (Kamble*et al.,* 2013).

1.2 Problem Statement

The inadequate method of preserving agricultural produce which is usually produced in larger quantities during harvest has remained one of the main problems facing Nigerian farmers. High crop losses due to inadequate drying, fungi attacks, insects, birds, rodent encroachment and unpredictable weather effects such as dust, rain, and the wind have remained some of the inherent limitations of the traditional open sun drying method widely being practiced by rural farmers (Eze and Agbo, 2011). The open sun drying also results in physical and structural changes in the agricultural produce such as unnecessary shrinkage, case hardening and loss of volatiles and nutrient components. (Rajkumar, 2007).Therefore, a control mode of drying which preserves the color, nutrient components and unnecessary shrinkage of the agro-produce is necessary. One of these control modes involves constructing a solar crop dryer. Different types of dryers were developed at different times and places in the world. The problem of most of these dryers is the variation of the final moisture content of the dried product at different trays position due to the poor airflow distribution, especially in a typical cabinet dryer. As the drying air goes up from the bottom tray to the upward tray, the drying rate decreases. This is because the drying air temperature into the upper tray is lower than that of the bottom tray, and also the drying air is relatively wet. Therefore, there is need to improve on the existing ones that can solve or mitigate this problem of non-uniform drying.

1.3 Present Research

The present work is concerned with the design, simulation, construction, and performance comparison of mixed-mode solar crop dryers with and without thermal storage. Two separate dryers were built; one with plane conventional flat plate absorber and the other with flat plate absorber integrated with thermal storage material. An experimental test of the dryers was done to validate the simulated results using TRANSYS 16.0 and MATLAB R2013a Softwares.

1.4 Aim and Objectives

The aim of the work is todesign, simulate,construct and carry out the performance comparison of mixed-mode solar crop dryers with and without thermal storage material integrated with the absorber for yam drying under the meteorological conditions of Zaria.

The specific objectives are to:

i. Carry outdesign analysis to determine the dimensions of the solar crop drying systems;
ii. Simulate the performance of the drying systems with and without thermal storage material under varying meteorological conditions of Zaria;
iii. Construct solar crop dryers with and without thermal storage materials; and
iv. Evaluate experimentally the performance of the solar dryers.

1.5 Justification

The escalation of fuel cost, fossil fuel depletion and high pollution potential of conventional fuels to the environment has resulted in a search for a safe alternative fuel for dryers. Solar energy is one of the most promising renewable energy sources in the world because of its abundance, inexhaustible and non-pollutant in nature compared with higher prices and shortages of fossil fuels (Rajkumar, 2007). The present study will address the problem of nonuniform drying in different trays coordinate position in solar cabinet dryer. The drying efficiency and uniformity in drying of the dried product depend on airflow distribution into the drying chamber. Proper airflow distribution will help in attaining uniform drying rate of the product being dried in the solar crop dryer and hence solve the problem of variation of moisture content of the product in the different trays coordinate position.

1.6 Scope of the Study

The scope of this research work is limited to design, simulation, construction and performance comparison of mixed-mode solar crop dryers with and without thermal storage. Using typical meteorological year (TMY) data of Zaria, TRANSYS 16.0 and MATLAB R2013a Softwares were used to predict the performance of the dryers. Performance evaluation covered determination of the amount of moisture loss, drying rate, collector efficiency and drying efficiency.

CHAPTER TWO
LITERATURE REVIEW

2.1 General Introduction on Yam

Yam is an economically useful plant belonging to the genus *Dioscorea* or the Tubers/rhizomes of the plants. Yams are cultivated for the consumption of their starchy tubers in Africa, Asia, Latin America and Oceania. The global yam production was almost 48.7 million tonnes per annum with 97% of this coming from sub-Saharan Africa. West and Central Africa accounted for 94%, Nigeria emerging as the largest producer with 34million tonnes, Cote d‟voire 5 million tonnes and Ghana 3.9 million tonnes (Amma, 2014). There are many widespread varieties of yam species, the most economic important species grown include: *Dioscorearotundata* (white yam), *D.cayenensis* (yellow yam), *D.alata* (water yam),*D.esculenta* (Chinese yam), *D.bulbifera* (aerial yam) and *D.dumentorum* (trifoliate yam) (Amma, 2014). Yam is a food security crop and a source of industrial starch in some sub-Saharan African countries. Besides, Yam plays a vital role in traditional culture, rituals and religion as well as a source of income of the African people. The utilization of yam in Nigeria has not been fully achieved due to insufficient processing technology obtainable in other developing countries. Its high moisture content poses a great challenge for its storage (Liberty *et al.*,2013).

2.2 Solar Dryers and Drying Principle

Solar crop drying utilizes the sun's energy either directly, indirectly or in the mixed-mode. Air flow can be generated by either natural or forced convection. In natural convection dryers the driving force for airflow is the buoyancy while the forced convection type uses a fan to aid the air flow (Bukola and Ayoola, 2008). The drying

process can be categorized into two; constant rate and falling rate drying periods. In constant rate drying period evaporations occur at pelt surface of the material being dried. In this condition, the rate of drying is controlled by the rate of evaporation from the surface of the material being dried.As the drying proceeds, a point is reached at which the rate of transfer of moisture within the material to the surface is less than the rate of evaporation from the surface. At this point the falling rate drying period starts. In falling rate drying involves two processes; movement of moisture within the material to the surface and removal of the moisture from the surface (Abdullahi, 1995). During this process, there is a possibility of the product being dried to form dry surface layers which are impervious to subsequent moisture transfer if the drying rate is very rapid (Drew, 2011). To avoid this effect, the heat transfers and evaporation rates must be closely controlled to guarantee optimum drying rates (Rajkumar, 2007). Quick drying is enhanced by high temperature, high wind speed, and low relative humidity (Bukolaand Ayoola, 2008).

2.3 Classification of Drying Systems

Drying equipment may be classified in several ways. The two most useful classifications are based on Hii*et al.*,(2012):

1) The method of transferring heat to the wet solids

2) The handling characteristics and physical properties of the wet material.

A classification chart of drying on the basis of heat transfer is shown in figure 2.1,

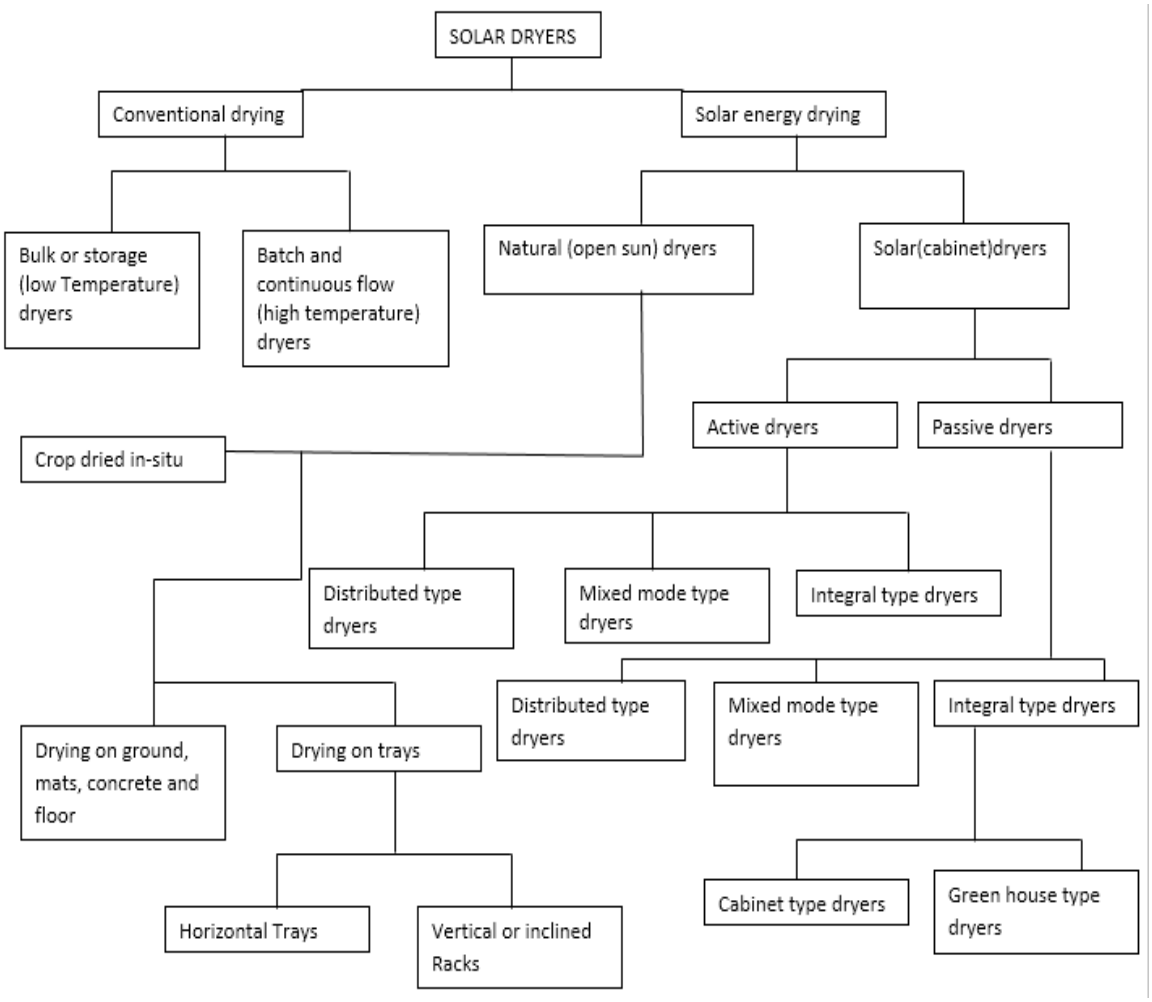


Figure 2.1 Classification of dryers and drying modes (Hii*et al.*, 2012)

In broad terms, solar dryers can be classified into two major groups namely(Hii*et al.*, 2012):

i. Passive solar energy drying systems (conventionally termed natural-circulation solar drying systems)

ii. Active Solar energy drying systems (most types of which are often termed hybrid solar dryer)

Three distinct sub-classes of either the active or passive solar drying systems can be identified namely(Hii*et al.,* 2012):

i. Direct type solar dryers

ii. Indirect type solar dryers

iii. Mixed-mode/Hybrid solar dryers

2.3.1 Types of Solar Dryer

On the basis of the mode of drying, e.g. direct or indirect, solar dryers may be classified as passive and active ones(Hii*et al.,* 2012):

A. Passive Type Solar Dryer

In passive dryers crops are dried by direct impingement from the sun's radiation with natural air circulation.

(i) Indirect Type Passive Solar Energy Dryers

These are indirect type dryers with natural convection of air for drying. In order to increase the capacity of a dryer, that is to operate with more than one layer of trays with some spaces in between consecutive trays. The additional resistance generated for the air movement due to this arrangement of the trays is achieved by the chimney effect (Hii*et al.,* 2012):

(ii) Direct Type Passive Solar Energy Dryers

Two basic types of dryers in this category can be identified as the cabinet and greenhouse dryers.

a. Solar Cabinet Dryers

The passive solar cabinet dryers are generally simple and inexpensive units having high applications for domestic purposes. The required air circulation is maintained by the

warm moist air leaving through the upper vent under the action of buoyancy forces and generating suction of fresh air from the inlet base.

b. Greenhouse Dryers

These are also known as tent dryers and are basically modified greenhouses. They are designed with vents of appropriate size and position to have a controlled air flow. They are characterized by extensive glazing cover of transparent glass or polyethylene sheet.

(iii) Mixed-Mode Type Passive Solar Energy Dryers

The mixed-mode type passive solar energy dryers would have the same typical structural features as the indirect type and in addition has glazed walls inside the drying chamber so that the solar radiation impinges directly on the product as in the direct type dryers.

B. Active Solar Drying System

In active solar drying system, hot drying air is circulated by means of a ventilator (forced convention)(Hii*et al.*, 2012).

(i) Indirect Type Active Solar Drying Systems

These active dryers have a separate collector and drying unit. They are generally comprised of four basic components viz: a solar air heater, drying chamber, a fan for air circulation and ducting.

(ii) Direct Type Active Solar Energy Drying Systems

The direct type active solar dryers are designed with an integrated solar energy collection unit. Three distinct types of direct type active solar dryers can be identified. The absorption dryers, Storage dryers and Greenhouse dryers.

(iii) Hybrid Type Active Dryers

The hybrid dryers combine the features of a solar energy with a conventional or some auxiliary source of energy and can be operated either in combination or single mode with either source of energy (Hii, *et al.*, 2012).

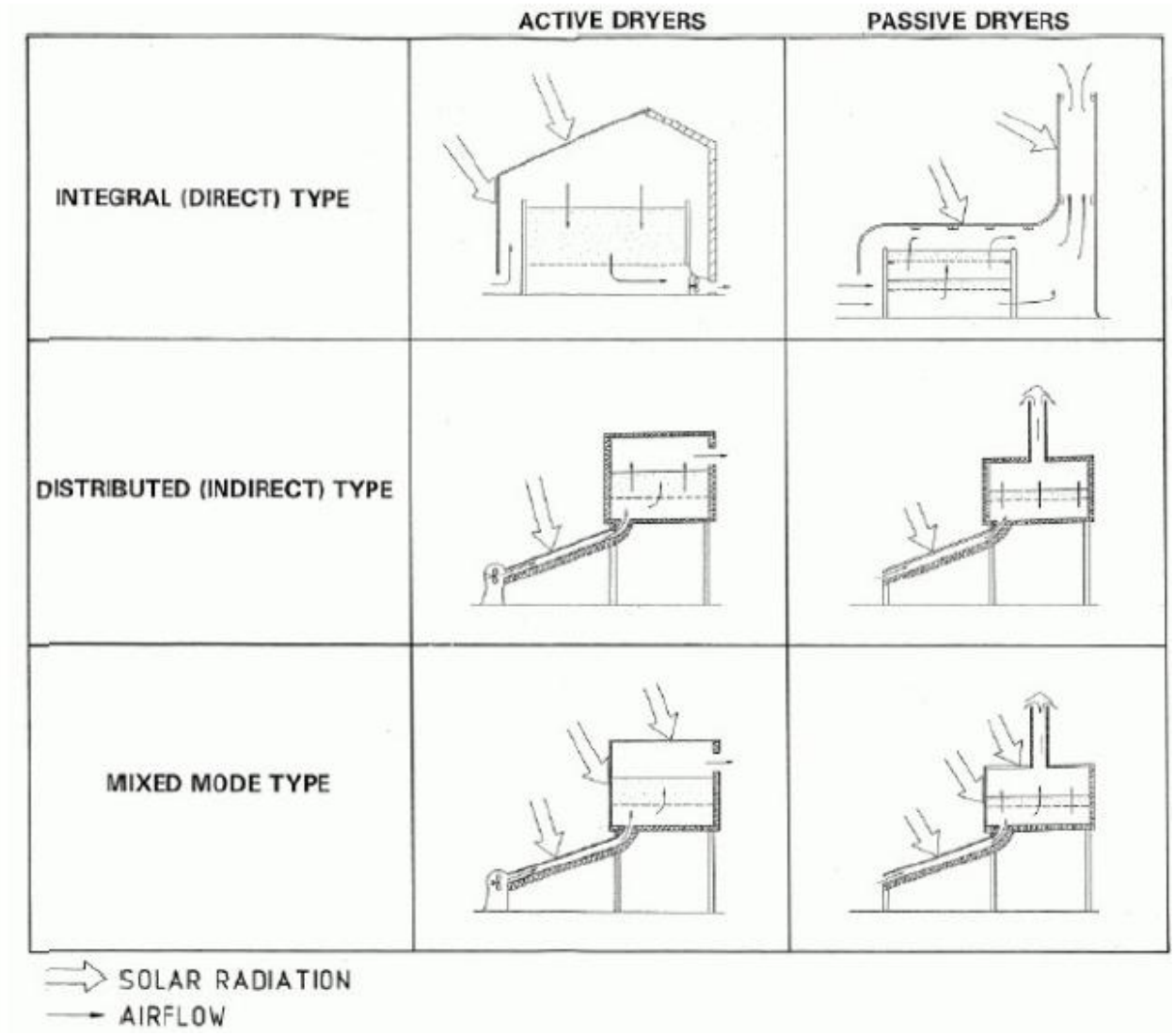


Figure 2.2: Typical Solar Energy Dryer Designs (Ekechukwu and Norton, 1999)

2.4 Theoretical Background of Solar Energy

Some very important terms frequently used to describe the relationships of some solar geometry and the nature of solar radiation availability are described below:

2.4.1 Solar constant

The actual amount of thermal radiation received from the sun, defined as the solar constant measured at a mean distance from the earth's surface. The value of the solar constant varies with each investigator. From 1913-1953, the most widely used and accepted value proposed by C.G Abbott, was 1357 W/m^2 with variation of $\pm$1.80% (Duffie and Beckmann, 1991).

2.4.2 Declination

Declination is the angle between the sun-earth center line and the projection of this line on the equatorial plane. Declinations north of the equator (summer in the Northern Hemisphere) are positive, and those south are negative (Duffie and Beckman, 1991).

$$\delta = \left(23.45 sin\left(2\pi \frac{n+284}{365}\right)\right) \text{degrees} \quad (2.1)$$

n= number of days

δ = declination

Declination varies from -23.45 degrees on December 21 and +23.45 on June 21. According to Duffie and Beckmann (1991), the solar declination during any given day can be considered constant in engineering calculations. Below is a table that gives the recommended average days for the months and the corresponding value of day of the year (n) by the month.

Table 2.1 Average days for the month and the corresponding values of n by month

Month	n for ith Day of Month	Date	n, day of the year	Declination (Degrees)
January	i	17	17	-20.9
February	31+i	16	47	-13
March	59+ i	16	75	-2.4
April	90+i	15	105	9.4
May	120 +i	15	135	18.8
June	151 +i	11	162	23.1
July	181 +i	17	198	21.2
August	212 +i	16	228	13.5
September	243 +i	15	258	2.2
October	273 +i	15	288	-9.6
November	304 +i	14	318	-18.9
December	334 +i	10	344	-23

Duffie and Beckmann, (1991)

2.4.3 Incidence angle

The solar incidence angle θ is the angle between the sun's rays and the normal on a surface. For a horizontal plane, the incidence angle θ and the zenith angle θ_z are the same. (Duffie and Beckman, 1991)

The solar incidence on the surface can be obtain from the relationship (Duffie and Beckmann, 1991)

$\cos\theta = \cos\emptyset \cos\gamma \sin\beta + \sin\emptyset \cos\beta$(2.2)

where,

γ = surface solar azimuth angle (degrees)

β = surface tilt angle from the horizontal (degrees)

2.4.4 Hour angle(ω)

The hour angle is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. For example, at 7am (solar time) the solar hour angle is equal to -75 degrees (7 a.m is five hours from noon, the negative sign indicates morning). The solar hour angle is given by (Duffie and Beckmann, 1991) as

$\omega = 15(S_T - 12)$ degrees(2.3)

$$S_T = solar\ time$$

2.4.5 Sunset hour angle (ω_s)

The sunset hour angle on an inclined surface is the solar angle corresponding to the time when the sun set. It is an indication of how long the sun is up during the day. It is given by (Duffie and Beckmann, 1991):

$\omega_s = \cos^{-1}(-\tan\emptyset \tan\delta)$degrees(2.4)

2.4.6 Extraterrestrial solar radiation on a horizontal surface

The theoretically possible radiation that would be available if there were no atmosphere is referred to as extraterrestrial radiation (Duffie and Beckmann, 1991).

$G_o = G_{sc}\left(1 + 0.033\frac{\cos\ 360n}{365}\right)\cos\theta_z$(2.5)

$$G_{sc} = Solar\ Constant$$

It is often necessary for calculation of daily solar radiation to have the integrated daily extraterrestrial radiation on a horizontal surface(Duffie and Beckmann, 1991).

$H_0 = \frac{24 \times 3600\, G_{sc}}{\pi}\left(1 + 0.033cos\left(360\frac{n}{365}\right)\right)(cos\emptyset \cos\delta\ sin\omega_s + \frac{\pi}{180}\omega_s \sin\emptyset \sin\delta\ )$(2.6)

The monthly mean daily extraterrestrial radiation $\overline{H_o}$ can also be calculated using n and δ for the mean day of the month.

2.4.7 Solar radiation at the earth surface

The Intensity solar radiation is reduced when passes through the atmosphere due to depletion of direct radiation, which occur by scattering and absorption due to air molecules, dust, water vapor and ozone. The total solar energy reaching the earth's surface is the sum of direct and diffuse components. Solar radiation intensity is affected

by season, latitude, altitude, degree of cloudiness and orientation of the receiving surface.Given by (Duffie and Beckmann, 1991)

$I_T = I_D + I_d$(2.7)

I_D =Direct incident solar radiation,(W/m^2)

I_d =Diffuse solar radiation,(W/m^2)

2.4.8 Direct solar radiation

The direct normal radiation at the earth's surface on a clear day I_{DN} is represented as given by Gayanilo(1980).

$$I_{DN} = \frac{A}{exp\left(B/\sin \alpha\right)} \quad (2.8)$$

where,

A= apparent solar radiation at the air mass, (dimensionless)

B= atmospheric extinction coefficient, (dimensionless)

α= Solar altitude angle, (degrees)

The solar altitude angle can be obtained from

$$\sin \alpha = \cos \emptyset \cos \delta \cos w + \sin \emptyset \sin \delta \quad (2.9)$$

where,

$\emptyset$= latitude angle of location, (degrees)

δ= declination angle at the date in question, (degrees)

ω= absolute value of solar hour angle, (degrees)

The direct incident solar radiation, I_D that falls on any surface on earth is therefore expressed as

$I_D = I_{DN} \cos\theta$ W/m^2 (2.10)

θ =the angle of solar incidence on the surface, (degrees)

2.4.9 Diffuse solar radiation

The diffuse radiation component I_d, is given by Gayanilo (1980) as:

$I_d = C\ I_{DN} F_{SS}$ (2.11)

C = diffuse radiation factor, (dimensionless)

F_{SS}= angle factor, (dimensionless)

$F_{ss} = \frac{1+\cos\beta}{2}$ (2.12)

2.4.10 Ratio of beam and diffuse radiation on tilted surface to that on the Horizontal

The most commonly available data are total radiation for hours or days on the horizontal surface, whereas the need is for beam and diffuse radiation on the plane of a collector (Duffie and Beckmann, 1991). Therefore, orientation factor to convert the direct horizontal radiation to incidence on tilted surface is necessary. The geometric factor R_b, i.e. the ratio of beam radiation on tilted surface to that on horizontal surface at any given time is given by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (2.13)$$

The optimum azimuth angle for tilt collector is usually zero degrees in the northern hemisphere. For $\gamma = 0$,

$$R_b = \frac{\cos(\emptyset-\beta)\cos\delta\cos\omega+\sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\cos\omega+\sin\emptyset\sin\delta} \text{(Duffie and Beckmann, 1991)} \quad (2.14)$$

The diffuse geometric factor/ orientation factor is the same as angle factor F_{ss}

Such that,

$$I_T = I_D + I_d = HR_D + HR_d \quad (2.15)$$

R_D, R_d (dimensionless) are the direct and diffuse orientation factors respectively.

H= Insolation rate on a horizontal surface, W/m^2

2.5 Thermal Storage

Thermal energy storage may be in the form of sensible heat of a liquid or solid medium. The choice of storage media depends on the nature of the application (Duffie and Beckmann, 1991). There are many thermal energy storage (TES) materials that are available for solar thermal application. The most common materials are the rock beds, aluminium composites, water, and paraffin wax. They work as sensible heat in solid (SHS), latent heat in storage (LHS) or both types of heat storages. The use of metal media is advantageous where high thermal conductivity is required and where cost is of the secondary priority.

Energy storage materials can be divided into two broad types(Abhishek and Varun, 2013):

i. Sensible Heat in Solid (SHS): They store energy in the form of sensible heat and the material experiences an increase in temperature without undergoing a change in its phase.example rocks or liquids such as water.

ii. Latent Heat Storage (LHS). The latent heat of fusion in some chemical compound is utilizes, example Paraffin waxes and inorganic salts. The heat storage medium absorbs the heat added and undergoes a phase transition from the solid to liquid state at a desired temperature within the operating temperature range of temperature provided by solar heat collectors.

Many materials are available for thermal storage. A packed bed storage unit uses the heat capacity of a bed of loosely packed particulate material to store energy. A variety of solids may be used, rock being the most widely used material (Duffie and beckman, 1991).

Well-designed packed beds using rocks have several characteristics that are desirable for solar energy applications (Duffie and beckman, 1991).

2.6 Review of Related Past Work

Sun is the cheapest source of renewable energy. Sun-drying is the most common method used to preserve agricultural produce in most tropical and sub-tropical countries (Rajkumar, 2007). Great number of researchers have over the years work on solar energy drying system.

2.6.1 Direct Mode Solar Dryers

The design, construction and performance evaluation of a simple solar cabinet dryer for food preservation was carried out by Bolaji(2005). The transparent top cover was a clear polyvinyl chloride (PVC) plastic sheet and the dryer cabinet was made of plywood. The average temperatures in the dryer and ambient air were found to be 47.3℃ and 31.3 ℃ during the day light respectively. The experimental drying rate and drying efficiency was found to be 0.46kg/h and 59% respectively.

The design and fabrication of an efficient cabinet solar dryer was carried out by Vidya*et al.*, (2013).The designed collector area of $1m^2$ was expected to dry 20kg fresh vegetables from 89.6% to 13% wb in two days. A prototype of the dryer with $1.03m^2$ solar collector area was constructed and used in the experimental drying test. 3000 grams of potatoes was dried to 920grams and 550 grams in open and cabinet dryer in two days of drying respectively. 2080 grams and 2450 gram of moisture was lost in the open and cabinet dryer respectively. 3000 grams of bitter-guard was dried to 790 grams and 470 gramsrespectively in two days of drying. 2210 grams and 2530 grams of moisture was lost in the open and cabinet dryer respectively. 3000 grams of chillies was dried to 2430 grams and 1755 grams in open and cabinet dryer respectively.570 grams and1245 grams of moisture was lost in the open and cabinet dryer respectively. The collector efficiency was found to be 30 %.

The design, construction and testing of direct solar dryer was carried out by Salaudeen (2015). The solar dryer consists of drying chamber with a transparent glass cover, a wooden frame and a single tray. The interior of the drying chamber was painted black and it was designed to accommodate and dry one kilogramme of pepper. From the

experiment conducted the percentage moisture lost (wet basis) for 400g, 300g and 300g of pepper were 75%. 66.6% and 67% respectively. The maximum temperature rise for the system was 69 ℃ and the system efficiency was 32%.

2.6.2 Indirect Mode Solar Dryers

An indirect type natural convection solar dryer with integrated collector- storage solar and biomass back up heaters has been designed, constructed and evaluated by Mandhlopa and Ngwalo (2007). The major components of the dryer are biomass burner with a rectangular duct and chimney, thermal storage material and drying chamber. The dryer was tested in three modes of operation (solar, biomass and solar-biomass) by drying twelve batches of fresh pineapple with each batch weighing about 20 kg. The average values of the final-day moisture pick up efficiency were 15, 11, and 13% in solar, biomass and solar-biomass modes of operation respectively.

Comparative performance of solar cabinet, vacuum assisted solar and open sun drying methods was carried out by Rajkumar (2007). A laboratory model of solar cabinet and vacuum assisted solar dryers were developed to study the drying kinetics of tomato slices (4, 6 and 8mm thickness) and the result were compared individually with open sun drying under the weather conditions of Canada. During drying, it was observed that the temperature inside the solar cabinet and vacuum chamber were increased to 63 ℃ and 48 ℃ when the maximum ambient temperature was only 30℃. The tomato slices of 4, 6, and 8mm thickness could be dried from 94 to 11.5 % wet basis moisture content respectively in 300, 420 and 570 minutes using solar cabinet, in 360, 480 and 600 minutes using vacuum assisted solar dryer and it took 435, 615 and 735 minutes under open sun drying method. The effective moisture diffusivity values were found to be 4.25 -7.67$\times 10^{-7}$ m^2/s in solar cabinet dried slices and 3.09 – 9.28 $\times 10^{-9}$ m^2/s in open sun dried tomato slices of 4 to 8 mm thickness.

Simulation of a solar crop dryer for drying agricultural products was developed by Habtamu (2007). A thermal solar collector model is developed to determine the available useful energy for heating the ambient air with the available solar radiation. A computer program was written to predict the collector outlet air temperature, mass flow rate and

also done for the drying chamber. Results of the system simulation were presented in graphical form suitable for system performance determination. A model was developed with 2 m^2 flat plate collector area. The initial moisture content of local cereal ranges from 16 – 30 % was reduced to the final or equilibrium moisture content ranges from 10 – 12 % wb. However, the materials at the entrance are dried, while those at the exhaust are under dried.

A simple solar maize dryer was designed, constructed and tested by Folaranmi (2008). Polystyrene was used as the insulating material. The absorber plate was an aluminium sheet painted black of size 100mmx50mm and a cover glass thickness of 5mm thickness. The maximum temperature in the drying chamber was found to be above 45 ℃ and the moisture content (20 %) of 5kg of maize was reduced to about 12.5% in three days of 9hrs each day of drying.

Assessing the drying rates of vegetables, tubers and grain crops was accomplished by Ajao and Adedeji (2008). Four tropical crops in the passive type solar dryer were considered. High drying rate at an average dryer efficiency of 18% was recorded for yam at an average value of 9.0 g/hr and lowest was recorded for pepper at 1.6 g/hr.

An indirect forced convention solar dryer combined with heat storage material for chili drying was designed and fabricated by Mohanraj and Chandrasekar (2009). The chili moisture content of 72.8% wb was reduced to 9.1 % and 9.8 % wb in the bottom and top trays respectively. The fresh chilies were loaded over the trays of the dryer chamber having about 90% perforation. The thermal efficiency of the solar dryer was found to be 21%. The extraction rate was found to be 0.87 kg/kWh.

The design and construction of an indirect solar dryer with a heat storage chamber for drying maize seed was developed by Lukman (2010). The dryer was made up of a solar collector, drying chamber, and a heat storage chamber (filled with gravels). The experimental test results gave temperature above 45 ℃ in the drying chamber. 5 kg of maize at 30% initial moisture content was reduced to 13% in three days of 9hr each day of drying.

A study by Krishnananth and Kalidasa (2012) revealed how solar collector was designed and fabricated. An integrated double pass solar air heater with thermal storage system was developed. Paraffin wax used as a thermal storage medium. A double pass solar air heater of 750mm Length x500mm width x 182mm height was fabricated using mild steel plate. The collector top was covered with a 4mm glass plate. Experiments were conducted with solar air heater for four different configurations. In configuration 1, no thermal storage was used, where as in other configurations the capsules were placed in different places in line with flow direction. The flow rate was estimated as 0.02 kg/s. the study concluded that the configuration with thermal storage perform better.

A mixed mode solar dryer was constructed and tested by Sean (2013). A box-type chimney and collector type chimney performance were compared. The relative humidity change across the dehydrator was most affected by the number of trays, but the chimney type did have an effect on the relative humidity at the chimney exit. The box type chimney was more efficient than a collector type. The efficiency of the collector ranges from 25 – 51 % for the testing period. The results revealed that the dryer was more efficient when using the maximum number of trays.

The solar cabinet dryer coupled with gravel bed heat storage system was evaluated for drying of green chilli by Kamble*et al.,* (2013). The loading capacity of the dryer was about 15 kg of fresh produce per batch. An exhaust fan was provided in the drying chamber to suck the hot air from gravel bed heat storage during off sunshine hours for better heat retrieval. The temperature was recorded in the solar dryer at three positions viz., lower, middle and upper drying trays using thermocouples and average temperature was observed in the range of 25 to 55°C. Drying time for drying green chilli from initial moisture content of 88.5% (wb) to 7.3% (wb) was estimated to be 56 h in solar dryer whereas 104 h was observed in the open sun drying. Drying efficiency of the solar cabinet dryer was found to be 34 %.

An indirect passive solar dryer was designed, constructed and simulated using TRANSYS simulation software and Engineering Equation Solver (EES) by Musa (2016).

The dryer was designed to accommodate a total quantity of 6 kg of tomatoes at a time and was tested by monitoring the hourly temperature variation of the ambient temperature, collector air temperature, drying chamber temperature and chimney temperature for four days of testing. The average result show that percentage moisture loss was 92.4 % wet basis. The calculated system drying efficiency and the collector efficiency were 69.6 % and 31.33 %. The simulated results were compared with the experimental results to determine the level of agreement between the experimental and the simulated results. However, there was a significant variation of drying rates with the coordinate position of the trays.

2.6.3 Summary of the Solar Dryer Review

A detailed literature review on solar drying has been carried out. From the accessible literatures, problems were identified with the existing design of the solar dryers. Poor airflow distribution in the drying chamber being the foremost. Crops on the tray at the bottom of the drying chamber dry faster than those at the top tray; this causes over drying of the crops at the bottom tray and under drying at the top tray. Over drying causes case hardening and makes crops not suitable for use as seed while under drying causes mold formation. The improved design is targeted at eliminating or reducing non-uniformity of drying and increases dryer efficiency. The gap identified in the literatures reviewed helped in identifying the objectives of this dissertation.

CHAPTER THREE
MATERIALS AND METHOD

3.1 Description of the Two Solar Crop Dryers

The solar dryers consist of the following components.

i.) **Solar Collector**: The collector which is essentially the air heater is an insulated box with a transparent glass cover. The collector was separated from the drying chamber by a duct, one side was opened to let the atmospheric air into the collector and the other end was connected to the air-duct. The connecting- air-duct was then connected to the drying chamber. During sunlight exposure, the absorber heats both the air and the thermal storage material. The storage material emits the stored energy during low sunshine hour and cloud cover.

ii.) **Absorber**: This was made up of black painted galvanized iron sheet metal, which absorbs the solar radiation. The black paint enhances the absorptivity of the galvanized sheet. A good absorber is needed to raise the temperature of the collector. Sean (2013) describes a good absorber as one that absorbs almost all the incoming radiation, lose a small portion to the surroundings and efficiently transfer the absorbed solar energy to the passing air within the collector.

iii.) **Thermal Storage Materials**: The storage material collects heat during sunlight exposure (high insolation) and dissipates during low sunshine, cloud cover and rains. A

thermal storage (gravels) was integrated with one of the collectors and the other has only a plain absorber.

iv.) **Drying Cabinet**: It houses the wire mesh trays in which the yam slices were spread on. At the side of the cabinet, chimneys were provided to facilitate and control the convective flow of air through the dryer. The two opposite sides of the drying chamber were glazed to collect additional solar radiation. This further increases the convective air flow and additional heating necessary for drying. Access door to the drying chamber was also provided. The interior of the drying cabinet was painted black to enhance elevated temperature within the dryer.

v.) **Tray**: The black painted trays were constructed from strong wire mesh that can be easily slotted and removed for maintenance purpose. The trays were designed for easier cleaning, loading and offloading of the yam slices.

vi.) **Support**: The supporting structure bears the load of the drying cabinet and the air heater. It was constructed from mild steel material.A sketch of the front view of the mixed-mode solar crop cabinet dryer is shown in figure 3.1.

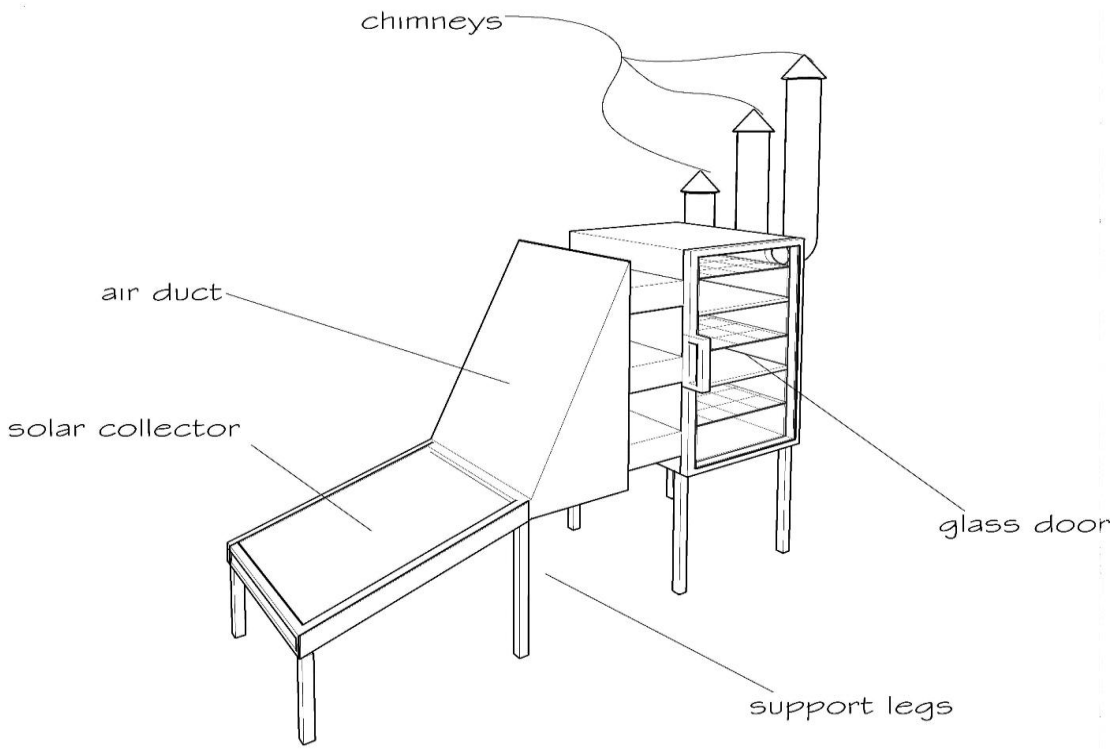


Figure 3.1 View of the Mixed-mode Solar CropDryer

3.2 Working Principle

The dryer is a passive type, sun's rays entering through the transparent top cover are being trapped, and trapping of the rays is enhanced by the black painted absorber. The greenhouse effect achieved within the dryer drives the air current necessary for faster drying. The yam slices were put on trays inside the drying chamber. Air enters through the open bottom end of the collector and it was heated while it passes over the absorber with and without thermal storage. The warm air outlet of the collector was connected to a duct to aid the airflow and distribution, the hot air is then channeled and distributed into the drying chamber. The heated air is allowed to flow over the wet yam slices and provided the heat for moisture evaporation by convective heat transfer between the hot air and the wet yam slices. Drying takes place due to the difference in moisture concentration between the drying air and the air in the vicinity of the yam slices surfaces.

3.3 Materials

Strength, cost effectiveness, availability, hygiene and non-reactivity of the materials with the yam slices were considered in the design.

3.3.1 Material Selection

i.) **Solar Collector**: The insulated box with a transparent glazing was constructed using a galvanized iron sheet metal. The collector is made up of absorber, transparent covering (glazing), and heat storage material in one of the collectors. Different materials are available for absorbers among which the dark materials are preferred due to their high absorptance. Treated black material with high absorptance and low long wave emittance are the most preferred absorber material (Sean, 2013). Galvanized steel naturally has a high absorptance and low long wave emittance. Hence, it was chosen as the absorber material in this work. Rock being the most widely used material with low cost was used as the storage material (Duffie and Beckman, 1991).

ii.) **Glazing**: Glazing is the top cover of a solar collector. Usually the common materials used for glazing materials are glass and polythene material. It performs three major functions in particular: To minimize convective and radiant heat loss from absorber, to transmit the incident solar radiation to the absorber plate with minimum loss, and to shield the absorber plate from outside environment. Therefore, factors for consideration in selecting glazing materials in this work include strength of material, durability, non-degradability when exposed to the UV ultra violet light. Polythene materials are transparent to long wavelength radiation and are therefore less effective in reducing radiated heat losses from the absorber plate. In addition, polythene cannot withstand high temperature encountered in collector especially when the collector is idle (Ramadhani*et*

al., 2014).Hence,glass was selected as the glazing material.Both the top of the collector and the drying cabinet sides were having a transparent glass cover to provide heating through the greenhouse effect.

iv.) **Insulation**: A wide range of insulation materials are available such as polyurethane form, expanded polystyrene, fiber glass, cork and plywood which are used to minimize heat loss from the collector. Selection of insulating material should be based on initial cost, effectiveness and durability. From an economic point of view, it may be better to choose an insulating material with a low thermal conductivity.In the present work, fibre glass was used to insulate both the air heaters and theremaining two sides of the drying chambers. Fiber glass was used as the insulating material, because it offers a lot of advantages such as: high resistance to fire, high resistance to microbial attack, high heat resistance and low thermal conductivity.

v.) Connecting Duct: Galvanized steel sheet was used to construct the duct and it was well insulated to prevent heat loss to the surrounding which will result in decrease in pick up efficiency of the dryer.

vi.) Drying Chamber: The drying chamber consist of chimneys, trays and transparent glassing. The drying cabinet alongside the structural support of dryer was built from a metallic material (galvanized sheet) which could withstand the unfavourable weather condition. Wooden cabinet are susceptible to termite attacks and buckling when exposed to rain and other weather conditions. Glass was selected as the glazing material for additional heating at the drying chamber because of it high transmitivity to short wave radiation. Chimneys are used to generate buoyant forces on the air, thereby increasing the rate of air flow through the dryer. The chimneys were fabricated from galvanized sheet

material. There are a lot of materials for use as trays, among which wire mesh have been extensively used. Wire mesh with relatively big hole sizes are used for drying materials with larger surface area such as meat pieces, vegetables and yam slices (Sean, 2013).

3.4 Design Considerations

The following parameters were considered during the design of the solar dryers:

a- Properties and the Quantity of the Material to be dried.

Solar drying system must be properly designed in order to meet particular drying requirement of specific products and to give optimal designed (Forson*et al.*, 2007). The initial and final moisture content of tuber crop (Yam) was obtained from literatures as given in Table 3.1.

b- Inclination of the Solar Collector

The flat plate solar collector is always tilted and oriented in such a way that it receives maximum solar radiation during the desired season of used. The best stationary orientation is due south in the northern hemisphere. Therefore, solar collector in this dissertation was tilted 10° more than the local geographical latitude of Zaria with respect to the horizontal. The inclination also allows easy runoff water and enhances air circulation (Bukola and Ayoola, 2008).

c- Average Meteorological Data for Zaria used for the Design of the System.

Meteorological data were obtained from the Nigerian College of Aviation Technology, Zaria, from 2010-2014. The month with the least solar insolation was found to be August, which also falls within the harvest period of yam. Therefore, it's considered as the design month.

Table 3.1: Design Specifications and Assumptions

Items	Optimum values and assumptions
Location and Latitude	Zaria (Latitude11.2°)
Crop	Yam(design)
Design Capacity	7.0 kg (design)
Bulk density	660 kg/m^3 (Ruth *et al.*,2012)
Max. allowable temperature for yam drying	65 ℃ (Papade and Boda, 2014)
Initial moisture content	60-80 % (Jelle, 2003)
Final moisture content	17 % (Bolaji, 2005, and Liberty *et al.*,2013)
Average Yam Slice Thickness	5 mm (Bolaji, 2005
Drying time per day (sunshine hours	5 hours average for 5 years (2010-14)
Drying Period	August
Wind speed	1.52 m/s average for august 2013
Ambient temperature	28.6℃ Average for August for 5 years
Incident Solar Radiation (H)	18.0 MJ/m^2/day (2010-2014)
Collector type	Flat Plate
Collector tilt angle	21° (Bukola and Ayoola, 2008)
Collector Efficiency	30-50% (Tonui *et al*., 2014)
Maximum Collector Temperature	70 ℃ (Amrutkar, 2012)
Thermal Storage Material	Gravel (design)
Size and volume of the gravel	25 mm and 6.99×10^{-3} m^3
Absorber thickness	0.8-1.0 mm (Vidya *et al.,* 2013)
Collector Channel Depth (Air gap)	70 mm (Papade and Boda, 2014)
Glazing thickness	4-5 mm (Vidya *et al.,* 2013)
Thickness of Insulation	25 mm
Vertical Distance between adjacent trays	300 mm (Design)

3.5 Design Theory

Assumptions underlying the design

i. The collector operates under steady state conditions.

ii. There is one dimensional heat flow through back and edge of the insulation.

i. Glazing cover material is thin.

ii. There is one dimensional heat flow through the cover.

iii. The effect of dust and dirt on the collector is negligible.

iv. All empirical equations used are valid for the design

3.5.1 Solar Radiation

Two types of solar radiation data are widely available. The first is monthly averaged daily total radiation on a horizontal surface H. the second is hourly total radiation on a horizontal surface I for each hour for extended periods such as one or more years (Duffie and Beckmann, 1991).

The instantaneous measured values are called irradiance and values integrated over some period of time are termed irradiation. Radiation are often available in form of daily and hourly radiation on a horizontal surface. Hourly radiation can be generated from typical meteorological year (TMY) data using TRANSYS package. TMY is a collation of selected weather data for a specific location.

3.6 Design Procedure for the Solar Dryers

3.6.1 Solar Collector Design

(i) Energy Balance of the Solar Collector

According to Bukola and Ayoola(2008) the energy balance on the absorber is obtained by equating the total heat gained to the total heat lose by the absorber of the solar collector. Therefore,

$IA_C = Q_U + Q_{cond.} + Q_{conv.} + Q_{Rad.} + Q_p$(3.1)

I = total radiation incident on the absorber's surface (W/m^2)

A_c = collector area (m^2)

Q_u = rate of useful energy collected by the air (W)

$Q_{cond.}$ = rate of conductive losses from the absorber (W)

$Q_{conv.}$ = rate of convective losses from the absorber (W)

Q_{Rad} = rate of long wave re-radiation from the absorber (W)

Q_p = rate of reflection losses from the absorber (W)

The three heat loss terms, Q_{cond}, Q_{conv} and $Q_{Rad.}$ combined into one term Q_L

$Q_L = Q_{cond.} + Q_{conv.} + Q_{R.}$ (3.2)

$IA_c = \tau I_T A_c$(Bukola and Ayoola,2008)(3.3)

τ = transmittance of the top glazing(dimensionless)

I_T = total radiation incident on the top surface of the collector (W)

The reflected energy from the absorber is given by the expression.

$Q_p = \rho\tau\ I_T A_c$(3.4)

ρ= reflection coefficient of the absorber

Substituting equations (3.2), (3.3), and (3.4) in equation (3.1)

$\tau I_T A_c = Q_U + Q_L + \rho\tau\ I_T A_c$

Or

$$Q_U = \tau A_c I_T (1-\rho) - Q_L$$

For an absorber, 1-ρ =α, (Duffie and Beckmann, 1991)

$Q_U = \alpha\ \tau I_T A_c - Q_L$ (3.5)

α = solar absorptance (dimensionless)

Q_L is composed of different convective and radiation parts.

$Q_L = U_L A_C (T_C - T_a)$ (3.6)

U_L = overall heat transfer coefficient of the absorber, W/m^{2}K

T_c = temperature of the collector's absorber, (K)

T_a = ambient air temperature, (K)

From equation 3.5,

$Q_U = (\alpha\,\tau) I_T A_c - \mathrm{U_L A_C}\,(\mathrm{T_C} - \mathrm{T_a})$(3.7)

$q_u = (\alpha\,\tau) I_T - \mathrm{U_L}(\mathrm{T_C} - \mathrm{T_a})$(3.8)

If the heated air leaving the collector is at collector temperature, heat gained by the air.

$Q_a = \dot{m}_a C_p (\mathrm{T_o} - \mathrm{T_a})$(3.9)

$\dot{m}_a$ = mass flow rate of air leaving the collector per unit area, (kg/s)

$\mathrm{T_o}$ = temperature of air at the collector outlet (K)

The collector heat removal factor $\mathrm{F_R}$ is the quantity that relates the actual useful energy gained by the collector (equation 3.9) to the gained by the air (equation3.7).

$\mathrm{F_R} = \frac{\dot{m}_a C_p (\mathrm{T_o} - \mathrm{T_a})}{A_c[(\alpha\,\tau) I_T - \mathrm{U_L}(\mathrm{T_c} - \mathrm{T_a})]}$(3.10)

From equation 3.10;

$Q_a = A_c \mathrm{F_R}[\alpha\,\tau I_T - \mathrm{U_L}(\mathrm{T_C} - \mathrm{T_a})$]

(3.11)

(ii) Solar Collector Area

In solar drying system design, one of the methods of sizing the collector is based on meteorological and crop parameters. The required surface area of the transparent cover for crop drying depends primarily on the heat load of the drying system given by (Kamble*et al.*, 2013).

$A_c = \frac{Q_{load}}{\eta I_T\ t_d}$(3.12)

where,

t_d= drying time,(hrs)

I_T = the total solar radiation incident on the collector surface (W/m^2).

I_T =H×R(Alamu *et al.*, 2010)(3.13)

H= horizontal radiation (W/m^2)

R= ratio of solar energy on tilted surface to that on the horizontal, (dimensionless)

η= efficiency of the collector which is between 30-50% as given by Tonui*et al.*, (2014).

(iv) Absorber Surface Area

The absorber surface area A_{ab} is approximately equal to the area of the collector A_c.The recommended collector length to width ratio is in the range of 1-2 (Tonui*et al.*, 2014). Therefore, in this work Collector length to width ratio is taken as 1.5.

$\frac{L_c}{W}$ = 1.5 (3.14)

$A_c = L_c \times W$(3.15)

Therefore, the absorber surface area becomes:

$A_{ab} = A_c = L_c \times W$(3.16)

3.6.2 Drying Chamber Design

(i) Energy Balance for Drying Process

The total energy required for drying a given quantity of food items can be estimated using the basic energy balance equation for the evaporation of water (Bolaji, 2005).

$m_w L_v = \dot{m}_a C_p (T_d - T_a)$(3.17)

L_v= Latent heat of vaporization of water from the yam slices surfaces (kJ/kg).

m_w = mass of water evaporated from the yam slices (kg)

T_d = temperature of outgoing air from the drying chamber (℃)

T_i = ambient air temperature (℃)

(ii) Drying Heat Load

The heat load is determined by the amount of crop to be dried, it's initial and final moisture contents and the time required to complete the drying operation (Kamble*et al.*, 2013).

$Q_{load} = M_w L_v$(3.18)

where,

M_w= amount of moisture to be removed (kg)

L_v= latent heat of vaporization of water from the yam slices, 2320 kJ/kg (Sengar *et al.*,2012)

(iii) Mass of Water to be evaporated from the Yam Slices

The mass of water M_w to be evaporated is estimated from the initial moisture content $M_i$and the final desired moisture content M_f (Bolaji, 2005). The total mass flow of air required for drying is determined from the amount of moisture loss from the crop (Forson*et al.,* 2007). The quantity of moisture to be removed is given by the following relationship:

$M_w = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right]$ (3.19)

where,

M_{we} = mass of the wet yam slices (kg)

$M_{i,}$= initial moisture content on wet basis (% wb).

M_f = final moisture content on wet basis (% wb)

(v) Volume of Air Required for Removing the Moisture

The total volume of air required for removing the moisture from 7 kg of yam slices is evaluated from the equation given by Forson*et al*., (2007) as:

$V_a = \frac{M_w h_{fg} R_a T_a}{C_p P_a (T_o - T_f)}$ (3.20)

where, T_f= temperature of air leaving the drying bed obtained from the following relationship.

$T_f = T_a + 0.25(T_o - T_a)$ (Forson *et al*., 2007) (3.21)

where,

R_a = gas constant (kJ/kgK)

T_o= temperature of air at the collector outlet (℃)

P_a= partial pressure of dry air in the atmosphere, (N/m^2)

C_p= specific heat capacity of air, (kJ/kgK)

(vi) Mass Flow Rate of Air Needed to Effect the Drying

The mass flow rate is given by (Tonui *et al.,* 2014)

$\dot{m}_a = \dot{V}_a \rho_a$(3.22)

Where $\dot{V}_a = \frac{V_a}{t_d}$(3.23)

t_d = Drying time per day (hrs)

V_a = total volume of air required for removing the moisture (m^3)

$\dot{V}_a$ = volume flow rate of the drying air (m^3/s)

(vii) Drying Chamber Capacity and Other Dimensions

The width of the collector (W) was considered equal to the width of the drying chamber (B).The volume of yam slices per tray can be obtained from equations given by Adzimah and Seckley(2009) as:

$V_y = W_T L_T Y_l$(3.24)

Total volume of the yam slices on the trays in the drying chamber can be obtained as;

$V_T = nV_y = nW_T L_T Y_l$(3.25)

Also, according to Balcomb (1992) the total volume can be related to the bulk density as:

$W_{we} = \rho_b V_T$(3.26)

Y_l = Thickness of the yam slices in the drying chamber, (m)

W_T = width of the tray which is equal to the width of the drying chamber, (m)

L_T = Length of tray, (m)

W_{we} = Total mass of yam slices, (kg)

ρ_b = Bulk density of yam, 660 kg/m^3 (Ruth *et al.,* 2012)

The length of the drying chamber is approximately equal to the length of the tray, $L_d \cong L_T$(3.27)

(viii) Chimney Design

To determine the height of the hot air column (chimney), it's necessary to determine the pressure drop through the drying bed. The resistance of air flow through the packed bed of agricultural produce is expressed in the form giving by Forson*et al.*,(2007).

$u = a\left(\frac{\Delta P_B}{h_L}\right)$(3.28)

where,

$u =$ Superficial air velocity (m/s), which is the volumetric flow rate divided by the cross-sectional area

h_L =Drying bed thickness, (m)

$a =$ Constant whose valueis determined experimentally. For natural convection of air through a thin layer of crop ($h_L \leq 0.2m$), the value of the constant is 0.465 m^{3}s/kg.

Total pressure drop through the system is approximately twice the pressure drop of the drying bed that is $\Delta P_T = 2 \times \Delta P_B$(3.29)

However, when all pressure drops are accounted for, experience shows that the gross pressure drop is about six times the value of ΔP_T (Forson et al., 2007) and is given by the equation.

$\Delta P_T = 6 \times (2 \times \Delta P_B)$(3.30)

Chimney height is given by;

$$H_{ch} = \frac{\Delta P_T R}{g\left(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}}\right)P_a} \quad (3.31)$$

where,

ΔP_T = the total pressure drop in the dryer in Pa

R = the gas constant = 0.287 kPa m^3/kgK

T_{dryer} = the temperature of air in the dryer in Kelvin

T_{amb} = the temperature of ambient air in Kelvin

g = the gravitational acceleration in m/s^2

Pa is the atmospheric pressure = 101.3kPa

3.6.3 Performance Evaluation of the Crop Dryers

The performance of the drying system was evaluated using the solar collector efficiency, drying rate, moisture loss, and drying efficiency of the dryer.

(i) Solar Collector Efficiency

Efficiency of a solar collector is the ratio of heat gained by the air leaving the collector to the incident solar energy over a particular time period (Bolaji, 2005). The steady state thermal efficiency of the solar collector is given by Hottel-Whillier- Bliss equation (Forson*et al.,* 2007) as:

$$\eta_c = \frac{\dot{m}_a C\rho(T_o - T_a)}{A_c I_T} \quad (3.32)$$

I_T = total solar radiation incident on the top surface, (W/m^2)

T_a = ambient air temperature, (℃)

T_o = temperature of outgoing air from the collector, (℃)

$\dot{m}_a$ =Mass flow rate of air, (kg/s)

(ii) Dryer Efficiency

Thermal performance or drying rates of the products are the key factors used for the evaluation of the solar drying system efficiency (Leon*et al.,* 2002). For natural convection solar dryer, the system efficiency can be expressed as given by Forson*et. al*,(2007) and Drew (2011)as:

$$\eta_{dryer} = \frac{M_w L_v}{I_T A_c t} \quad (3.33)$$

where;

M_w = mass of water evaporated, (kg)

L_v= latent heat of vaporization of water, 2320 kJ/kg Sengar*et al., (*2012).

t = Drying time, (hr)

A_c= Collector area, (m^2)

(ix) Percentage Moisture Loss

The quantity of moisture in percentage of the initial mass of a material can be represented on wet and dry basis and expressed as percentage given by Mohanraj and Chandrasekar (2009) as:

MC = $\left[\frac{M_1-M_2}{M_1}\right] \times 100\%$ wet basis (3.34)

M_1 = Initial mass of the yam slices, (kg)

M_2 = Final mass of the yam slices, (kg)

(x) Average Drying Rate:

The quantity of moisture removed from the food item over the drying time is given by Tonui*etal.* (2014) as:

$m_{dr} = \frac{M_w}{t_d}$ (3.35)

M_w = mass of water evaporated from the yam slices, (kg)

t_d = drying time per day, (hr)

3.7 Heat Loss from the Collector

In solar collector system, the solar energy absorbed by the absorber plate is distributed to useful gain and to thermal losses through the cover glazing, through the insulation from the bottom and edges (Habtamu, 2007).

The total heat transmitted and absorbed is given by Alamu*et al.*,(2010) as:

$I_T A_c \tau\alpha = Q_u + Q_l + Q_s$ (3.36)

Q_s = energy stored which is negligible, (kJ/kg)

Q_l = Heat loss from the collector, (kJ/kg)

Q_u = Useful energy gained by the air, (kJ/kg)

From equation 3.6 the heat loss from the collector Q_l is given by;

$$Q_l = \mathrm{U_L A_C\ (T_C\ -\ T_a)}$$

From equation 3.9 Q_u is given by;

$$Q_u = Q_a = \dot{m}_a C_p (T_o - T_a)$$

The collector overall heat transfer coefficient is given by;

$U_l = \frac{I_T A_c \tau\alpha - \dot{m}_a C_p \Delta T}{A_c \Delta T}$(3.37)

3.8 Design Calculations

Table 3.2 gives the numerical values of the dimensions of the solar drying system, obtained using the equations established in section 3.6.1(equations 3.1 -3.37).

Table 3.2: Design calculations

Initial Data	**Calculations**	**Remarks**
M_{we} = 7.0 kg M_f = 17% M_i= 80%	**(i) Mass of water to be evaporated from seven (7) kg of yam slices.** From equation (3.19) $M_w = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right]$ $M_w = 7\left[\frac{0.80 - 0.17}{1 - 0.17}\right]$	M_w = 5.31 kg
Tc = 70°C Ta = 28.6°C	**(ii) Temperature of air leaving the drying bed** From equation (3.21) $T_f = T_a + 0.25(T_c - T_a)$ $T_f = 28.6 + 0.25(70 - 28.6)$	T_f =39°C

M_w = 5.31 kg L_v= 2320 kJ/kg	**(iii) Drying Heat Load** From equation (3.18) $Q_{load} = M_w L_v$ Q_{load} =5.31 kg× 2320 kJ/kg	Q_{load} = 12.32 MJ
η =50% H=18 MJ t_d = 5 hrs R= 1.0035 I_T=18.063 MJ/m^2/day	**(iv) Solar Collector Area** From equation 3.13 I_T =H×R I_T =18MJ × 1.0035 From equation (3.12) $A_c = \frac{Q_{load}}{\eta I_T \ t_d}$ $A_c = \frac{12.32\ MJ}{0.5 \times 18.063 MJ/m^2 \times 5\ hrs}$	I_T=18.063 MJ/m^2/day A_c = 0.277m^2
$\frac{L_c}{W}$ =1.5 L_c = 0.65 m	**(v) Width of the Collector for Optimum Performance** Fom equation (3.15) Ac = L_c × W 0.277 m^2= 1.5W× W	W = 0.43 m
C_p = 1005 J/ kg K P_a = 101325 N/m^2	**(vi) Volume of Air Required for Removing the Moisturefrom the yam slices**. From equation (3.20)	

R_a = 287J/kgK T_a = 28.6 ° C M_w = 5.31 kg h_{fg} = 2358.794 kJ/kg	$$V_a = \frac{M_w h_{fg} R_a T_a}{C_p P_a (T_c - T_f)}$$ $$V_a = \frac{5.31\ kg \times 2358.794\ kJ/kg \times 287\ J/kg \times 28.6℃}{1005 J/kg \times 101325\ N/m2 \times (70-39)}$$	V_a=32.5 m^3
V_a =32.5 m^3 t_d = 5 hrs	**(vii) Volume Flow Rate of Air Needed to Effect the Drying** From equation (3.23) $\dot{V}_a = \frac{V_a}{t_d}$ $\dot{V}_a = \frac{32.5\ m^3}{5\ hrs \times 60 \times 60}$	$\dot{V}_a$ = 0.00178 m^3/s
ρ_a = 1.2 kg/m^3	**(viii) Mass Flow Rate of Air Needed to Effect the Drying** From equation (3.22) $$\dot{m}_a = \dot{V}_a \rho_a$$ $\dot{m}_a$ = 0.00178 m^3/ s × 1.2 kg/m^3	$\dot{m_a}$ = 0.00213kg/s
M_w = 5.31 kg t_d = 5 hrs	**(ix) Required Drying Rate** From equation (3.35) $m_{dr} = \frac{M_w}{t_d}$ $m_{dr} = \frac{5.31\ kg}{5\ hrs}$	m_{dr} = 1.062kg/hr
	(x) Total Volume of the Yam Slices on the Trays in the Drying Chamber	V_T =

ρ_b = 660 kg/m^3 W_{we} = 7.0 kg	From equation (3.26) $W_{we} = \rho_b V_T$	0.0106m^3
W_T = 0.43m Y_l =0.005m n= 3	**(xi) Length of the Drying Chamber** From equation (3.25) $V_T = nW_T L_T Y_l$ $0.0106 = 3 \times 0.43 \times L_T \times 0.005$ $L_T = L_d$ from equation (3.27)	L_T = 1.64 m L_d = 1.64 m
u =0.652 m/s a = 0.465m^{3}s/kg. h_L = 0.2 m	**(xii) Pressure Drop Through the Drying Bed** From equation 3.28 $u = a\left(\frac{\Delta P_B}{h_L}\right)$ $0.652 = 0.465\left(\frac{\Delta P_B}{0.2}\right)$ **(xiii) Gross Pressure Drop** From equation 3.30 $\Delta P_T = 6 \times (2 \times \Delta P_B)$ $\Delta P_T = 6 \times (2 \times 0.280)$	ΔP_B=0.280Pa ΔP_B=3.36Pa
ΔP_T =3.36 Pa R =0.287 kPam^3/kgK g = 9.8 m/s^2 T_{amb} = 301 K T_{dryer} = 338 K P_a = 101.3 kPa	**(xiv) Chimney Height** From equation 3.31 $H_{ch} = \frac{\Delta P_T R}{g\left(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}}\right)P_a}$ $H_{ch} = \frac{3.36 \times 0.287}{9.8\left(\frac{1}{301} - \frac{1}{338}\right)101.3}$	H_{ch} =2.7m

I_T= 18.063 MJ/m^2/day A_c=0.277 m^2 $\tau\alpha$=0.88 $\dot{m}_a$=0.00213 kg/s C_p=1005 J/ kgK ΔT=41.4K	**(xv) Collector Overall Heat Transfer coefficient** From equation (3.37) $$U_l = \frac{I_T A_c \tau\alpha - \dot{m}_a C_p \Delta T}{A_c \Delta T}$$ U_l =(1003.5 W/m^2×0.277m^2×0.88−0.00213 kg/s×1005×41.4K)/ 0.277m^2×41.4K	U_l=13.6 W/m^{2}K
U_l=13.6 W/m^{2}K A_c=0.277 m^2 ΔT=41.4K	**(xvi) Heat Loss from The Collector** From equation 3.6 $$Q_l = \mathrm{U_L A_C\ (T_C - T_a)}$$ Q_l = 13.6 W/m^{2}K×0.277m^2× 41.4K	Q_l = 155.96W

Table 3.3 Summary of the Dimensions of the Prototype Fabricated

S/No	Parameter	Dimensions of the fabricated dryers
1	**Solar Collector**	
	Length (L_c)	0.65m
	Width (W)	0.43m
	Area of the Collector (A_c)	0.27m
2	**Drying Chamber**	

	Length(L)	0.5m
	Width (B)	0.43m
3	**Chimney Height(H_{ch})**	0.7m

3.9 TRANSYS Simulation of Solar Collectors

Simulation models are developed for predicting the performance of the solar crop dryers. The performances of the solar collectors were simulated using TRANSYS 16 software using Typical Meteorological Year (TMY) weather data of Zaria for 19th and 20th of June 2016. The components are connected together where a given output can be used as the input of any number of other components (TRANSYS, 2003). The absorptivity of the storage material and reduction in collector channel depth were considered during the simulation of the collector with storage materials.

The TRANSYS components models used were:

i. Solar Collector (Type 73 _Solar Collector)

This component models the thermal performance of a theoretical flat plate collector containing user defined parameters such as collector area, absorber plate emittance and absorptance.

ii. Weather Data (Type 109_TMY 2)

These files contain hourly data of solar radiation, ambient temperature, wind velocity and other meteorological measures. The function of Type109-TMY2 model is to read the meteorological data from a specific data file and provide them as outputs to other simulation components.

iii. Printer (Type 25c)

Use to print user selected quantities over a period of time.

iv. Equation Component _ Mass flow rate

This component gives the ability to create equations which can be functions of outputs of other components, numerical values, or another defined equation. It is placed in the assembly panel and linked to the inputs and outputs of other components as if it were a normal component.

v. Quantity Integrator (Type 24)

Use to integrate user selected quantities over a period of time.

The outputs were processed for collector temperature, ambient temperature and solar insolation from 10:00am to 06:00pm (8 hours) for 19th and 20th days of June, 2016. Figures 3.2 to 3.5 showthe TRANSYS simulation process of the solar collector.

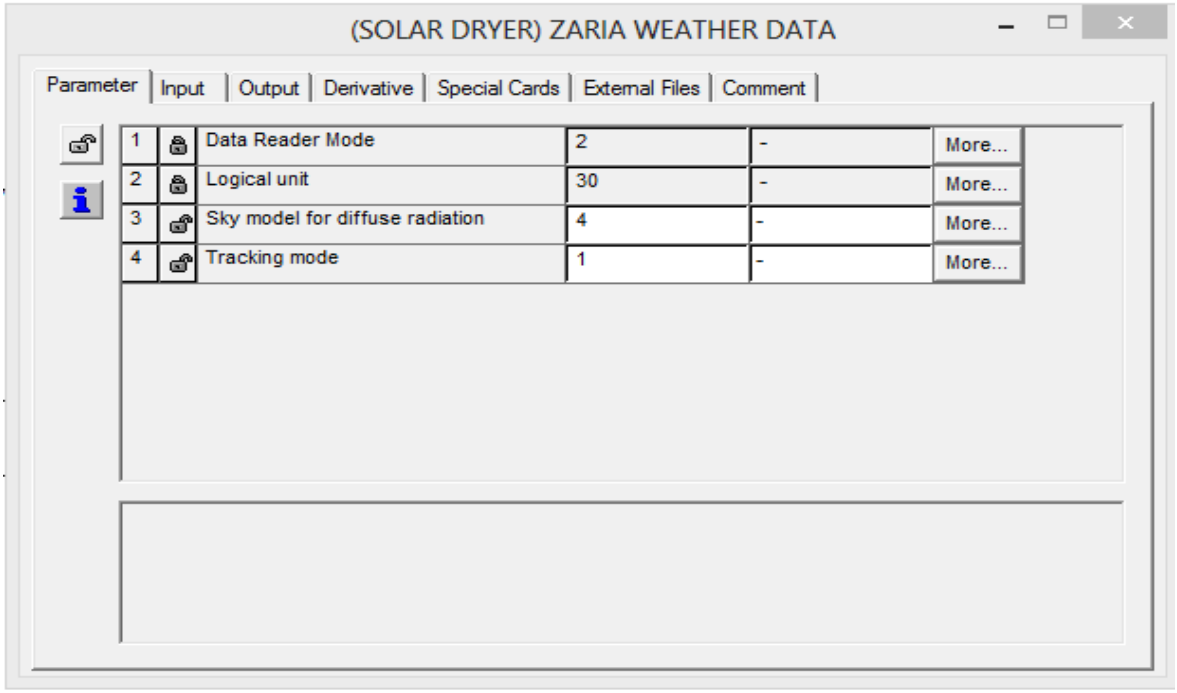


Figure 3.2: Weather data parameter

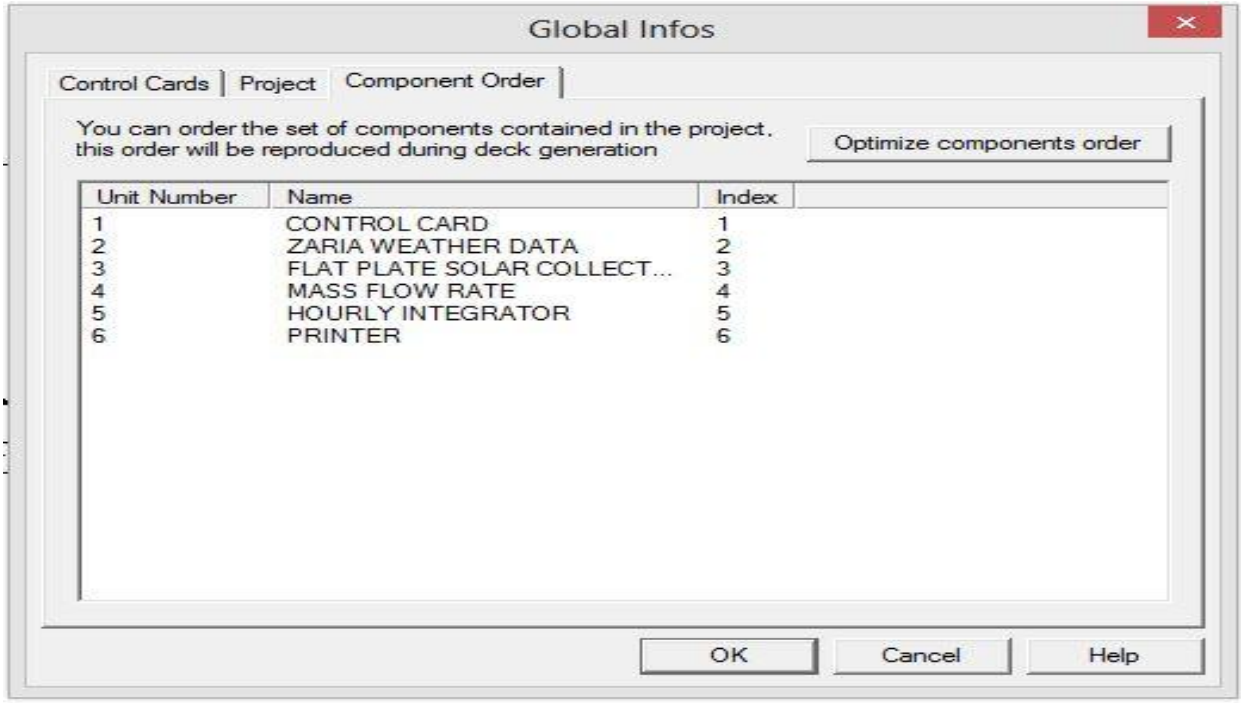


Figure 3.3: Components of Simulation

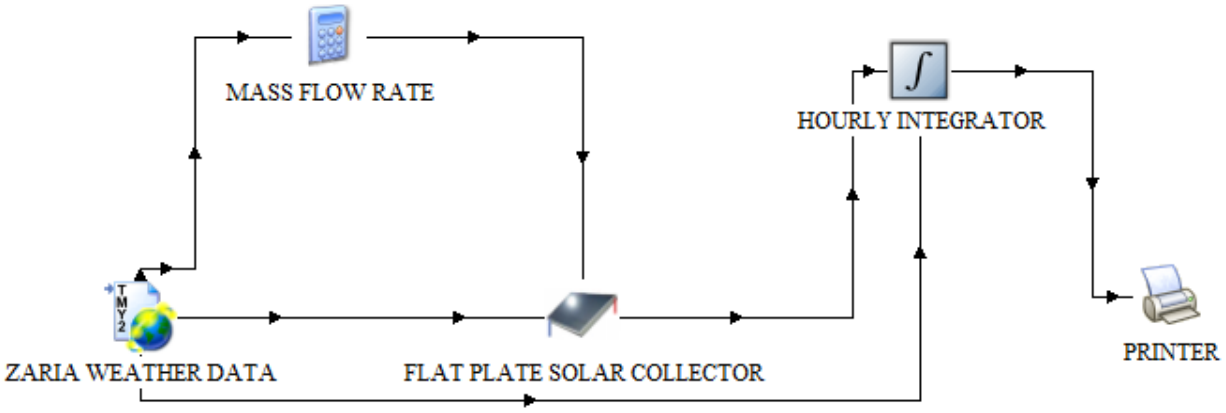


Figure 3.4: Design of the collector in TRANSYS environment

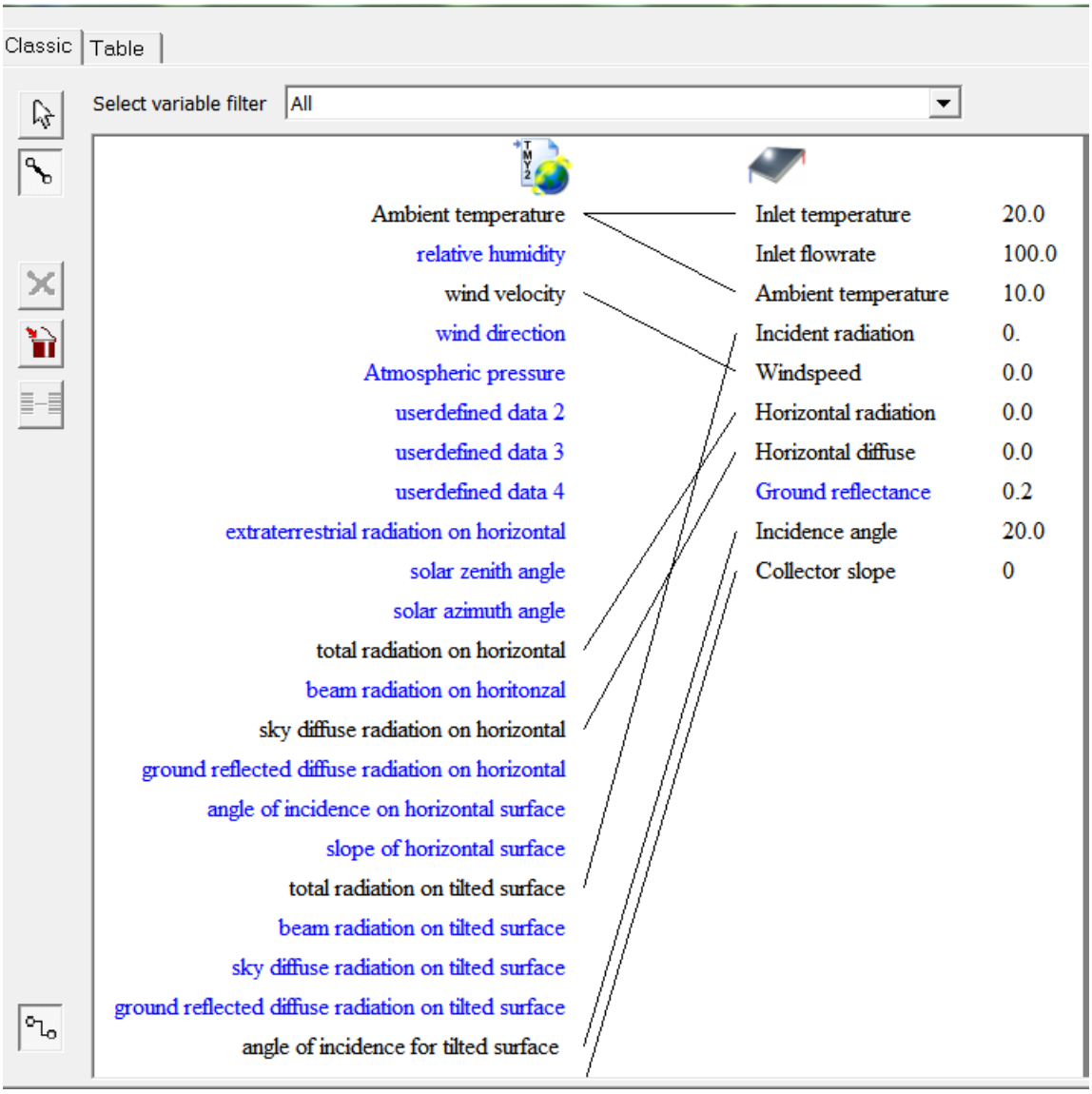


Figure 3.5: Connection of the weather data with input of the collector

3.10 Drying Modelling

The general equation of the moisture-time relation proposed by Newman can be represented by the first term (Habtamu, 2007).

$M_r = Ae^{-akt} + Be^{-bkt} + Ce^{-ckt}$ (3.38)

Where,

M_r =moisture ratio, (decimal)

k= drying constant, (sec^{-1})

t=time, (sec)

A,B,C,a,b,c=characteristic constants of the drying product.

The rate of change of moisture content of a thin layer product inside the dryer can be expressed by an appropriate thin layer drying equation. The Newton equation in differential form is (Fuller *et al.*, 2005):

$\frac{dM}{dt} = -k(M - M_e)$(3.39)

M_e =equilibrium moisture content(%wet basis)

M=moisture content at any given time(%wet basis)

where,

k =139.3exp$\left(\frac{-7676}{1.8T+492}\right)$(3.40)

T= drying temperature (K)

Weight loss during drying is given by;

$m_f = m_i \times \left(\frac{1-M_o}{1-M}\right)$(3.41)

m_f = Final weight of the crop (kg)

m_i = Initial weight of the crop (kg)

M_o = Initial Moisture Content (%wet basis)

M = Final moisture content (%wet basis)

Matlab R2013a was used to model the conditions in the drying chamber using equations 3.19, 3.39, 3.40 and 3.41.

3.11 Error Analysis and Validation of Simulation Model in Comparison with the Experimental Results

The Root Means Square Errors (RMSE) and Nash-Sutcliffe Coefficient of Efficiency (NSE) are the two statistical tools mostly used for comparing the experimental hourly collector temperatures with the predicted result from the model to determine the level of agreement between the two results. The Root Means Square Error was used to determine the level of deviation of the predicted result from the actual result. The Root Means Square Error measures the quality of fit between the actual data and the predicted model (Julien *et al.*, 2013).

The Root Means Square Error of a model prediction with respect to the estimated variable X_{model} is defined as the square root of the mean squared error (Neil, 2010).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}} \qquad (3.42)$$

where

X_{obs} is observed values

X_{model} is modelled values

The lower the Mean Absolute Error or the Bias Percentage value, the better the performance of the model (Neil, 2010).

Furthermore, the Nash-Sutcliffe Coefficient of Efficiency (NSE) defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2} \quad (3.43)$$

Where:

X_{obs} is observed value

X_{model} is modelled value

NSE is generally used to quantitatively describe the accuracy of model outputs. Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of 1 (NSE = 1) corresponds to a perfect match between model and observations. An efficiency of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (-∞< E < 0) occurs when the observed mean is a better predictor than the model (Julien *et al.*, 2013)

3.12 Solar Crop Dryer Construction

The constructions of the crop dryers were carried out at the Mechanical Engineering Department workshop of Ahmadu Bello University, Zaria. The Fabrication procedures are as presented in Table 3.4.

Table 3.4 Fabrication Process and Equipment used

S/No	Component	Fabrication Process Description	Equipment used
1	Collector	The structural frame of the collectors was formed from 25mm square pipes. Four (4) pieces of 1mm thickness Galvanized was cut to the size of 700mm× 70 mm to form the sides of the collectors, two(2) for each collector. From the remaining sheet, two (2) pieces 650mm ×430mm were cut to form the bottom of each collector. Two (2) pieces of 650mm×430mm were cut from the remaining sheet and it was painted black for maximum absorption and radiation of heat energy to form the absorber. Clear glass was cut into size of 700mm×430mm, and two (2) of these were required to form the collector cover	✓ Glass Cutter ✓ Drilling bit ✓ Scriber ✓ Tape rule ✓ Rivet Plier ✓ Hammer ✓ Plier ✓ Welding machine ✓ Straight edge ✓ Steel meter rule ✓ Protractor

		of each collector. Fiber glass insulation of 25mm thickness was sandwich between the inner side and the outer side of the collector. The bottom of the collector was also insulated to minimize heat loss to the surrounding. The gravels were painted black and spread on top of the absorber in one of the collectors.	
2	Connecting duct	The connecting duct was fabricated from galvanized steel sheet of 1mm thickness. Two (2) pieces of 430mm×200mm and 710mm × 430mm were cut to form the sides and front of the main connecting duct respectively two (2) for each dryer.100mm×100mm×430mm smaller distributing duct into the various compartment of the drying chamber was also fabricated. Six (6) pieces were required of which three connect to each drying chamber.	✓ Drilling bit ✓ Scriber ✓ Tape rule ✓ Rivet Plier ✓ Hammer ✓ Plier ✓ Straight edge ✓ Steel meter rule
3	Drying	The structural frame of the dryers was	✓ Glass Cutter

	Chamber	formed from 25mm square pipes, four (4) pieces of 900mm ×430mm size of galvanized sheet, two for each dryer, was cut to form the two unglazed sides of the drying chamber. These two sides accommodate the chimneys and air distributing duct. Four number of clear glass size of 875mm×475mm, two for each dryer, was cut to form the two glazing sides of the drying chamber. Inside the drying chamber, ply wood of 500mm×430mm was cut to form the wooden partition. The trays were made using longer size wire mesh. Three vertically-arranged-trays of 450mm×430mm were used in each drying chamber.	✓ Drilling bit ✓ Scriber ✓ Tape rule ✓ Rivet Plier ✓ Hacksaw ✓ Hammer ✓ Plier ✓ Welding machine ✓ Steel meter rule
4	Chimney	Six (6) pieces of 320mm×700mm was cut and fold from 1mm galvanized steel sheet to form the chimneys. Three (3) on each dryer.	✓ Steel meter rule ✓ Plier ✓ Scriber

3.13 Cost Analysis

The costs of the materials incurred in the fabrication of the two solar crop dryersare as follows:

Table 3.5 Cost analysis for the fabrication of the solar dryersas at June, 2016

S/No	MATERIALS	DRYER A AMOUNT (₦)	DRYER B AMOUNT (₦)
1	18mm 3/4" (2244 by 1122mm) plywood sheet	700	700
2	Galvanised Sheet	2400	2400
3	1mm wire mesh (2740 by 1220mm)	3000	3000
4	4mm 820 mm by 600 mm Glazing	2450	2450
5	Body filler	600	600
6	Black paint	1000	1000
7	Fiber glass insulation	2000	2000
8	Rivet pin	600	600
9	25 mm Gravel Stones	-	1500
10	Transport and labor	5000	5000
11	Total	17,750	19,250

3.14 Yam Tuber Sample Preparation

Fresh white yam was obtained from Samaru market and thoroughly cleaned. It was manually peeled and cut to a thin slices of 5mm thickness using a stainless steel kitchen knife. The yam slices were loaded into the drying chamber. An average of 0.67kg of yam slices were distributed and spread evenly (without overlapping) on each tray to ensure that all the surface areas of the slices were in contact with the incoming hot air. This will enhance uniform drying of the yam slices on each tray.

3.15Instrumentation of the Solar Dryers

i. **Solarimeter**: It is an instrument used to measure combined direct and diffuse solar radiation. The energy received from the sun on the collector surface measured in W/m^2 was measured using a solarimeter. See appendix D for the plate of the instrument.

ii. **Thermocouple Wire and Digital Thermometer**: The equipment mostly used for temperature measurement are thermocouple and thermometer. Thermocouple is a device consisting of two dissimilar conductors or semiconductors that contact each other at one or more points. Thermocouples are widely used type of temperature sensor for measurement and control. Ambient air temperatures, collector outlet air temperature and the drying chamber temperature were measured using these instruments. See appendix D for the plate of the instrument.

iv. **Weighing Scale**: Is a device used to measure weight. It was used to evaluate the moisture loss of the yam slices. The sample was measured using a weighing scale calibrated in kilogramme. See appendix D for the plate of the instrument.

v. **Anemometer:** The wind speed of the ambient air was measured using an aero vane digital anemometer. See appendix D for the plate of the instrument.

3.16 Testing and Performance Evaluation

Test procedure was followed using ASHRAE/ANSI 93-2003 standard, which requires that during a collector test, the operating collector to be exposed to solar radiation and measure the fluid inlet and outlet temperatures, the fluid flow rate, radiation on the collector, ambient temperature and wind speed be recorded (Duffie and Beckmann, 2013). The solar dryers were operated simultaneously under the same operating conditions in order to compare their performance. Experiments were conducted from 18th to 20th June, 2016 under the meteorological conditions of Zaria, Nigeria. On the 18th of June, 2016 the experiment was carried out under no load condition. The moisture removal and thermal analysis were the basic standard procedure for evaluating solar dryer performance as recommended by Leon *et al.,* (2002). Therefore, the performances of these systems were evaluated using the instantaneous moisture loss at any given time, drying rate, and the system drying efficiency. Plate 3.1 shows the experimental set up of the dryers.

(a) Aim of the experiment:

The aim of the experiment was to determine and compare the performances of the solar crop dryers by monitoring the moisture loss and drying rate of the yam slices placed on trays in the drying chamber; and the efficiency at which the moisture is lost to the drying air.

(b) Procedure

The two solar dryers were exposed to solar radiation and loaded with yam chips 5 mm average thickness. The hourly temperatures of air into the various trays, temperature from the collector outlet, temperature from the chimney outlet, ambient air temperature, as well as the wind speed were measured from 10:00am to 06: 00pm.Each dryer was fed with 2 kg of yam slices. During sunshine hours, the air flow over the absorber plate gets heated and at the same time the heat storage materials (gravel) packed on the absorber in the collector accumulate the heat energy and dissipate it during low solar insolation. After 06:00 pm, the yam chips were transferred to the polyethylene sheet to avoid reabsorption of moisture. The air mass flow rate into the collector were obtained as the product of the collector cross sectional area, density of air and wind speed measured using anemometer. The weight of the yam chips on each tray was measured at the commencement of the drying and at 2- hour intervals. The final weight was attained at a point when no further weight loss of yam chips was observed. The weight loss was used to calculate the moisture removed at intervals as the yam dried.



Plate 3.1: Experimental set up of the solar dryers.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Simulated and Experimental Results for the Solar Dryers

Reading of solar insolation I(W/m^2), Ambient temperature Ta (°C), Collector air temperature Tc (°C), Temperature of air into different Trays in the drying chamber T_{tr} (°C), and moisture loss were measured during the experiments. The experimental data obtained were tabulated in Tables B.1, B.2,B.3,B.4,B.5,B.6,B.7,B.8,B.9,B.10,B.11, and B.12, as shown in appendix B. Table B.13,B.14, and B.15 are the simulated results alsoshown in appendix B.Figure 4.1,4.2, 4.3, 4.4, 4.5, 4.6,4.7,4.8,4.9, 4.10,4.11,4.12,4.13,4.14, 4.15, and 4.16were drawn from the results in Tables B.1, B.2, B.3, B.4, B.5,B.6,B.7,B.8,B.9,B.10,B.11,B.12,B.13,B.14 and B.15.

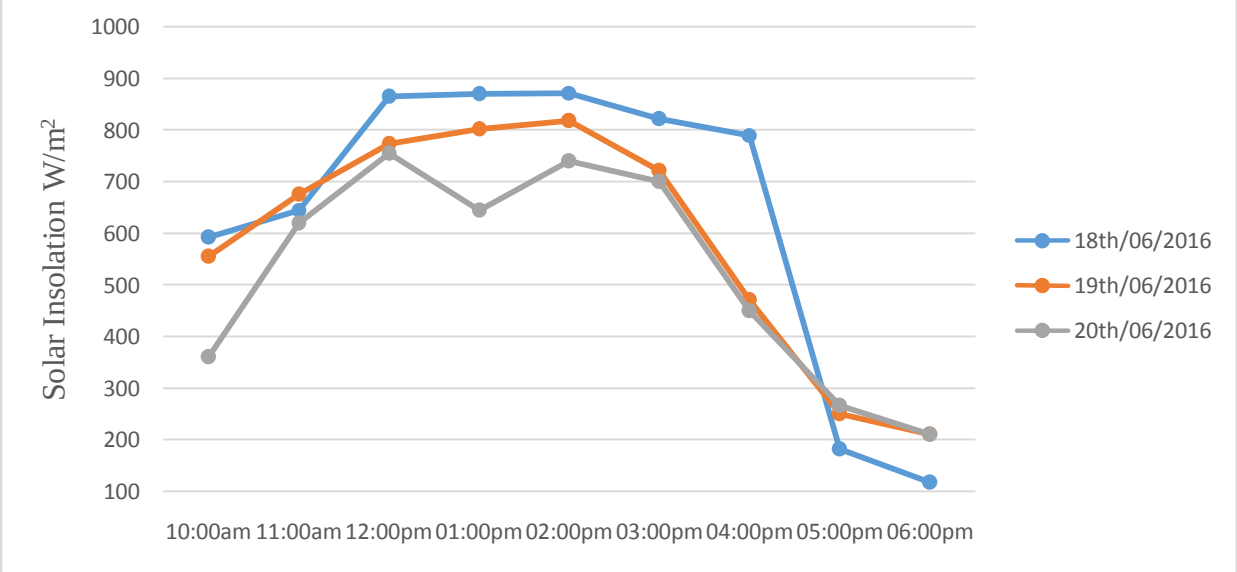


Figure 4.1: Variation of Solar Intensity with Time from 18/06/2016 to 20/06/2016

Figure 4.1 shows a variation of solar intensity with time. The maximum value of the solar insolation recorded was 872 W/m^2 and the minimum was 117 W/m^2.

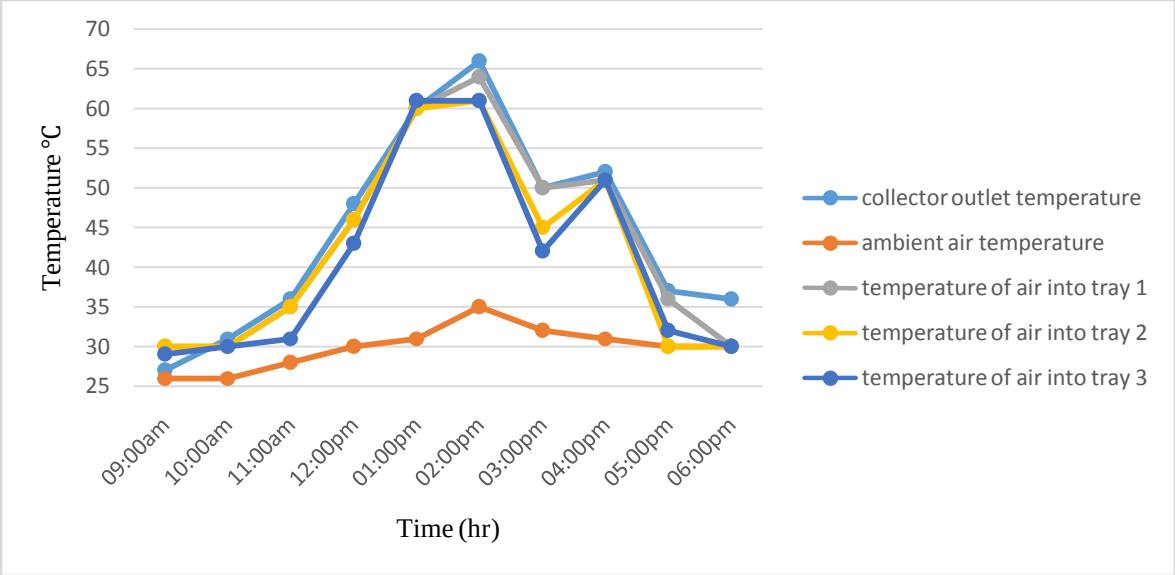


Figure 4.2: Variation of temperature with time for no load test with thermal storage for 18th June 2016.

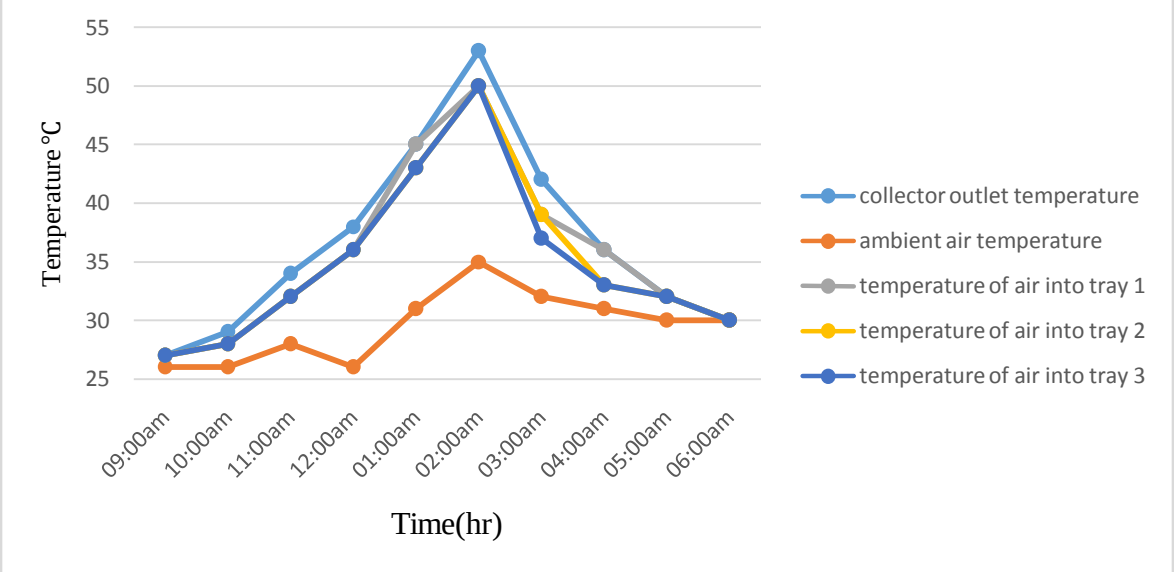


Figure 4.3: Variation of temperature with time for no load test without thermal storage for 18th June, 2016.

Figure 4.2 and figure 4.3 shows the result of the no load test carried out on 18th June 2016. The hourly variation of the collector outlet air temperature and the drying chamber temperatures were higher than the ambient air temperature during the testing hours. This

shows that the dryer can perform better than the open-air sun drying. The maximum collector outlet air temperature for the collectors with and without thermal storage materials for no load test were 66°C and 53°C respectively at 02:00 pm with corresponding solar insolation of 872 W/m^2.

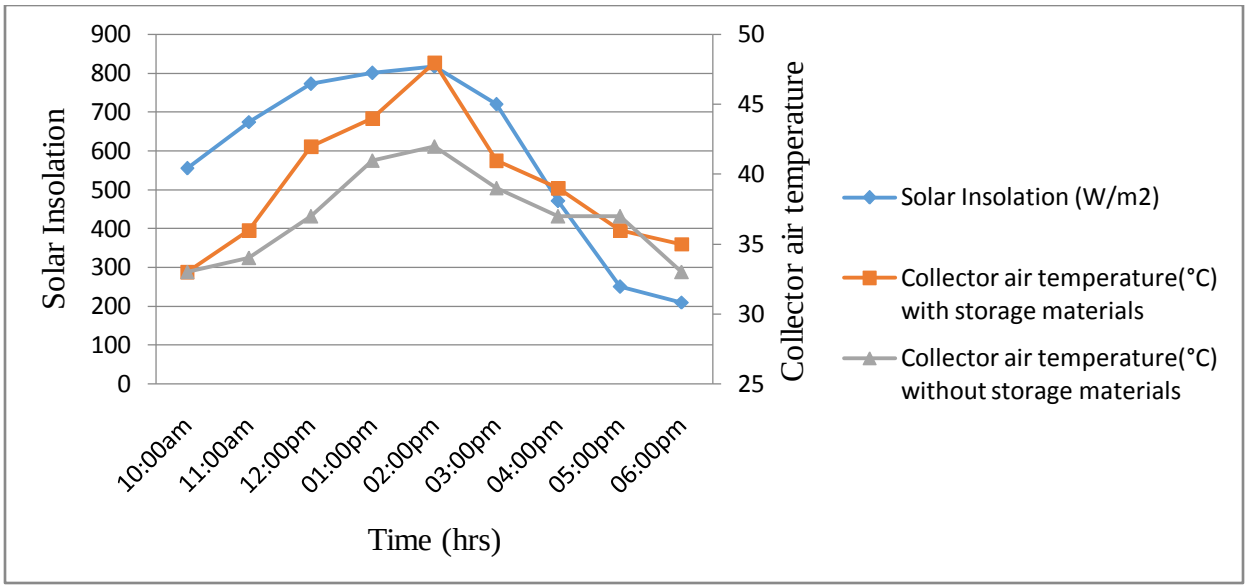


Figure 4.4: Variation of solar intensity and collector air temperature with time for 19/06/2016

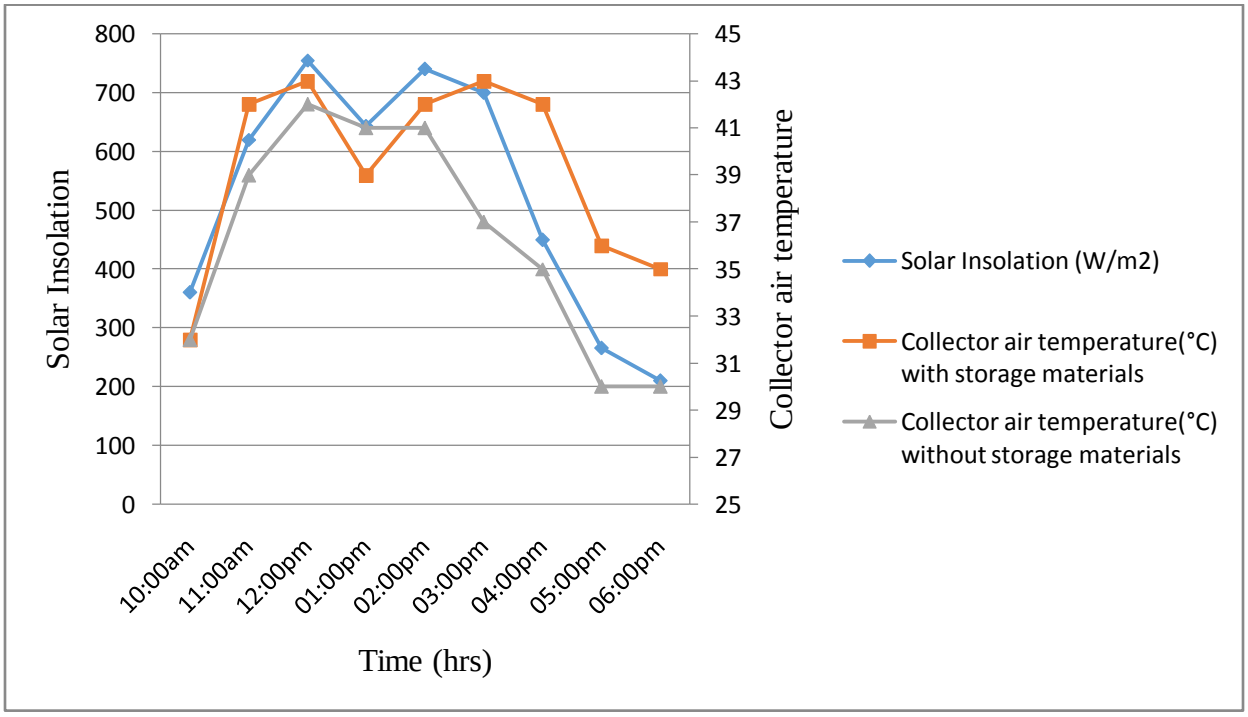


Figure 4.5: Variation of solar intensity and collector air temperature with time for 20/06/2016

Figure 4.4 and figure 4.5 show that the temperature started increasing reasonably immediately after 11:00 am and keeps increasing during afternoon hours. The temperature is higher and stable for collector with storage materials. This is due to the

accumulation of the solar heat energy into the gravel bed, which is being discharged even if the insolation is low.

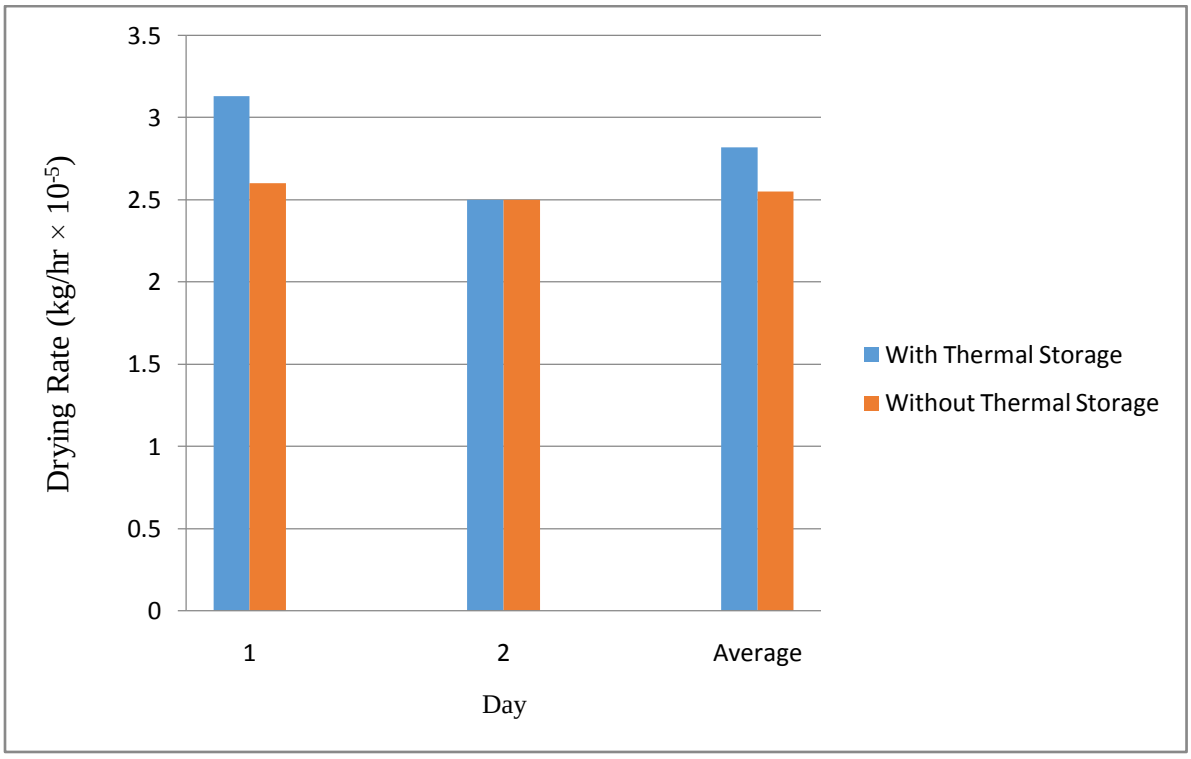


Figure 4.6: Average Drying Rates for Yam

The average drying rate shown in figure 4.6 reveals that the collector with the storage material has higher average drying rate. It was observed that the thermal storage has increased the drying rate by 10%.The results presented in Table B.11 revealed that the drying rate of the yam slices on the first and second trays for dryer with thermal storage are the same and that on the third tray has a percentage decrease of 2 % relative to the first tray. Similarly, for dryer without thermal storage there was a percentage decrease of 3 % in second tray and 8 % in the third tray relative to the first tray. Moreover, the result

revealed that there was no significant difference between the drying rates in the coordinate positions of the trays.

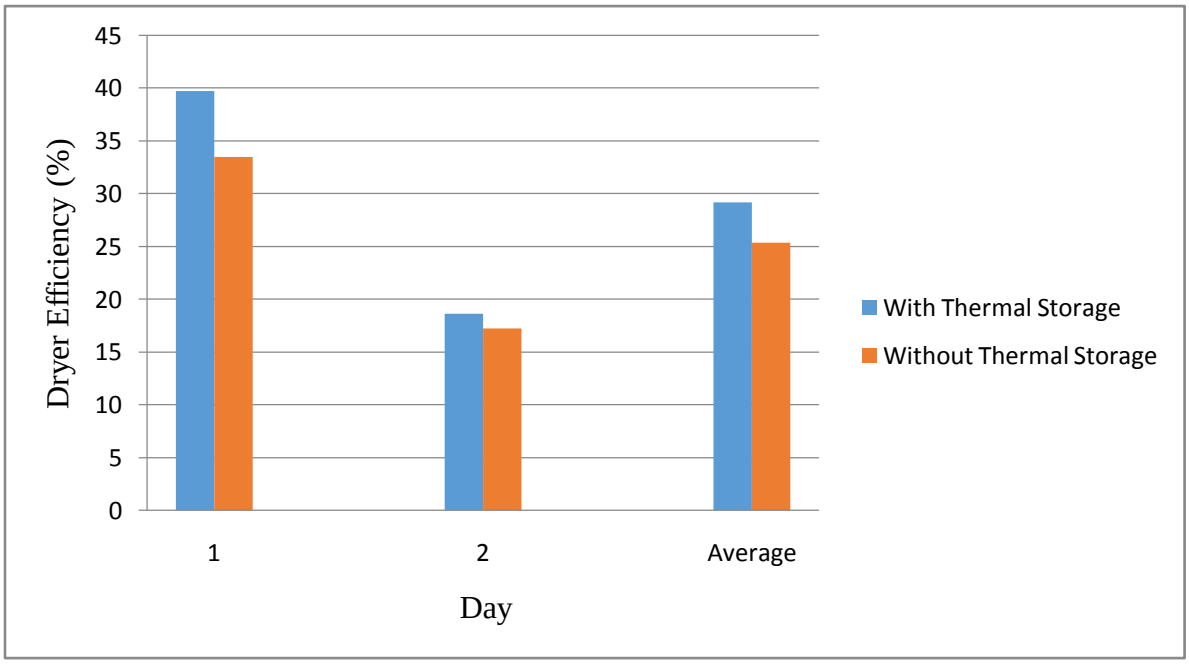


Figure 4.7: Variation of Drying Efficiency for Yam

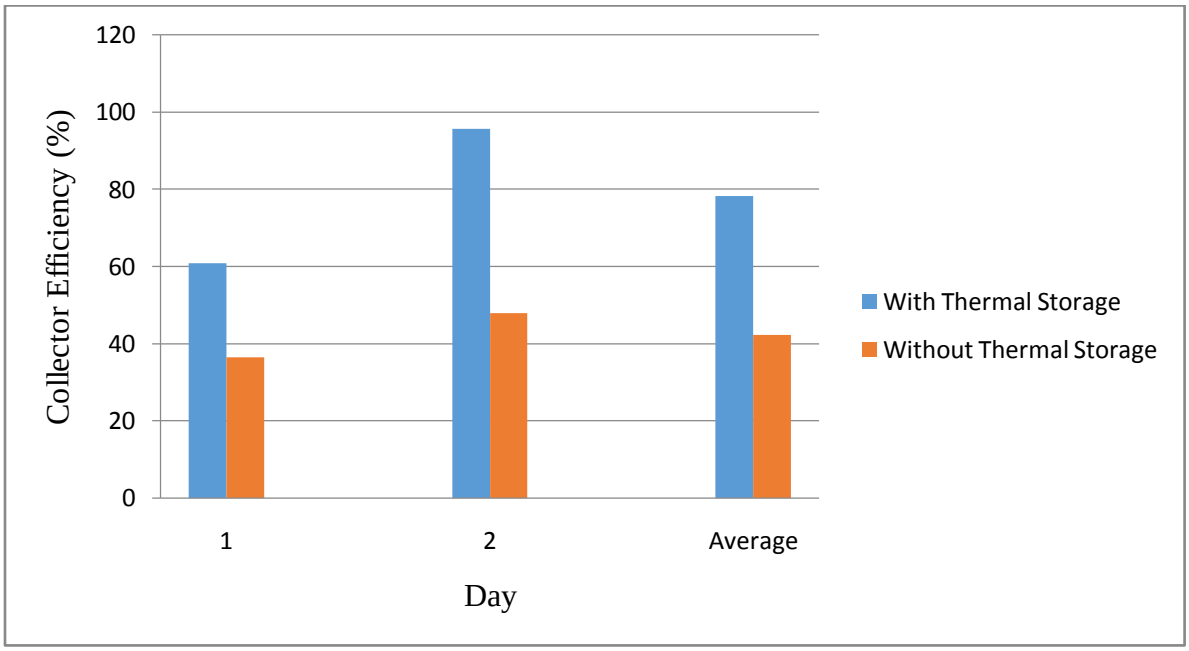


Figure 4.8: Variation of Collector Efficiency with time

Figure 4.7 and figure 4.8 show the drying and collector efficiencies respectively for collector with and without thermal storage materials. The collector with the thermal storage materials gives higher collector and drying efficiency. The efficiency of the dryer with the storage material has increased by about 13% due to the thermal storage used. This is because the storage materials helped in maintaining constant collector temperature even if there is fluctuation of solar radiation.

The results obtained revealed a better performance compare with that obtained by Ajao and Adedeji, (2008) who obtained a drying rate and drying efficiency of 2.50×10^{-6} kg/s and 18% respectively. Moreover, the results also show a better drying efficiency compare with the 21% drying efficiency obtained by Mohanraj and Chandrasekar (2009). Therefore, the performance of the dryers is satisfactory.

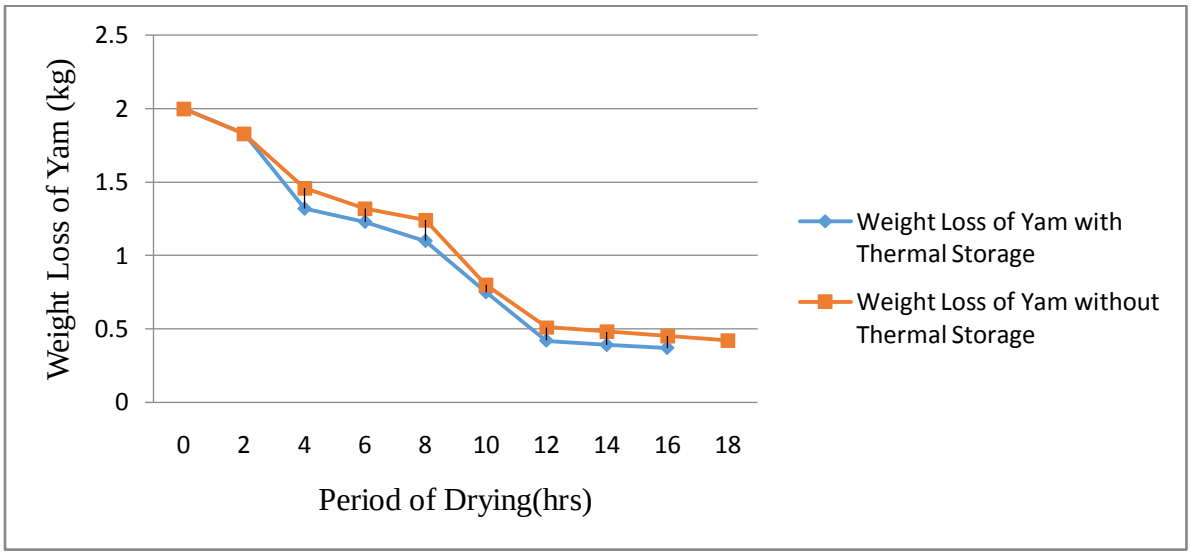


Figure 4.9: Weight Loss of Yam with Time

A total drying period of 18 hours and 16 hours were obtained for dryer with plain absorber and that with storage materials respectively as indicated in figure 4.9.

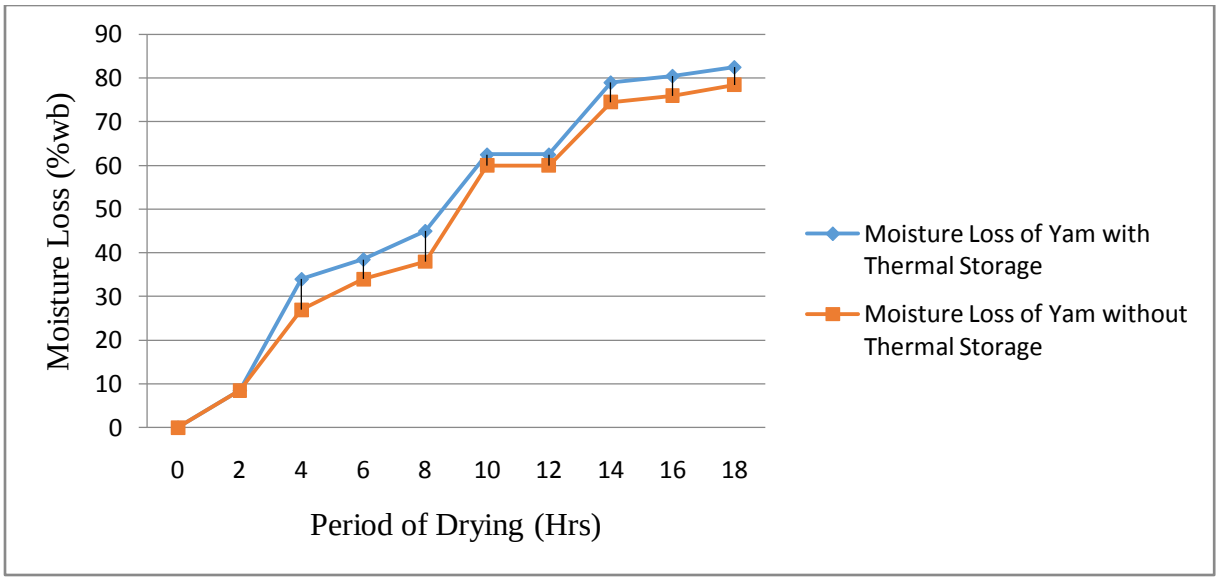


Figure 4.10: Moisture Loss against Drying Period

Figure 4.10 reveals about 81% of moisture was removed over the drying period of the yam slices to it equilibrium moisture content. Similarly, the results in Table B. 10 revealed that there was no difference between the moisture loss in the first and the second trays but, a difference of 1.8 % in the third tray relative to the first tray was noticed for dryer with thermal storage. In the dryer without thermal storage there was no significant difference in moisture loss of the yam slices at the different coordinate positions of the trays, with differences ranging from 3 - 6 %.

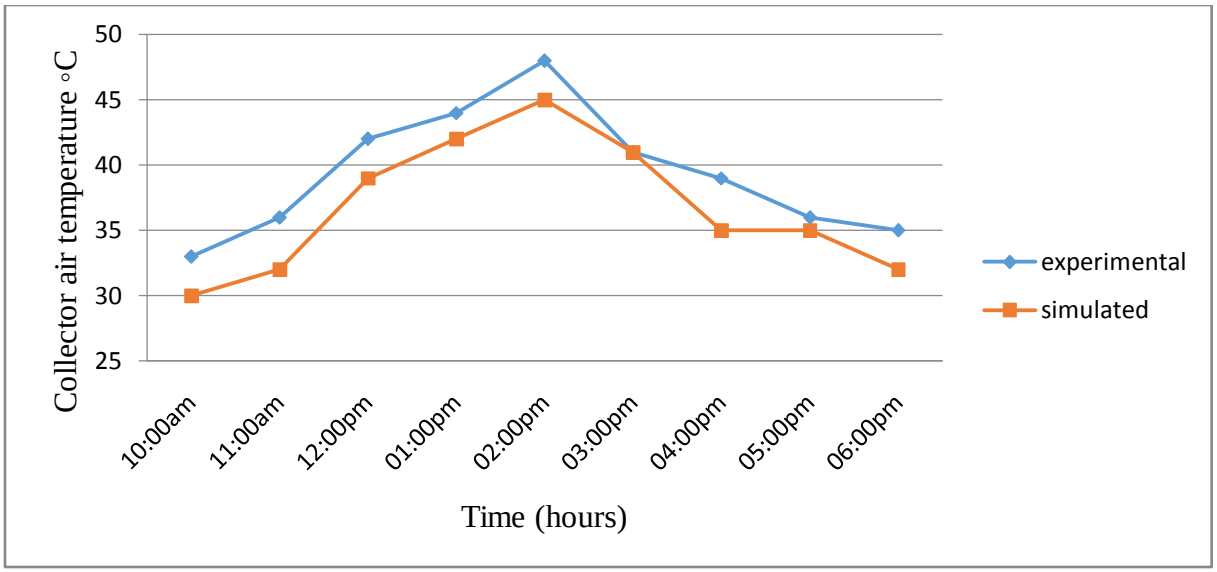


Figure 4.11: Comparison of hourly collector air temperature with thermal storage recorded during the experiment with the values obtained using the simulation software for 19th June, 2016

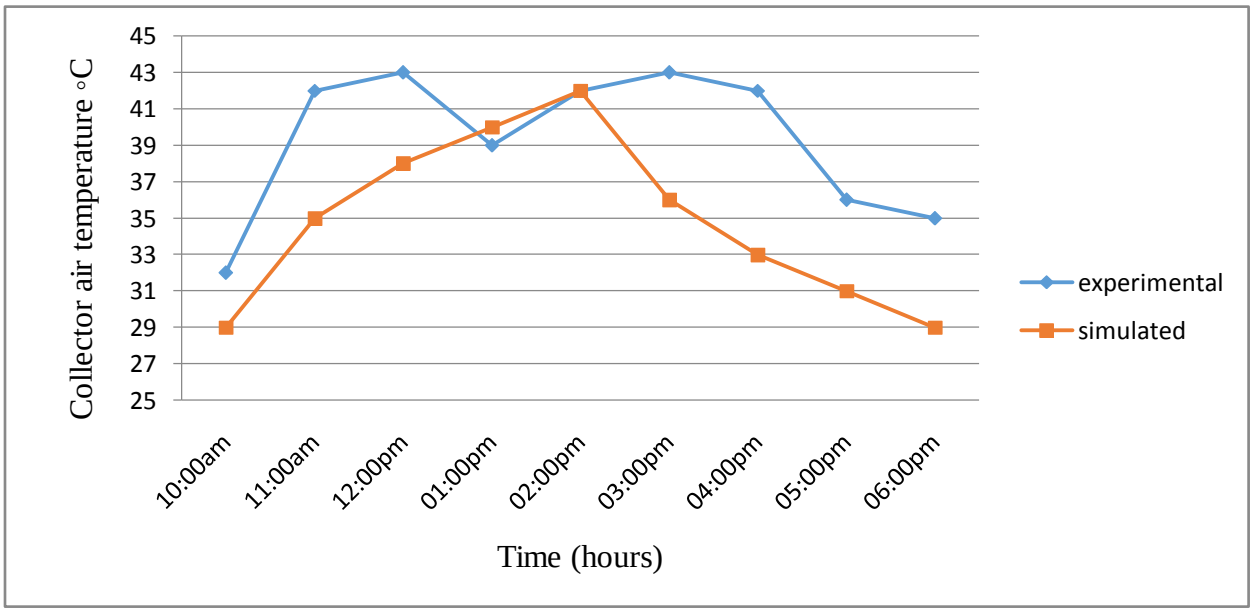
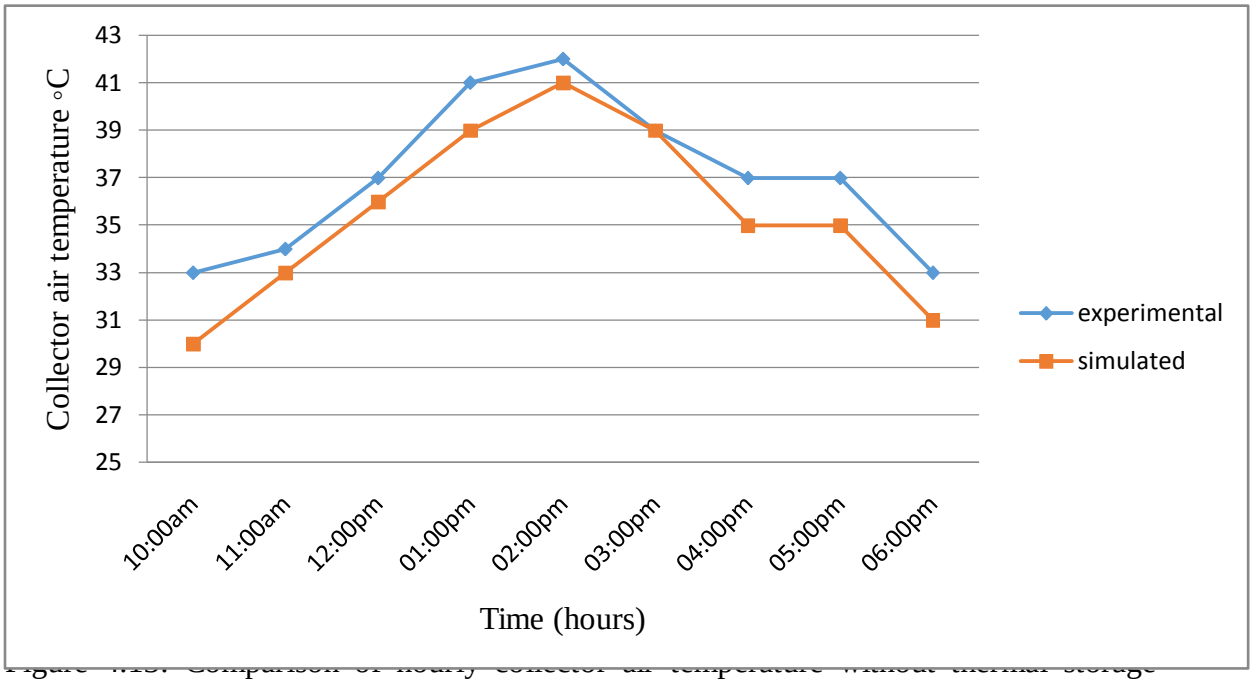


Figure 4.12: Comparison of hourly collector air temperature with thermal storage recorded during the experiment with the values obtained using the simulation software for 20th June, 2016



recorded during the experiment with the values obtained using the simulation software for 19th June, 2016

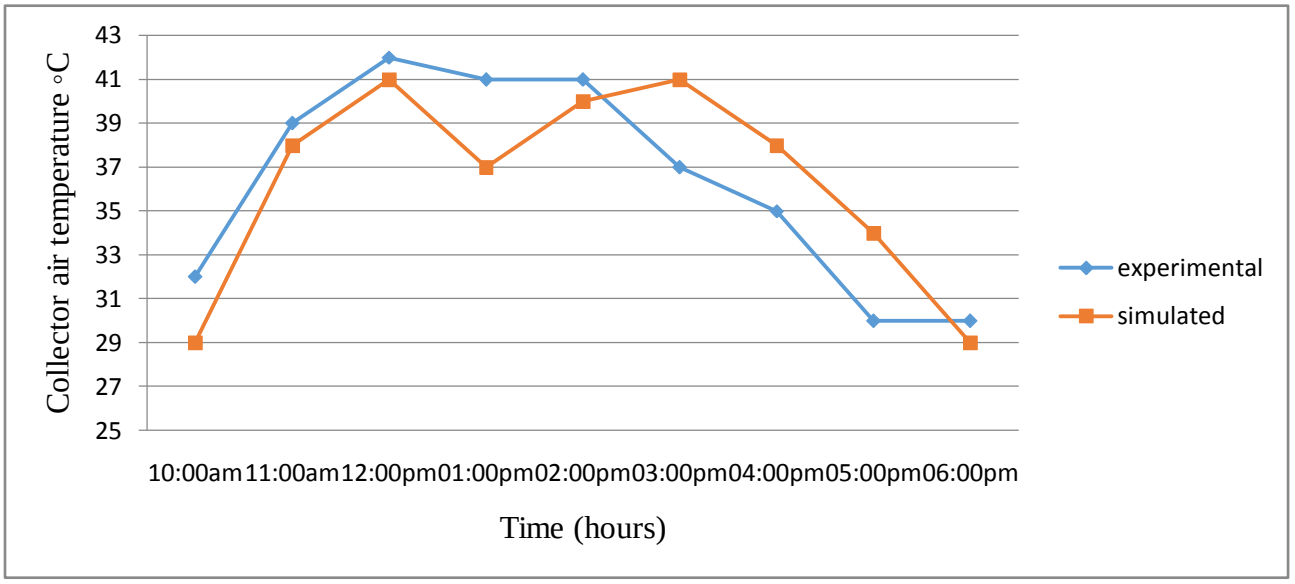
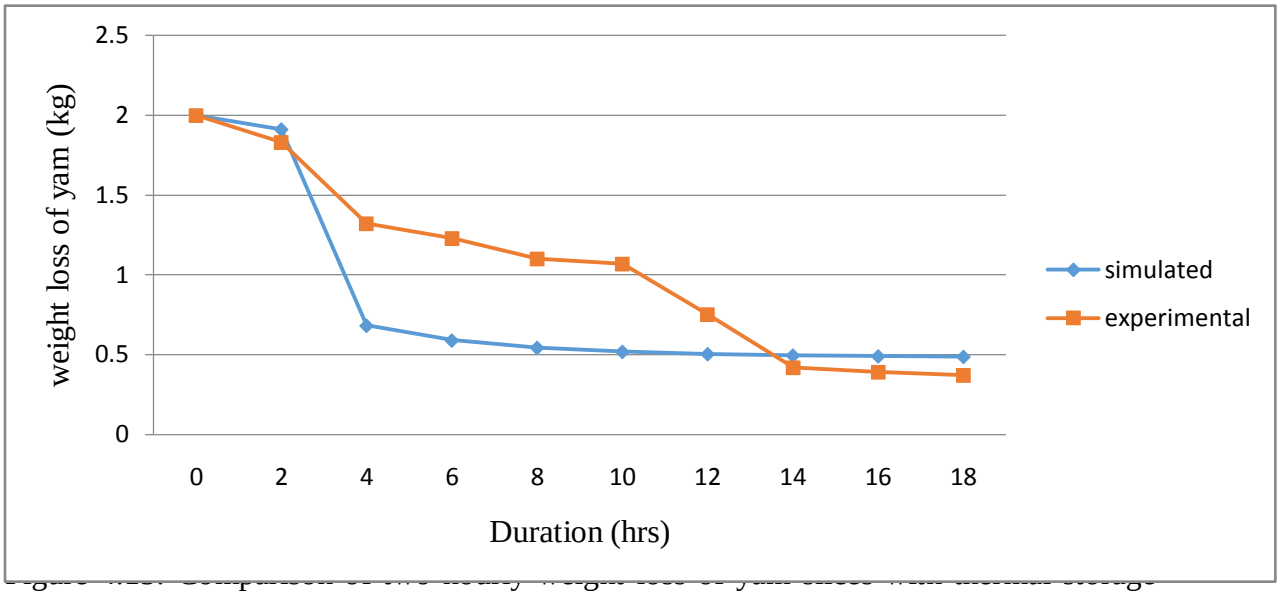


Figure 4.14: Comparison of hourly collector air temperature without thermal storage recorded during the experiment with the values obtained using the simulation software for 20th June, 2016.



recorded during the experiment with the values obtained using the simulation software from 19th-20th June, 2016.

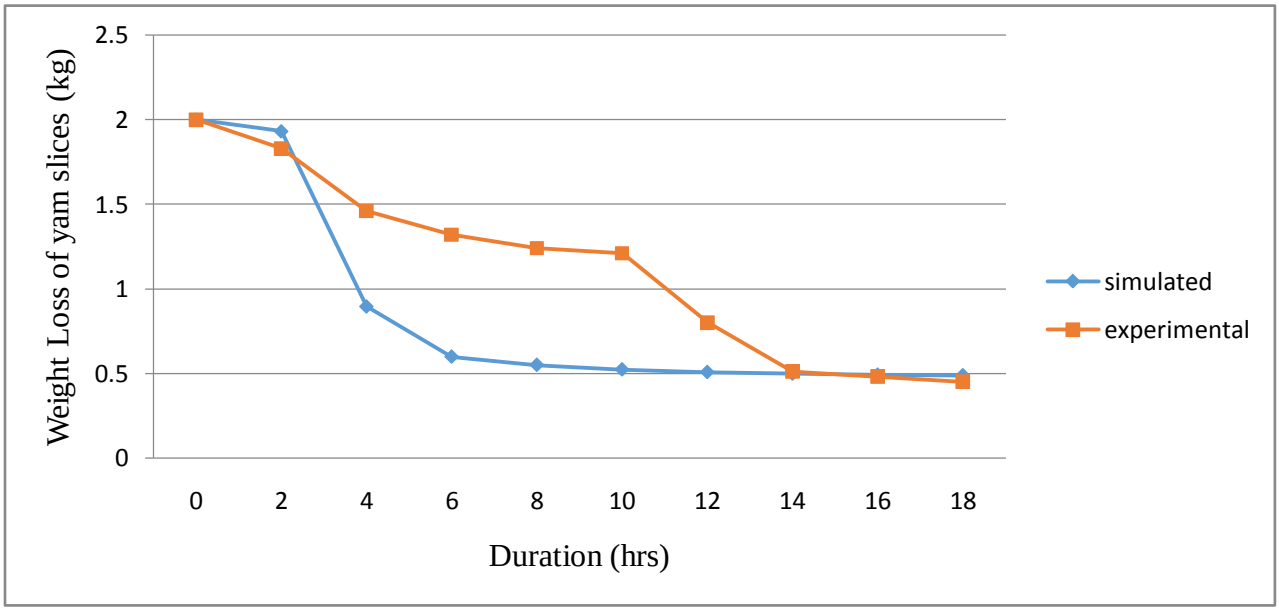


Figure 4.16: Comparison of two hourly weight loss of yam slices without thermal storage recorded during the experiment with the values obtained using the simulation software from 19th-20th June, 2016.

Figure 4.11, 4.12, 4.13, and 4.14 show the comparison of the experimental hourly collector air temperature recorded for 19th and 20th of June 2016 with the predicted results obtained from the model using solar data processor, type 55. Moreover, the figures also

revealed a very good agreement and trend between the experimental results and the simulated results. The collector with the thermal storage gives higher temperature in all days of experiment. The experimental weight loss of yam slices and the predicted using MATLAB software shown in figures 4.15 and 4.16 also show a good agreement.

4.1.2 Error Analysis of the Comparison between Experimental and Simulated Results

Table 4.1: Validation of simulated results with experimental results with thermal storage materials of 19th June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
TIME	TCsim	TCexp	TCsim -TCexp	$(TCsim - TCexp)^2$	$(TCexp - \overline{TCexp})^2$
10:00am	30	33	-03	09	36
11:00am	32	36	-04	16	09
12:00am	39	42	-03	09	09
01:00pm	42	44	-02	04	25
02:00pm	45	48	-03	09	81
03:00pm	41	41	0	0	04
04:00pm	35	39	-04	16	0
05:00pm	35	36	-01	01	09
06:00pm	32	35	-03	09	16
TOTAL				**73**	**189**
AVERAGE		**39**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{73}{9}} = 2.8\ ^{o}\text{C}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{\sum_{i=1}^{N}\left[\boldsymbol{TC_{expt} - \overline{TC}_{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{73}{189} = 0.6$$

Table 4.2: Validation of simulated results with experimental results without thermal storage materials of 19th June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
TIME	TCsim	TCexp	TCsim - TCexp	$(TCsim - TCexp)^2$	$(TCexp - \overline{TCexp})^2$
10:00am	30	33	-03	09	16
11:00am	33	34	-01	01	09
12:00pm	36	37	-01	01	0
01:00pm	39	41	-02	04	16
02:00pm	41	42	-01	01	25
03:00pm	39	39	0	0	04
04:00pm	35	37	-02	04	0
05:00pm	35	37	-02	04	0
06:00pm	31	33	-02	04	16
TOTAL				**28**	**86**
AVERAGE		**37**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}[\boldsymbol{TC_{sim} - TC_{expt}}]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{28}{9}} = 1.8\ ^{o}\text{C}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{\sum_{i=1}^{N}\left[\boldsymbol{TC_{expt} - \overline{TC}_{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{28}{86} = 0.7$$

Table 4.3: Validation of simulated results with experimental results without thermal storage materials of 20th June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
TIME	TCsim	TCexp	TCsim - TCexp	$(TCsim - TCexp)^2$	$(TCexp - \overline{TCexp})^2$
10:00am	29	32	-03	09	49
11:00am	38	42	-04	16	09
12:00pm	41	43	-02	04	16
01:00pm	37	39	-02	04	0
02:00pm	40	42	-02	04	09
03:00pm	41	43	-02	04	16
04:00pm	38	42	-04	16	09
05:00pm	34	36	-02	04	09
06:00pm	29	35	-06	36	16
TOTAL				**97**	**133**
AVERAGE		**39**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{97}{9}} = 3.283\ ^{o}\text{C}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{\sum_{i=1}^{N}\left[\boldsymbol{TC_{expt} - \overline{TC}_{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{97}{133} = 0.3$$

Table 4.4: Validation of simulated results with experimental results with thermal storage materials of 20th June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
TIME	TCsim	TCexp	TCsim - TCexp	$(TCsim - TCexp)^2$	$(TCexp - \overline{TCexp})^2$
10:00am	29	32	-03	09	16
11:00am	35	39	-04	16	09
12:00am	38	42	-04	16	36
01:00pm	40	41	-01	01	25
02:00pm	42	41	01	01	25
03:00pm	36	37	-01	01	01
04:00pm	33	35	-02	04	01
05:00pm	31	30	01	01	36
06:00pm	29	30	01	01	36
TOTAL				**50**	**185**
AVERAGE		**36**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{50}{9}} = 2.36\ ^{o}\text{C}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\boldsymbol{TC_{sim} - TC_{expt}}\right]^2}{\sum_{i=1}^{N}\left[\boldsymbol{TC_{expt} - \overline{TC}_{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{50}{185} = 0.7$$

Table 4.5: Validation of simulated results with experimental results with thermal storage materials of 19th and 20th of June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
Duration (hours)	m_f sim	m_f exp	m_f sim - m_f exp	(m_f sim - m_f exp)^2	(m_f exp - $\overline{mf\,exp}$)^2
0	2.0000	2.0000	0	0	0.9063
2	1.9124	1.8300	0.0824	0.0067	0.6115
4	0.6819	1.3200	-0.6381	0.4072	0.0739
6	0.5894	1.2300	-0.6406	0.4104	0.0331
8	0.5436	1.1000	-0.5564	0.3096	0.0027
10	0.5185	1.0700	-0.5515	0.3041	0.0005
12	0.5040	0.7500	-0.2460	0.0605	0.0888
14	0.4954	0.4200	-0.0754	0.0057	0.3944
16	0.4902	0.3900	0.1002	0.0100	0.4329
18	0.4870	0.3700	0.1170	0.0137	0.4597
TOTAL		**10.48**		**1.528**	**3.004**
AVERAGE		**1.048**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{sim}} - \text{mf}_{\boldsymbol{expt}}\right]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{1.528}{10}} = 0.3909 \text{ kg}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{sim}} - \text{mf}_{\boldsymbol{expt}}\right]^2}{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{expt}} - \overline{\text{mf}}_{\boldsymbol{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{1.528}{3.004} = 0.5$$

Table 4.6: Validation of simulated results with experimental results without thermal storage materials of 19th and 20th of June, 2014 using the RMSE and NSE statistical tools.

			RMSE Calculation		NSE Calculation
Duration (hours)	m_f sim	m_f exp	m_f sim - m_f exp	(m_f sim - m_f exp)^2	(m_f exp - $\overline{mf\ exp}$)^2
0	2.000	2.0000	0	0	0.7569
2	1.9311	1.8300	0.1011	0.0102	0.4900
4	0.8950	1.4600	-0.5650	0.3192	0.1089
6	0.5986	1.3200	-0.7214	0.5204	0.0361
8	0.5501	1.2400	-0.6899	0.4759	0.0121
10	0.5231	1.2100	-0.6869	0.4718	0.0064
12	0.5073	0.8000	-0.2927	0.0857	0.1089
14	0.4978	0.5100	-0.0122	0.0001	0.3844
16	0.4919	0.4800	0.0119	0.0001	0.4225
18	0.4882	0.4500	0.0382	0.0015	0.4624
TOTAL				**1.8868**	**2.7886**
AVERAGE		**1.1300**			

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{sim}} - \text{mf}_{\boldsymbol{expt}}\right]^2}{N}}$$

$$\text{RMSE} = \sqrt{\frac{1.8868}{10}} = 0.4344\ \text{kg}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{sim}} - \text{mf}_{\boldsymbol{expt}}\right]^2}{\sum_{i=1}^{N}\left[\text{mf}_{\boldsymbol{expt}} - \overline{\text{mf}}_{\boldsymbol{expt}}\right]^2}$$

$$\text{NSE} = 1 - \frac{1.8868}{2.7886} = 0.4$$

Table 4.1,4.2,4.3, 4.4,4.5 and 4.6 show the results of statistical analysis (RMSE and NSE) employed to analyze the predictive power of the system model using (TRANSYS 16) and (MATLAB R2013a) based on the simulated and experimental results obtained on the 19th and 20th of June, 2016.

The result of Table 4.1 shows RMSE of 2.8 ℃ and NSE of 0.6 between the model and the experimental collector air temperature. This RMSE value implies that the error between the mean of the experimental collector air temperature and the mean of the simulated collector air temperature is 2.8 ℃. NSE value of 0.6 indicates a good quality of fit between the experimental data and the system model; hence a good model predictive power as the NSE value is positive and approaches unity (Julien *et al.*, 2013). Similarly, Table 4.2, 4.3 and 4.4 shows RMSE and NSE values of 1.8 ℃ and 0.7, 3.2 ℃ and 0.3, 2.36 ℃ and 0.7 respectively. The result of Table 4.5 and Table 4.6 shows RMSE and NSE values of 0.3909kg and 0.5, 0.4344kg and 0.4 respectively between the model and the experimental weight loss of the yam slices. The NSE values indicate a good quality of fit between the experimental data and the system model.

CHAPTER FIVE
SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

The solar dryers were designed, simulated, constructed, and tested at Ahmadu Bello University, Zaria using the meteorological conditions of Zaria, Nigeria.

The dryer was designed to dry 7 kg of yam slices. The dimensions of the dryer are: Collector length L_c = 0.65m, collector area A_c= 0.277 m^2, Height of the drying chamber, H =0.9,total chimney height, h_{ch}= 2.7 m, Length of the drying chamber, L_d = 1.64 m and Width of the drying chamber, W= 0.43 m. However, a section of 0.5 m of the dryer along the dryer length with chimney height of 0.7 m each were fabricated and tested with 2 kg of yam slices in each of the drying chambers.

The dryers' conditions were simulated using TRANSYS 16.0 and MATLAB R2013a Softwares. Typical Meteorological Year (TMY) solar data of Zaria obtained fromwww.solaranalytical.com was processed to obtain the monthly average daily solar resources of Zaria using the solar radiation and weather data processor TYPE 109 component of TRANSYS 16 software. Programmes were written using MATLAB software to generate the weight loss of the yam slices in the drying chamber. The solar dryers were tested one with and the other without thermal storage materials at the Mechanical Engineering Workshop ABU Zaria, Kaduna State, Nigeria from 18th to 20th of June 2016. The hourly percentage moisture loss (wet basis), drying rates, system efficiencies and collector's efficiencies were all calculated from the results of the testing.The dryer with the storage materials gives better drying efficiency.

5.2 Conclusion

1. The performances of the solar collectors were simulated under varying meteorological conditions of Zaria. TRANSYS 16.0 software was used to simulate the collectors' with and without thermal storage outlet air temperature. Since a drying model is not available in the TRNSYS library, a MATLAB code was written to computes the weight loss of the yam slices in the drying chamber. The computed NSE values and its corresponding RMSE between the modeled collector air temperature and weight loss of yam slices and the observed collector air temperature and weight loss of yam slices with and without thermal storage for 19^{th} and 20^{th} of June, 2016 confirms that the model formulation using TRANSYS 16 and Matlab Softwares used for the performance simulation of the system is valid and realistic owning to the good quality of fit between the experimental and the simulated results.

2. The performances of the drying systems were evaluated using the percentage moisture loss, drying rate, collector efficiency and drying efficiency. The average drying rates, collector efficiency, and drying efficiency of the drying system with and without thermal storage are 2.82×10^{-5} kg/s and 2.55×10^{-5} kg/s, 78.25 % and 42.20 %, 29.15 % and 25.35% respectively. Maximum collector outlet air temperature of 66°C and 52°C at 872W/m^2 for collector with and without thermal storage under no load conditions were obtained. Temperatures of 48°C and 42°C at 818 W/$m^2$and 43°C and 41°C at 755 W/$m^2$for second and third days of drying for collector with and without thermal storage under load test were measured. The collector with the storage materials shows increase in both the collector and drying efficiencies. During the experiment, the results in table B.11 shows the drying rates do not vary much with the coordinate positions of the trays. This

is because the inlet drying air temperature goes to the individual trays without picking moisture from lower bed first to the upper bed. The air ducting provided serves this purpose.

5.3 Recommendations

1. The developed dryers can help in mitigating the problem of non-uniform drying. Therefore, Government should encourage local farmers on the use of the improved solar dryers.

2. The dryer performance can be improved by using flexible air distributing duct to reduce the pressure drop across the duct, this will increase the drying efficiency.

3. The dryer can be tested using different thickness of yam slices to get the optimum value under themeteorological conditions of Zaria.

4. The performance of the dryer can be improved by optimizing the design.

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APPENDICES

APPENDIX A: SAMPLE CALCULATIONS

a) Percentage Moisture Loss (wet basis %)

Two hourly moisture loss was calculated from equation (3.34) using table (B.5) and (B.9) in appendix B. The moisture loss (wet basis) is as shown below:

$$\text{MC} = \left[\frac{0.67-0.61}{0.67}\right] \times 100\% \quad = 8.96\ \%$$

The remaining moisture contents were similarly calculated as shown above. The results were presented in Tables (B.6) and (B.10) in appendix B.

b) Drying Rate

Drying rates were calculated from equation (3.35) using Tables (B.5) and (B.9) as shown below.

$$m_{dr} = \frac{2.0-1.10}{8\times60\times60} = 3.13 \times 10^{-5}\text{kg/s}$$

The remaining drying rate was similarly calculated and the results were presented in table (B.11), in appendix B.

c) Collector Efficiency

The daily efficiency of the collector was calculated from equation (3.32) using Tables (B.3) (B.4), (B.7) and (B.8) as follows: $\eta_c = \frac{0.01966 \times 1005 \times (39-34)}{0.277 \times 586}$ = 60.8 %

The remaining collector efficiencies were similarly calculated as above. The results were presented in Table (B.12) in appendix B.

d) Drying Efficiency

The daily drying efficiency of the drying system was calculated from equation (3.33) using Tables (B.5) and (B.9) as follows: $\eta_{dryer} = \frac{0.9 \times 2320000}{586 \times 0.277 \times 9 \times 3600}$= 40%

The remaining drying efficiencies were similarly calculated as above. The results were presented in Table (B.12) in appendix B.

APPENDIX B: EXPERIMENTAL AND SIMULATED RESULTS

Date of experiment: 18th June,2016 (Day 1)

Table B.1: No load test with thermal storage at air mass flow rate of 0.03277 kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
09:00am	300	26	27	30	30	29	31	32	32
10:00am	592	26	31	30	30	30	33	33	33
11:00am	645	28	36	35	35	31	33	34	36
12:00pm	865	30	48	46	46	43	45	45	42
01:00pm	870	31	60	60	60	61	48	47	49
02:00pm	872	35	66	64	61	61	53	50	53
03:00pm	822	32	50	50	45	42	50	50	51
04:00pm	790	31	52	51	51	51	40	40	40
05:00pm	182	30	37	36	30	32	36	35	37

06:00pm	117	30	36	30	30	30	34	36	36
Mean	**615**	**30**	**44**	**43**	**42**	**41**	**40**	**40**	**41**

Table B.2: No Load Test without Thermal Storage at air mass flow rate of 0.03277kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
09:00am	300	26	27	27	27	27	28	28	28
10:00am	592	26	29	28	28	28	31	32	31
11:00am	645	28	34	32	32	32	32	32	31
12:00pm	865	26	38	36	36	36	39	39	38
01:00pm	870	31	45	45	43	43	47	49	46
02:00pm	872	35	53	50	50	50	53	52	52
03:00pm	822	32	42	39	39	37	40	38	39
04:00pm	790	31	36	36	33	33	36	34	32
05:00pm	182	30	32	32	32	32	31	31	31
06:00pm	117	30	30	30	30	30	30	30	30

Mean	**615**	**30**	**37**	**36**	**35**	**35**	**37**	**37**	**36**

Date of Experiment: 19th June, 2016 (Day 2)

Table B.3: Reading obtained for Yam Drying with Thermal Storage at air mass flow rate of 0.01966 kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
10:00am	555	30	33	31	30	30	33	31	31
11:00am	675	33	36	34	33	33	33	35	34
12:00p[m	773	34	42	37	37	35	35	34	39
01:00pm	802	35	44	40	38	38	38	39	40
02:00pm	818	36	48	40	39	39	39	40	40
03:00pm	721	36	41	35	35	35	36	37	35
04:00pm	471	36	39	35	35	35	36	36	35
05:00pm	250	35	36	35	35	35	35	35	35

06:00pm	210	32	35	31	30	30	33	33	33
Mean	**586**	**34**	**39**	**35**	**35**	**34**	**35**	**36**	**36**

Table B.4: Reading Obtained for Yam Drying Without Thermal Storage at air mass flow rate = 0.01966 kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
10:00am	555	30	33	31	30	30	33	31	31
11:00am	675	33	34	34	33	33	33	35	34
12:00pm	773	34	37	37	37	35	35	34	39
01:00pm	802	35	41	40	38	38	38	39	40
02:00pm	818	36	42	40	39	39	39	40	40
03:00pm	721	36	39	35	35	33	36	37	35
04:00pm	471	36	37	35	35	35	36	36	35
05:00pm	250	35	37	35	35	35	35	35	35
06:00pm	210	32	33	31	30	30	33	33	33
Mean	**586**	**34**	**37**	**35**	**35**	**34**	**35**	**36**	**36**

Table B.5: Two Hourly Weight Loss of Yam on Drying Trays in the Drying Chamber

Time in Hours	Weight Loss of Fresh Yam in kilogramme (kg)							
	Dryer With Thermal Storage				Dryer Without Thermal Storage			
	Tray 1	Tray 2	Tray 3	All	Tray 1	Tray 2	Tray 3	All
10:00am	0.67	0.67	0.67	2.00	0.67	0.67	0.67	2.00
12:00pm	0.61	0.61	0.61	1.83	0.61	0.61	0.61	1.83
02:00pm	0.42	0.45	0.45	1.32	0.48	0.49	0.49	1.46
04:00pm	0.40	0.41	0.42	1.23	0.42	0.45	0.45	1.32
06:00pm	0.35	0.35	0.40	1.10	0.40	0.42	0.42	1.24

Table B.6: Two Hourly Moisture loss of Yam on Drying Trays in the Drying Chamber

Time in Hours	Percentage Moisture loss (wet basis (%))							
	Dryer With Thermal Storage				Dryer Without Thermal Storage			
	Tray 1	Tray 2	Tray 3	All Trays	Tray 1	Tray 2	Tray 3	All Trays
10:00am	-	-	-	-	-	-	-	-
12:00pm	8.96	8.96	8.96	8.50	8.96	8.96	8.96	8.50
02:00pm	37.31	32.84	32.84	34.00	28.40	26.87	26.87	27.00
04:00pm	40.30	38.81	37.31	38.50	37.30	32.84	32.84	34.00
06:00pm	47.76	47.76	40.30	45.00	40.30	37.31	37.31	38.00

Date of Experiment: 20th June, 2016 (Day 3)

Table B.7: Reading obtained for Yam Drying with Thermal Storage at air mass flow rate of 0.02621 kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
10:00am	360	30	32	28	28	27	32	31	32
11:00am	620	33	42	42	40	41	36	37	37
12:00pm	755	33	43	44	43	43	41	42	41
01:00pm	644	34	39	40	40	40	37	37	38
02:00pm	740	34	42	38	37	33	40	41	40
03:00pm	700	34	43	38	36	33	41	40	40
04:00pm	450	33	42	38	36	34	41	41	41
05:00pm	266	30	36	34	34	34	39	34	39
06:00pm	210	30	35	33	33	33	36	35	36

Mean	**596**	**33**	**39**	**37**	**36**	**35**	**38**	**38**	**38**

Table B.8: Reading Obtained for Yam Drying without Thermal Storage at air mass flow rate = 0.02621 kg/s

				Temperature of air into Trays in the drying chamber (T_{tr} °C)			Chimney Exit Temperature (T_{ch} °C)		
Time(hours)	I(W/m^2)	Ta (°C)	T_C(°C)	Tray 1	Tray 2	Tray 3	T_{ch} 1	T_{ch} 2	T_{ch} 3
10:00am	360	30	32	28	28	27	33	33	34
11:00am	620	33	39	39	37	35	35	35	35
12:00pm	755	33	42	40	40	39	40	40	41
01:00pm	644	34	41	39	38	38	39	38	38
02:00pm	740	34	41	37	37	35	38	38	38
03:00pm	700	34	37	35	36	34	33	34	36
04:00pm	450	33	35	33	33	32	35	33	33
05:00pm	266	30	30	30	30	31	31	30	30
06:00pm	210	30	30	28	27	27	30	30	30
Mean	**596**	**33**	**36**	**34**	**34**	**33**	**35**	**35**	**35**

Table B.9: Two Hourly Weight Loss of Yam on Drying Trays in the Drying Chamber

Time in Hours	Weight Loss of Fresh Yam in kilogramme (kg)							
	Dryer With Thermal Storage				Dryer Without Thermal Storage			
	Tray 1	Tray 2	Tray 3	All Trays	Tray 1	Tray 2	Tray 3	All Trays
10:00am	0.34	0.34	0.39	1.07	0.39	0.41	0.41	1.21
12:00pm	0.23	0.24	0.28	0.75	0.25	0.26	0.29	0.80
02:00pm	0.13	0.13	0.16	0.42	0.15	0.17	0.19	0.51
04:00pm	0.12	0.12	0.15	0.39	0.14	0.16	0.18	0.48
06:00pm	0.12	0.12	0.13	0.37	0.13	0.15	0.17	0.45

Table B.10: Two Hourly Moisture Loss of Yam on Drying Trays in the Drying Chamber

Time in Hours	Percentage Moisture loss (wet basis (%))							
	Dryer With Thermal Storage				Dryer Without Thermal Storage			
	Tray 1	Tray 2	Tray 3	All Trays	Tray 1	Tray 2	Tray 3	All Trays
10:00am	-	-	-	-	-	-	-	-
12:00pm	65.70	64.20	58.20	62.50	62.70	61.20	56.70	60.00
02:00pm	80.60	80.60	76.10	79.00	77.60	74.60	71.60	74.50
04:00pm	82.10	82.10	77.60	80.50	79.10	76.10	73.10	76.00
06:00pm	82.10	82.10	80.60	81.50	80.60	77.60	74.60	77.50

Table B.11 Average Drying Rate for Drying of Yam

Day	Average drying rate ($kg/sec \times 10^{-5}$)							
	With Thermal Storage				Without Thermal Storage			
	Tray 1	Tray 2	Tray 3	All trays	Tray 1	Tray 2	Tray 3	All trays
1	1.11	1.11	0.94	3.13	0.94	0.87	0.87	2.60
2	0.76	0.76	0.90	2.50	0.90	0.90	0.83	2.50
Average	**0.94**	**0.94**	**0.92**	**2.82**	**0.92**	**0.89**	**0.85**	**2.55**

Table B.12: Average Collector and Dryer Efficiency for Yam Drying

Day	Collector Efficiency (%)		Dryer Efficiency (%)	
	With Thermal Storage	Without Thermal Storage	With Thermal Storage	Without Thermal Storage
1	60.80	36.50	39.70	33.50
2	95.70	47.90	18.60	17.20
Average	**78.25**	**42.20**	**29.15**	**25.35**

Result Generated from Transient Simulation Software (TRANSYS)

Table B.13: Simulated Temperature Profile and Solar Insolation for 19th June, 2016

Time	Solar Insolation (W/m^2)	Ambient Temperature Ta(°C)	Collector Air Exit Temperature (°C)	
			With Storage Material	Without Storage Material
10:00 am	651	29	30	30
11:00 am	819	31	32	33
12:00 pm	929	34	39	36
01:00 pm	971	36	42	39
02:00 pm	940	37	45	41
03:00 pm	842	36	41	39
04:00 pm	207	34	35	35
05:00pm	334	34	35	35
06:00 pm	215	31	32	31
Average	656	34	37	35

Table B.14: Simulated Temperature Profile and Solar Insolation for 20th June, 2016

Time	Solar Insolation (W/m^2)	Ambient Temperature Ta(°C)	Collector Air Exit Temperature (°C)	
			With Storage Material	Without Storage material
10:00 am	625	29	29	29
11:00 am	812	32	35	38
12:00 pm	928	34	38	41
01:00 pm	967	36	40	37
02:00 pm	932	39	42	40
03:00 pm	832	37	36	41
04:00 pm	211	33	33	38
05:00pm	720	31	31	34
06:00 pm	210	29	29	29
Average	534	33	35	36

Result Generated from MATLAB Software (R2013a)

Table B.15: Simulated Moisture Content, Mass of the Yam Slices, and Mass of Water Evaporated Using Matlab R2013a.

Duration (hours)	Moisture Content (wb%)		Mass of Water Evaporated (kg)		Mass of the Yam Slices m_f (kg)	
	With storage	Without storage	With storage	Without storage	With storage	Without storage
0	0.8000	0.8000	0	0	2.0000	2.0000
2	0.5616	0.5704	0.0876	0.0689	1.9124	1.9311
4	0.4134	0.4245	1.3181	1.1050	0.6819	0.8950
6	0.3213	0.3318	1.4106	1.4014	0.5894	0.5986
8	0.2641	0.2728	1.4564	1.4499	0.5436	0.5501
10	0.2285	0.2354	1.4815	1.4769	0.5185	0.5231
12	0.2063	0.2115	1.4960	1.4927	0.5040	0.5073
14	0.1926	0.1964	1.5046	1.5022	0.4954	0.4978
16	0.1840	0.1868	1.5098	1.5081	0.4902	0.4919
18	0.1787	0.1807	1.5130	1.5118	0.4870	0.4882

APPENDIX C: SOLAR DRYERS WITH DRIED PRODUCTS



Plate C1: Display of the dryers before fixing the glazing and chimneys



Plate C2: Yam slices before drying



Plate C3: Yam slices after drying

APPENDIX D: INSTRUMENT USED FOR MEASUREMENTS



Plate D1: Weight Balance (Camry Premium)



Plate D2: Thermocouples Device (Kane-May 340 Digital Thermometer)



Plate D3: Anemometer (EL-3 Aerovane)



Plate D4: Solarimeter (SL 100 Solarimeter)

APPENDIX E: MATLAB CODE FOR SIMULATION OF WEIGHT LOSS OF YAM SLICES

Matlab Code for Dryer with Storage Materials

```
functiondmdt=dryer(time t,moisture_content m,)
Tc=48°C% maximum collector air temperature%
T= Tc+273;                % conversion from degrees to kelvin%
k= 139.3*exp(-7676/(1.8*T+497));
m_e=0.17;               % equilibrium moisture content of yam%
m1=m(1);
dmdt(1)=-k*(m1-m_e);      %rate of change of moisture content%
dmdt=dmdt(:);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%

clc
clearall
m_o=0.8;              %initial moisture content of yam%
tspan=[0:2:18];           %duration of drying%
[t,m]=ode45(@dryer,tspan,m_o);
disp(m);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%

clc
clearall
tspan=[0:2:18];           % duration of drying %
m_i=2;                   % initial weight of yam in kilogram%
m_o=0.8;                 %initial moisture content%
```

```
m=[ 0.8000
   0.5616
   0.4134
   0.3213
   0.2641
   0.2285
   0.2063
   0.1926
   0.1840
   0.1787];            %change of moisture content with drying time%
m_f=m_i*((1-m_o)./(1-m)); %weight loss during drying%
m_w=m_i*(m_o-m)./(1-m);  %mass of water evaporated%
disp(m_f);                            % weight loss of yam slices%
disp(m_w);                            % mass of water evaporated%
end

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

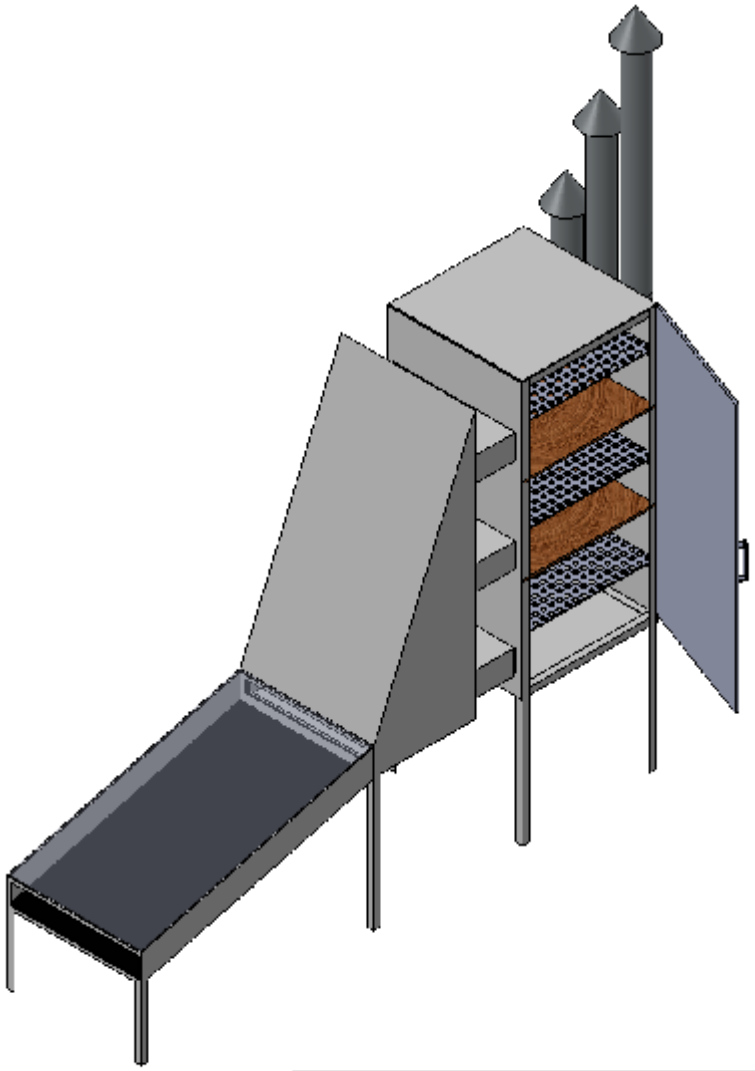
Matlab Code for Dryer without Storage Materials

```
functiondmdt=dryer(time t,moisture_content m,)
Tc=42°C% maximum collector air temperature%
T= Tc+273;               % conversion from degrees to kelvin
k= 139.3*exp(-7676/(1.8*T+497));
m_e=0.17;                % equilibrium moisture content of yam%
m1=m(1);
dmdt(1)=-k*(m1-m_e);     %rate of change of moisture content%
dmdt=dmdt(:);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
clc
clearall
m_o=0.8;                 %initial moisture content of yam%
tspan=[0:2:18];          %duration of drying%
[t,m]=ode45(@dryer,tspan,m_o);
disp(m);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%
clc
clearall
tspan=[0:2:18];          % duration of drying %
m_i=2;                   % initial weight of yam in kilogram%
m_o=0.8;                 %initial moisture content%
m=[ 0.8000
   0.5704
   0.4245
   0.3318
   0.2728
```

```
    0.2354
    0.2115
    0.1964
    0.1868
    0.1807];            %change of moisture content with drying time%
m_f=m_i*((1-m_o). / (1-m)); %weight loss during drying%
m_w=m_i*(m_o-m). / (1-m)  %mass of water evaporated%
disp(m_f);                              % weight loss of yam slices%
disp(m_w);                              % mass of water evaporated%
end
```

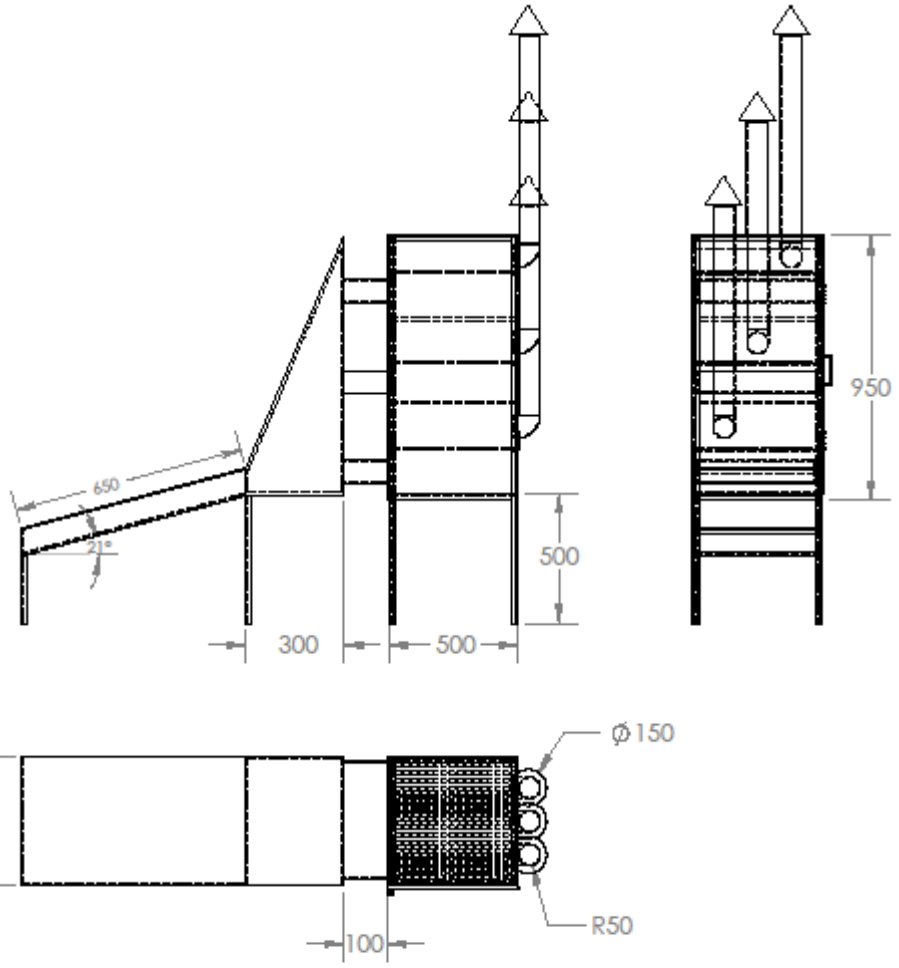
APPENDIX F: DRAWINGS



DEPARTMENT OF MECHANICAL ENGINEERING
AHMADU BELLO UNIVERSITY,ZARIA

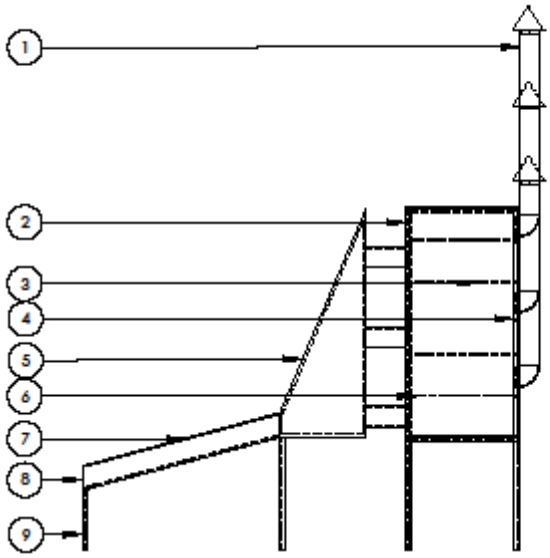
TITLE: ASSEMBLY OF THE MIXED-MODE SOLAR CROP DRYER

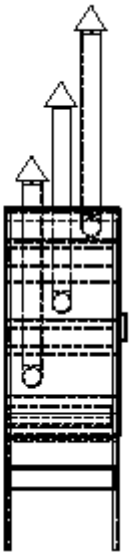
	NAME	SIGNATURE	DATE	DRAWING NO:01
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:25

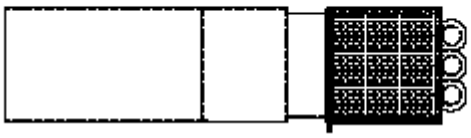


ALL DIMENSIONS ARE IN mm

DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:ASSEMBLY OF THE MIXED-MODE SOLAR CROP DRYER				
	NAME	SIGNATURE	DATE	DRAWING NO:02
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:50







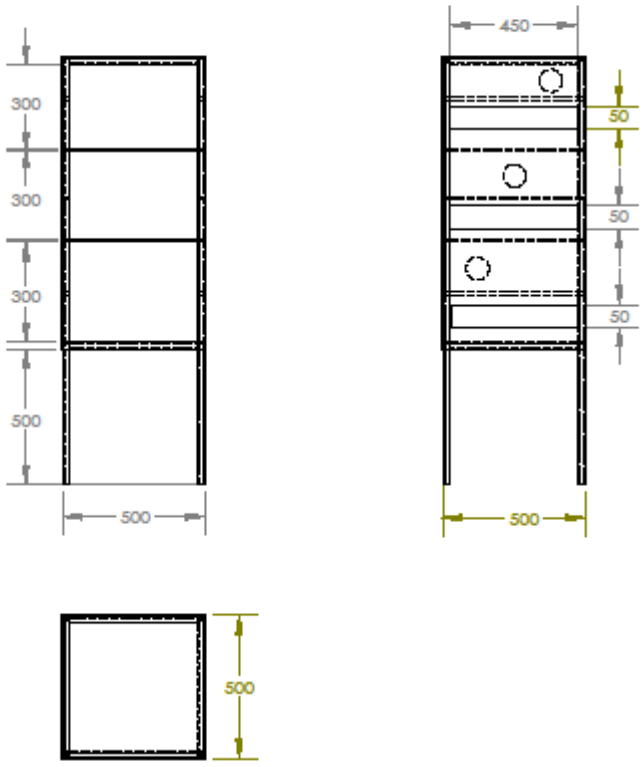
DETAIL	DESCRIPTION	QTY.	MATERIAL	REMARK
9	Frame	1	Angle iron	Fabricated
8	Absorber plate	1	Galvanised steel sheet	Fabricated
7	Glazing	1	Transparent glass	Standard
6	Tray	3	Galvanised steel sheet	Fabricated
5	Air duct	1	Galvanised steel sheet	Fabricated
4	Drying chamber	1	Galvanised steel sheet	Fabricated
3	Partition	2	Wood	Fabricated
2	Access Door	1	Transparent glass	Fabricated
1	Chimney	3	Galvanised steel sheet	Fabricated

ALL DIMENSIONS ARE IN mm

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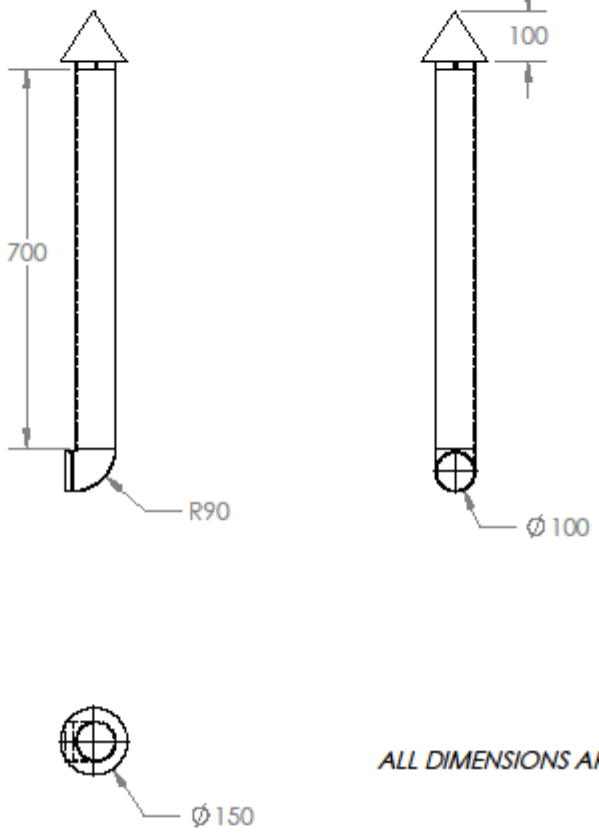
TITLE: ASSEMBLY OF THE MIXED-MODE SOLAR CROP DRYER

	NAME	SIGNATURE	DATE	DRAWING NO:03
DRAWN	ABUBAKAR SHITU			
REG. NO.	P13EGME8001			
CHKD	DR. UMARU SAMAILA			
APPV'D	DR. F.O ANAFI			SCALE:1:50



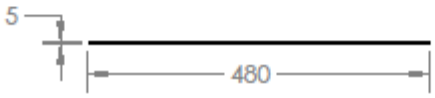
ALL DIMENSIONS ARE IN mm

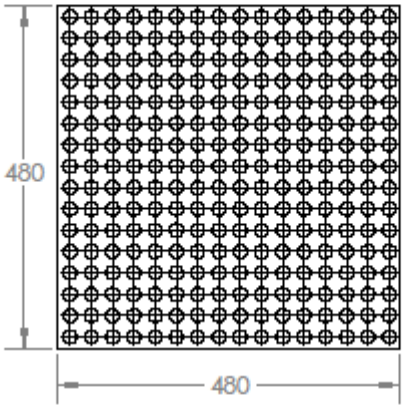
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE: SUBASSEMBLY OF DRYING UNIT				
	NAME	SIGNATURE	DATE	DRAWING NO:04
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20



ALL DIMENSIONS ARE IN mm

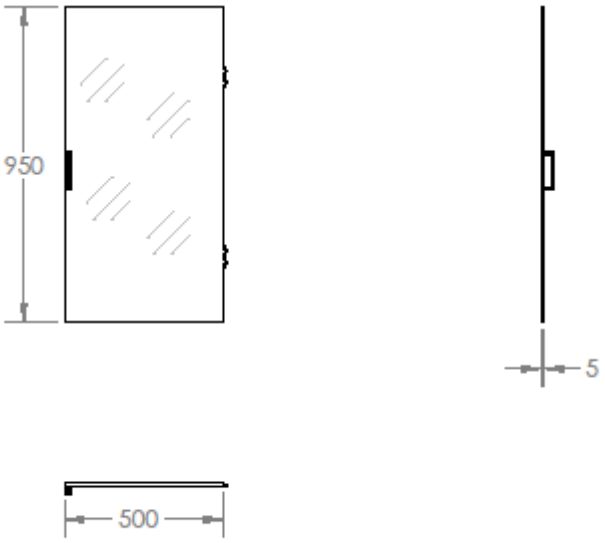
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:	CHIMNEY UNIT			
	NAME	SIGNATURE	DATE	DRAWING NO:05
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20





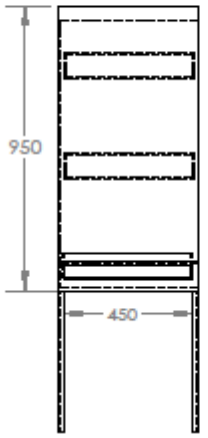
ALL DIMENSIONS ARE IN mm

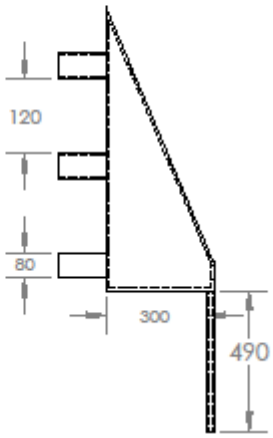
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE: TRAY				
	NAME	SIGNATURE	DATE	DRAWING NO:06
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:10

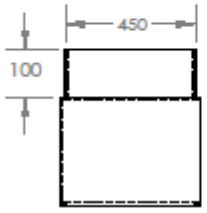


ALL DIMENSIONS ARE IN mm

DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE: GLASS DOOR UNIT				
	NAME	SIGNATURE	DATE	DRAWING NO:07
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20

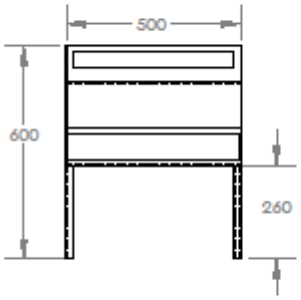


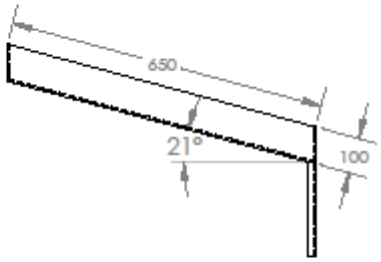




ALL DIMENSIONS ARE IN mm

DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:	SUBASSEMBLY OF AIR DUCT UNIT			
	NAME	SIGNATURE	DATE	DRAWING NO:08
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20

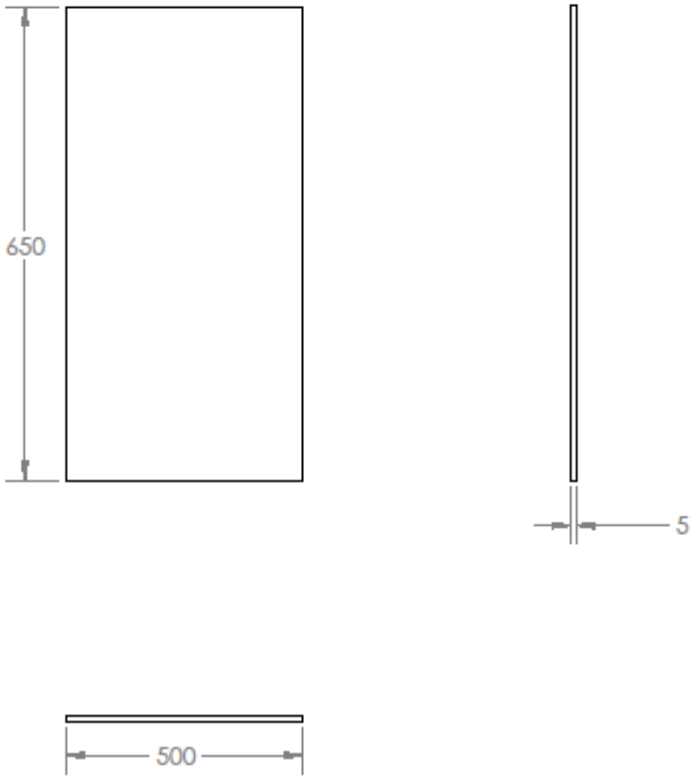






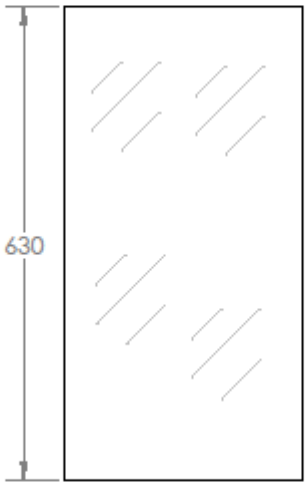
ALL DIMENSIONS ARE IN mm

DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:	SUBASSEMBLY OF SOLAR COLLECTOR UNIT			
	NAME	SIGNATURE	DATE	DRAWING NO:09
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20



ALL DIMENSIONS ARE IN mm

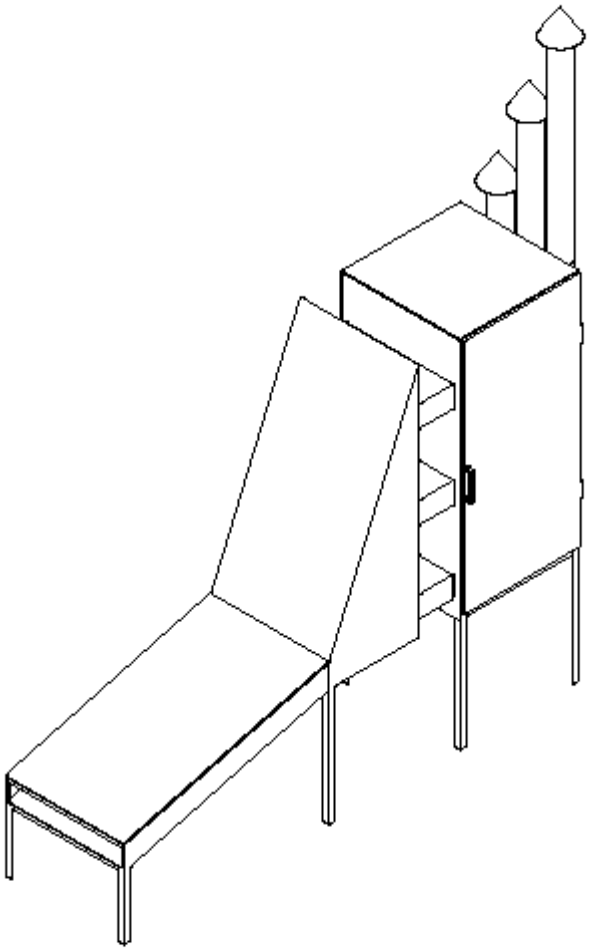
DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:	ABSORBER PLATE			
	NAME	SIGNATURE	DATE	DRAWING NO:10
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20



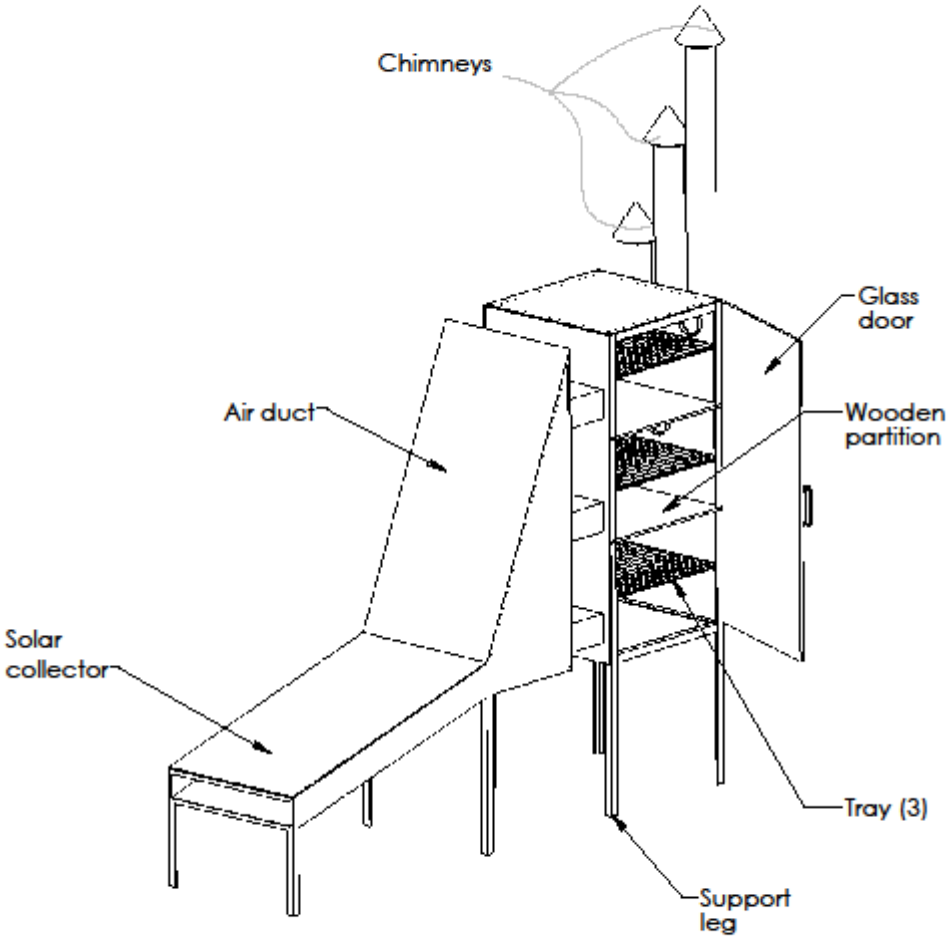


ALL DIMENSIONS ARE IN mm

DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE:	GLAZING			
	NAME	SIGNATURE	DATE	DRAWING NO:11
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:20



DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE: ASSEMBLY OF THE MIXED-MODE SOLAR CROP DRYER				
	NAME	SIGNATURE	DATE	DRAWING NO:12
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:25



DEPARTMENT OF MECHANICAL ENGINEERING AHMADU BELLO UNIVERSITY,ZARIA				
TITLE: ASSEMBLY OF THE MIXED-MODE SOLAR CROP DRYER				
	NAME	SIGNATURE	DATE	DRAWING NO:13
DRAWN	*ABUBAKAR SHITU*			
REG. NO.	*P13EGME8001*			
CHK'D	*DR. UMARU SAMAILA*			
APPV'D	*DR. F.O ANAFI*			SCALE:1:25