DEVELOPMENT OF SOLAR DRYER FOR FOOD PRESERVATION

BY

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CERTIFICATION

This is to certify that **IJALANA**, Oyindamola Gabriel, an undergraduate student in the Department of Agricultural and Bioresources Engineering, Federal Universiy Oye-Ekiti with Matriculation Number ABE/13/1041, has successfully carried out and completed this project work in partial fulfilment of the requirements for the award of the degree of Bachelor of Engineering in Agricultural and Bioresources Engineering. The work embodied in this report is original and has not been submitted in part or full for any other Diploma or Degree in this University or any other University.

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DEDICATION

I dedicate this project in a special way to my elder brothers Mr. Ijalana Oladipo and Ijalana Olatunde for the encouragement and their financial support they gave to me throughout my pursue of academics to this extend.

To my great friends, and sisters for their persistent support and encouragement throughout my academic life

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ABSTRACT

A solar dryer integrated with a simple bed rock was designed and constructed with locally available materials to dry tomatoes and pepper. The dryer was composed of solar collector, drying chamber, back - up heater and airflow system all integrated together. The back-up heater provided alternative heating during cloudy weather conditions or at night when solar radiations were low. The dryer was designed based on climatic conditions of Ikole summit located in Ikole - Ekiti Nigeria. The average ambient conditions were 26°C air temperatures and 83% relative humidity with daily global solar radiation incident on horizontal surface of about 600W/M^2 .This study describes the design considerations and results of calculations of design parameters. A minimum of 3.77 solar collector area was required to dry a batch of 1kg tomatoes and pepper vegetables in 8 hours under force convection from the initial moisture content of 84.7% to final moisture content of 10.1% wet basis. Using similarity laws a dryer with collector area of 1.78 was fabricated and used in experimental drying tests under varied heat source conditions namely; solar, bed rock and a combination of solar and bed rock. Solar assisted dryer system efficiency was estimated at 70%.

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CHAPTER ONE

INTRODUCTION

Drying is a very important method in the processing of food items especially the preservation of fruits and vegetables for longer periods. The heat from the sun coupled with the wind has been used to dry food for preservation for several years. The use of proper drying techniques can significantly reduce the post- harvest losses of agricultural product. Traditionally drying had been accomplished by the open sun drying. Then electricity had been used to accelerate the process of dying by use of tray dryer etc .Opening sun drying is still the common one however; there exist many technical problems associated with the open sun drying namely atmospheric condition, insect infestation, cloudiness, intrusions from animals and man. Drying is also the oldest method of preserving agricultural products and it is energy intensive process. High prices and shortages of fossil fuels have increased the emphasis on using alternative renewable energy resources. Drying of agricultural products using renewable energy such as solar energy is environmental friendly and has little environmental impact. Development of solar drying has brought a techniques and equipment for fast drying of various agricultural product foods. Product dried in solar dryer are superior in quality (colour and flavour). Though the same superior quality product can be obtained by using electricity or electrical power, but the electric operations are expensive and are not within the reach of our rural and tribal population. In agricultural dryer, drying occurs by supplying heat to the wet material and thus vaporizing the liquid content. Generally, heat may be supplied by convection (direct dryer), conduction (contact or indirect dryers), and radiation or volumetrically by placing the wet product in a microwave or radio frequency electromagnetic field (Orsat ét al., 2006). Most industrial dryers are of the convective type with hot air or direct combustion gases as drying medium. Almost all drying application involves removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundary of the drying product so that the heat may be diffuse into the solid product primarily by conduction (Nwajinka, 2014).

Solar dryer is equipment for drying agricultural product under controlled conditions. The controlled drying means controlling the parameters like drying air, temperature, humidity, drying rate and air flow rate. The designing of solar, dryer parameters must be put into consideration. Since there are many options in design of solar dryers. Dryer are classified into several categories depending upon the mode of heating or the operational mode of heat derived from the solar radiations, and is use to remove the moisture from the wet product. The solar dryers are classified into three (3) categories: e.g. direct solar dryer, indirect solar dryer and forced circulation type dryers or continues flow dryers.

In direct solar dryer, the agricultural product is placed in shallow layer in an enclosure with a transparent cover to reduce heat losses, and it simultaneously gives the product assertive production from rain and dust. The food product is heated up and the moisture from the product evaporates and goes out by the natural convection these kinds of dryers are popular in the developing countries. This type of dryer has three parts: the collector, the drying cabinet, and the air blower. The temperature inside the chamber increases above the crops. Direct convective temperature losses are then reduced to ambient levels using a glass cover, which is advantageous for increasing crop and chamber temperature. However, this type of solar dryer also has some limitations. For example, the crops may become discolored because of direct exposure to solar cell radiation. Moisture compression inside the glass cover also decreases its transitivity.

In an indirect solar dryer, the sun's heat is first collected by the solar collectors and is then passed onto the dryer cabinet, where the drying occurs and the product is not directly exposed to the solar radiations. The solar air that enters the chamber is heated and is then made to pass through over the wet crops. The air heaters are connected. In some designs dryers, the drying chamber receives hot air only from the air heater. These dryers are little superior than the direct solar because the drying temperature, humidity and the drying rates can be controlled to some extent. The performance of an indirect-type solar dryer can be found under hostile weather situations, the dryer is capable of giving good output. Moreover, it is ideal for small farms because of its low-cost requirements.

In a forced convection system, a fan is used to move air through the dryer at higher air velocities - up to 3ms -1 through the crop usually improve drying rates especially in the constant rate drying period. The product is loaded or unloaded continuously or periodically. The type of dryer is comparatively thermodynamically efficient, faster which can be used to dry large agricultural product. The airflow rate can also be controlled and varied depending on the stage of drying. In addition, the quantity of the crop in the dryer can be increased because the fan can overcome any additional resistance to airflow. It is generally agreed that well designed forced-convection distributed solar dryers are more effective and more controllable than the natural-circulation types. The availability of solar energy at a particular location is essential in order to perform any activity regarding management, design and research of solar appliances. Since the availability of solar radiation is varies seasonally, daily and hour as well as the orientation, it is compulsory to know the optimum orientation of that particular geographical area by considering other climatic parameters that would receive the maximum solar radiation.

The disadvantages of a forced convection system are the increased capital and running costs and the requirement for electricity.

1.1. PROBLEM STATEMENT

Drying is one of the oldest methods using solar energy where the products such as vegetables, fruits, fish, and meat, etc to be dried exposed directly to the sun. This method has many disadvantages such as spoilt products due to rain, wind, dust, insect infestation, animal attack and fungi. The speed of drying especially in open sun drying which is solar radiation exposed directly to the products will cause the product's surface becomes hard before the moisture inside has a chance to evaporate and it will affect the quality of dried product due to over drying. Open sun drying also suffers from a high labor requirement and excessive crop handling particularly in periods of inclement weather which can result in high costs, crop damage and a loss in quality. Although the spreading of the crop on the ground or on a platform and drying it directly by the sun is cheap and successfully employed for many products throughout the world, where solar radiation and climatic conditions are favorable, because of the above mentioned factors of open sun drying process and a better understanding of the method of utilizing solar energy to advantage, have given rise to a scientific method called solar drying. Solar drying of farm crops offers the following advantages by permitting: early harvest which reduces the field loss of products from storm and natural shattering.

Food scientists have found that by reducing the moisture content of food to between 10 and 20%, bacteria, yeast, mold and enzymes are prevented from spoiling it. The flavor and most of the nutritional value is preserved and concentrated. Wherever possible, it is traditional to harvest most vegetables crops during a dry period or season and simple drying methods such as sun drying are adequate. However, maturity of the crop does not always coincide with a suitably dry period. Furthermore, the introduction of high-yielding varieties, irrigation, and improved farming practices have led to the need for alternative drying practices to cope with the increased production and vegetables harvested during the wet season as a result of multi-cropping.

The field conditions (dry and fewer weeds) are often better for harvesting earlier in the season, planning the harvesting season to make better use of labor. Farm crops can be harvested when natural drying conditions are unfavorable, long-time storage with little deterioration. Extended storage periods are becoming increasingly important with large amount of grain being stored and carried over through another storage year by the farmer, government, and industry, and the farmer's taking advantage of higher price a few months after harvest although in some years there may be no price advantage. By removing moisture, the possibility of the vegetables heating with subsequent reduction or destruction of mould is decreased.

The farmer's selling a better quality product which is worth more to him and to those who must use those products. Therefore, by providing a sheltered drying area or chamber in which the crops to be dried and stored, a stream of air is heated by solar energy to reduce its relative humidity which is then passed over the crops. This form of solar drying could improve the quality of the crop to be dried, reduce spoilage by contamination and local overheating, reduce spillage losses, speed up the drying process, achieve better quality control, and reduction in drying time.

1.2. GENERAL OBJECTIVES

The general objective of this study is to develop an active solar dryer in which the vegetables are dried simultaneously by both direct radiations through the transparent walls and roof of the cabinet and by the heated air from the solar collector.

1.2.1. SPECIFIC OBJECTIVES

The specific objectives of this study are

1. To develop and construct a solar dryer system.
2. To evaluate the performance of the designed solar dryer.

1.3. JUSTIFICATION

A very large proportion of food product in developing countries like Nigeria is destroyed before they reach market. This waste may be reduced considerably if the products are dried before they are transported to the market.

Most crops are being sun-dried on the ground; this is however a slow ineffective method because it takes days to achieve tangible results. Also, crops are exposed to attack by bacterial and the like. Ordinary sun drying method was found to be tedious, time wasting, wastage in terms of produce and consequently having a very low hygienic level.

The direct exposure to sunlight, or more precisely ultraviolet radiation, can greatly reduce the level of nutrients such as vitamins in the dried product. Solanum lycopersium(tomatoes), Abelmoschus esculentus (okro), Zea mays (maize), which are used extensively in Nigeria.

This project presents the design, construction and performance of an active solar dryer for food preservation. In the dryer, the heated air from a separate solar collector is passed through a vegetable bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls and roof. The results obtained during the test period revealed that the temperatures inside the dryer and solar collector were much higher than the ambient temperature during most hours of the day-light. The temperature rise inside the drying cabinet was up to 74% for about three hours immediately after 12.00h (noon). The dryer exhibited sufficient ability to dry food items reasonably rapidly to a safe moisture level and simultaneously it ensures a superior quality of the dried product.

1.4. SCOPE OF THE STUDY

The study takes into account the preservation of fruits and vegetables for longer periods of time.

CHAPTER TWO

REVIEW OF LITERATURE

Drying is one of the methods used to preserve food products for longer periods. The heat from the sun coupled with the wind has been used to dry food for preservation for several thousand years. The purpose of drying is to remove moisture from the agricultural product so that it can be processed safely and stored for increased periods of time. Crops are also dried before storage or, during storage, by force circulation of air, to prevent spontaneous combustion by inhibiting fermentation. Drying is the oldest preservation technique of agricultural products and it is an energy intensive process. High prices and shortages of fossil fuels have increased the emphasis on using alternative renewable energy resources. Drying of agricultural products using renewable energy such as solar energy is environmental friendly and has less environmental impact. It is estimated that 20% of the world's grain production is lost after harvest because of inefficient handling and implementation of post-harvest technology, says Hartman's (1991). Grains and seeds are normally harvested at a moisture level between 18% and 40% depending on the nature of crop. When biological products, including cereal grains, are dried in batch rather than as individual particles, they will display a constant rate drying period (Brooker et al.,1997). Because of the different in drying behaviour of individual kernels and a bed thickness less than 200mm is termed as thin layer drying whereas, drying with crop bed thickness more than 200mm, it is called deep bed drying (Chakraverty, 1995). Heat transfer must occur to change the temperature of the material to be dried and mass transfer occurs when moisture is removed from within the material to the surface accompanied by its evaporation from the surface to the surrounding atmosphere (Hii et al., 2012). For successful drying, enough heat to draw out moisture without cooking the food and adequate dry air circulation to carry off the released moisture should be applied. In addition, the moisture must be removed as quickly as possible at a temperature that does not seriously affect the flavor, texture and color of the food (Sanni et al., 2012). Drying is a very suitable preservation technique for developing countries with poorly established low-temperature and thermal processing facility (Hii et al., 2012). Drying can ensure continuous food supply and production of high quality marketable products (Weiss and Buchinger, 2002).

Solar drying may be classified into direct and indirect solar dryer. In direct solar dryers the air heater contains the grains and solar energy which passes through transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed. However, in indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed, while in the mixed-mode type of dryer, the heated air from a separate solar collector is passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or the roof.

Energy is important for the existence and development of human kind and is a key issue in international politics, the economy, military preparedness, and diplomacy. To reduce the impact of conventional energy sources on the environment, much attention should be paid to the development of new energy and renewable energy resources. Solar energy, which is environment friendly, is renewable and can serve as a sustainable energy source.

Hence, it will certainly become an important part of the future energy structure with the increasingly drying up of the terrestrial fossil fuel. However, the lower energy density and seasonal doing with geographical dependence are the major challenges in identifying suitable applications using solar energy as the heat source. Consequently, exploring high efficiency solar energy concentration technology is necessary and realistic

Solar energy is free, environmentally clean, and therefore is recognized as one of the most promising alternative energy recourses options. In near future, the large-scale introduction of solar energy systems, directly converting solar radiation into heat, can be looked forward. However, solar energy is intermittent by its nature; there is no sun at night. Its total available value is seasonal and is dependent on the meteorological conditions of the location. Unreliability is the biggest retarding factor for extensive solar energy utilization. Of course, reliability of solar energy can be increased by storing its portion when it is in excess of the load and using the stored energy whenever needed.

Solar drying is a potential decentralized thermal application of solar energy particularly in developing countries. However, so far, there has been very little field penetration of solar drying technology. In the initial phase of dissemination, identification of suitable areas for using solar dryers would be extremely helpful towards their market penetration.

Solar drying is a viable option to open sun drying. Solar dryers can increase the drying temperature and reduce relative humidity resulting in lower moisture content of dried product. Unlike sun drying, a solar dryer constitutes a specialized structure that controls the drying process and protects the produce from damage by dust, rain and insects (Raju et al., 2013). Since the products are protected and the drying time is reduced significantly, the quality of dried product obtained by solar drying is better than that of sun drying (Seveda, 2013). Solar energy has been used throughout the world to dry products. Such is the diversity of solar dryers that commonly solar-dried products include grains, fruits, meat, vegetables and fish. A typical solar dryer improves upon the traditional open-air sun system in five important ways.

It is more efficient. Since materials can be dried more quickly, less will be lost to spoilage immediately after harvest. This is especially true of products that require immediate drying such as freshly harvested grain with high moisture content. In this way, a larger percentage of products will be available for human consumption. Also, less of the harvest will be lost to marauding animals and insects since the products are in safely enclosed compartments. It is hygienic. Since materials are dried in a controlled environment, they are less likely to be contaminated by pests, and can be stored with less likelihood of the growth of toxic fungi. It is healthier. Drying materials at optimum temperatures and in a shorter amount of time enables them to retain more of their nutritional value such as vitamin C. An added bonus is that products will look better, which enhances their marketability and hence provides better financial returns for the farmers. It is cheap. Using freely available solar energy instead of conventional fuels to dry products, or using a cheap supplementary supply of solar heat, so reducing conventional fuel demand can result in significant cost savings.

Solar drying refers to a technique that utilizes incident solar radiation to convert it into thermal energy required for drying purposes. Most solar dryers use solar air heaters and the heated air is then passed through the drying chamber (containing material) to be dried. The air transfers its energy to the material causing evaporation of moisture of the material.

2.1. Drying Mechanism

In the process of drying heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry the evaporated moisture. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of an individual vegetable to the surface, and the evaporation of moisture from the surface to the surrounding air. The rate of drying is determining by the moisture content and the temperature, the (velocity) humidity and the velocity of the air in contact with the vegetable.

The drying of a product is a complex heat and mass transfer process which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables which depend on parameters like surface characteristics (rough or smooth surface), chemical composition (sugars, starches, etc.), physical structure(porosity, density, etc.), and size and shape of products. The rate of moisture movement from the product inside to the air outside differs from one product to another and depends very much on whether the material is hygroscopic or non-hygroscopic. Non-hygroscopic materials can be dried to zero moisture level while the hygroscopic materials like most of the food products will always have residual moisture content. This moisture, in hygroscopic material, may be bound moisture which remained in the material due to closed capillaries or due to surface forces and unbound moisture which remained in the material due to the surface tension of water.

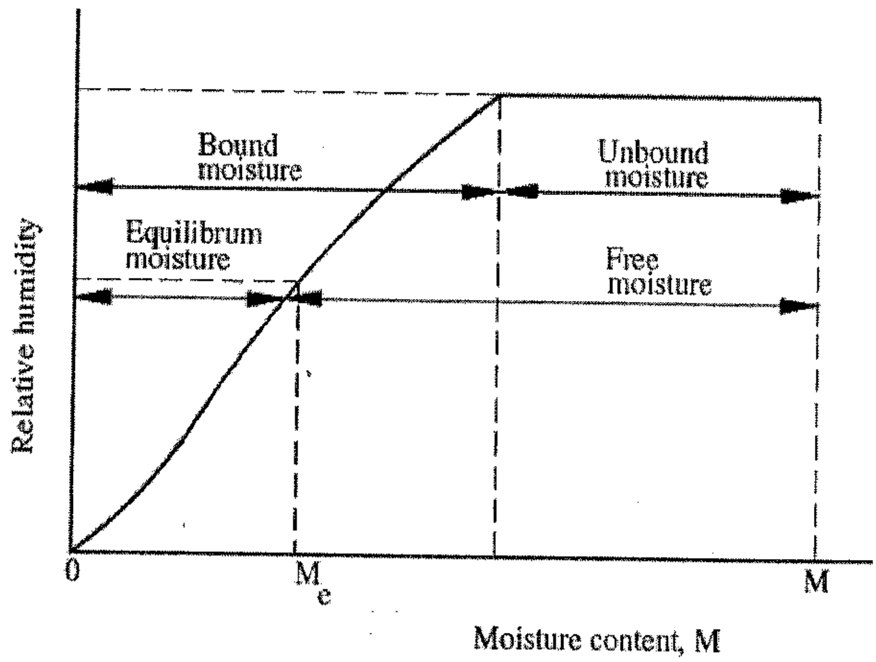

Figure 2.1 Moisture in the drying material.

When the hygroscopic material is exposed to air, it will absorb either moisture or desorbs moisture depending on the relative humidity of the air. The equilibrium moisture content (EMC = Me) will soon reach when the vapour pressure of water in the material becomes equal to the partial pressure of water in the surrounding air. The equilibrium moisture content in drying is therefore important since this is the minimum moisture to which the material can be dried under a given set of drying conditions. A series of drying characteristic curves can be plotted. The best is if the average moisture content M of the material is plotted versus time as shown in Figure 2. 2.

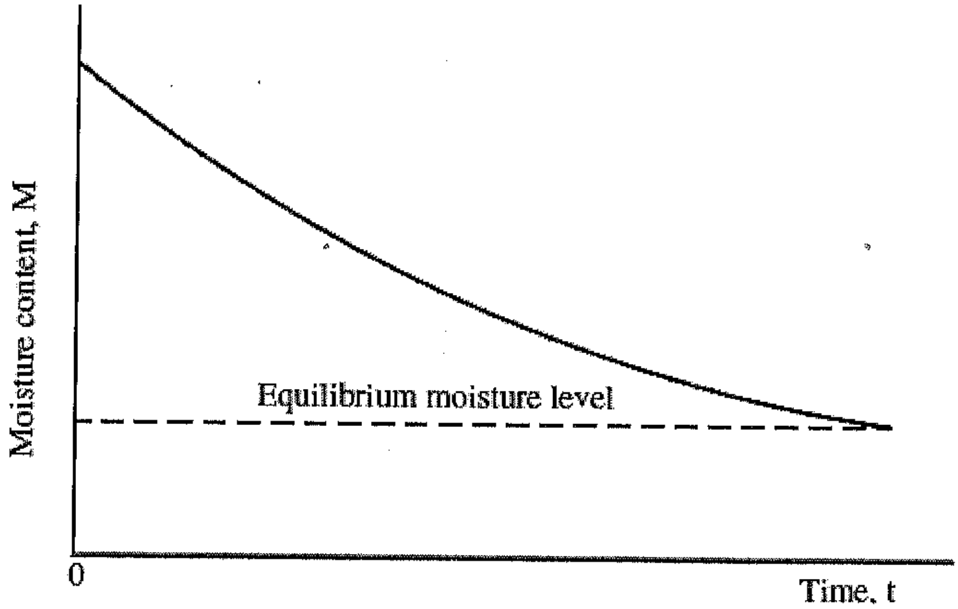

Figure 2.2 Rate of moisture loss

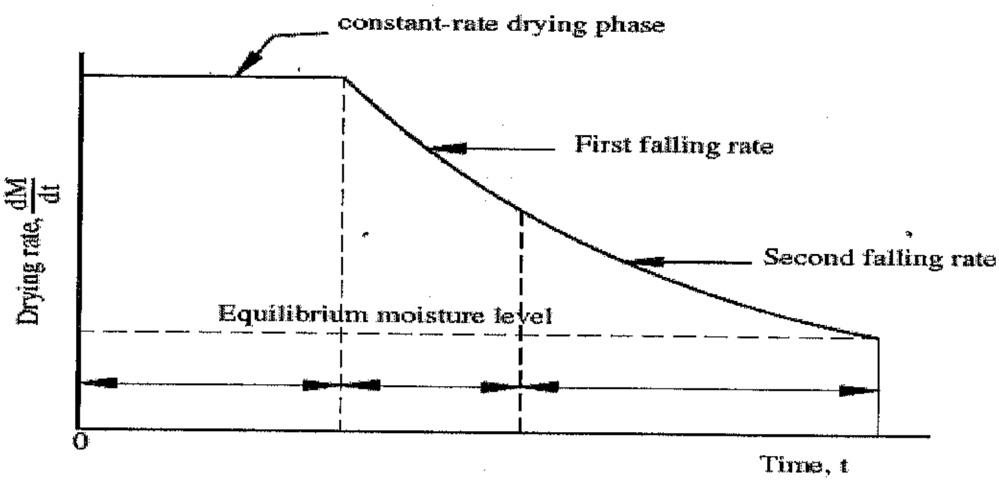

Figure 2.3 Drying rate with time curve

As is seen from Figure 2.3 for both non-hygroscopic and hygroscopic materials, there is a constant drying rate terminating at the critical moisture content followed by falling drying rate. The constant drying rate for both non-hygroscopic and hygroscopic materials is the same while the period of falling rate is little different. For non-hygroscopic materials, in the period of falling rate, the drying rate goes on decreasing till the moisture content become zero. While in the hygroscopic materials, the period of falling rate is similar until the unbound moisture content is completely removed, then the drying rate further decreases and some bound moisture is removed and continues till the vapour pressure of the material becomes equal to the vapour pressure of the drying air. When this equilibrium reaches then the drying rate becomes zero. The period of constant drying for most of the organic materials like fruits, vegetables, etc is short and it is the falling rate period in which is of more interest and which depends on the rate at which the moisture is removed. In the falling rate regime moisture is migrated by diffusion and in the products with high moisture content, the diffusion of moisture is comparatively slower due to turgid cells and filled interstices. In most agricultural products, there is sugar and minerals of water in the liquid phase which also migrates to the surfaces, increase the viscosity hence reduce the surface vapour pressure and hence reduce the moisture evaporation rate.

2.2 Air Properties

The properties of the air flowing around the product are major factors in determining the rate of removal of moisture. The capacity of air to remove moisture is principally dependent upon its initial temperature and humidity; the greater the temperature and lower the humidity the greater the moisture removal capacity of the air. The relationship between temperature, humidity and other thermodynamic properties is represented by the psychometric chart. It is important to appreciate the difference between the absolute humidity and relative humidity of air. The absolute humidity is the moisture content of the air (mass of water per unit mass of air) whereas the relative humidity is the ratio, expressed as a percentage, of the moisture content of the air at a specified temperature to the moisture content of air if it were saturated at that temperature. The changes in condition of air when it is heated using the solar energy and then passed through a bed of moist product are shown in Figure 2.4. The heating of air from temperature T_A to T_B is represented by the line AB. During heating the absolute humidity remains constant at *A* whereas the relative humidity falls from A to B As air moves through the material to be dried, it absorbs moisture. Under (hypothetical) adiabatic drying; sensible heat in the air is converted to latent heat and the change in the condition of air is represented along a line of constant enthalpy, BC. Both absolute humidity and relative humidity increase from *B* and *C* and from B to *C*, respectively, but air temperature decreases to, *TC*. The absorption of moisture by the air would be the difference between the absolute humidity's at C and B. (*C* - *A*). If unheated air is passed through the bed, the drying process would be represented by the line

AD. Assuming that the air at D to be at the same relative humidity, *C* , as the heated air at C, then the absorbed moisture would be((*D* - *A*), considerably less than that absorbed by the heated air ((*C* - *A*).

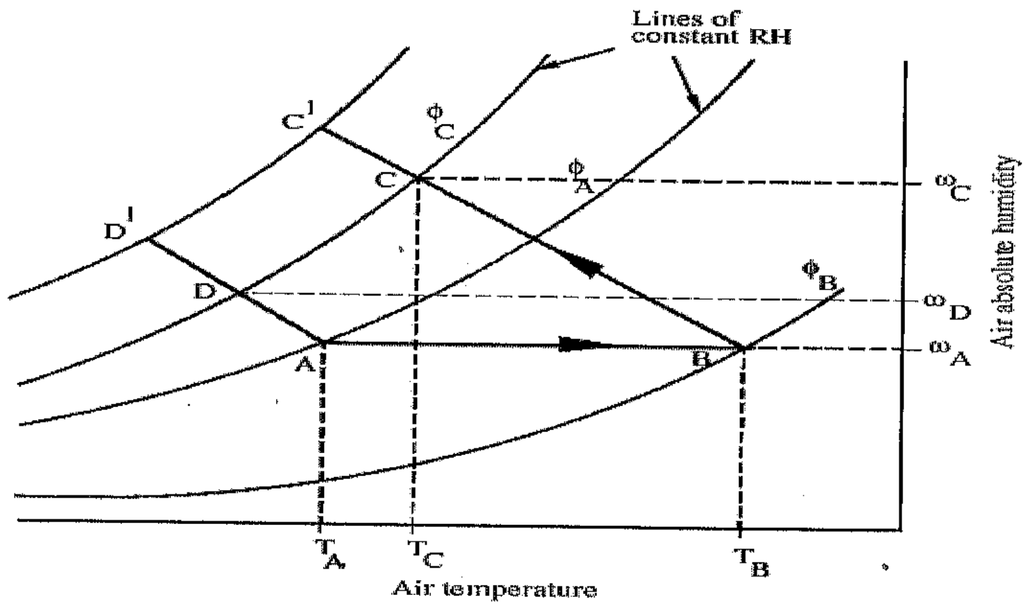

Figure 2.4 Representation of drying process

2.3 Classification of drying systems

All drying systems can be classified primarily according to their operating temperature ranges into two main groups of high temperature dryers and low temperature dryers. However; dryers are more commonly classified broadly according to their heating sources into fossil fuel dryers (more commonly known as convèntional dryers) and solar-energy dryers. Strictly, all practically-realized designs of high temperature dryers are fossil fuel powered, while the low temperature dryers are either fossil fuel or solar-energy based systems.

1. High temperature dryers

High temperature dryers are necessary when very fast drying is desired. They are usually employed when the products require a short exposure to the drying air. Their operatiñg temperatures are such that, if the drying air remains in contact with the product until equilibrium moisture content is reached, serious over drying will occur. Thus, the products are only dried to the required moisture contents and later cooled. High temperature dryers are usually classified into batch dryers and continuous-flow dryers. In batch dryers, the products are dried in a bin and subsequently moved to storage. Thus, they are usually known as batch-in-bin dryers. Continuous-flow dryers are heated columns through which the product flows under gravity and is exposed to heated air while descending. Because of the temperature ranges prevalent in high temperature dryers, most known designs are electricity or fossil-fuel powered. Only a very few practically-realized designs of high temperature drying systems are solar-energy heated

2. Low temperature dryers

In low temperature drying systems, the moisture content of the product is usually brought in equilibrium with the drying air by constant ventilation. Thus, they do tolerate intermittent or variable heat input. Low temperature drying enables products to be dried in bulk and is most suited also for long term storage systems. Thus, they are usually known as bulk or storage dryers. Their ability to accommodate intermittent heat input makes low temperature drying most appropriate for solar-energy applications. Thus, some conventional dryers and most practically-realized designs of solar-energy dryers are of the low temperature type.

2.4 Types of solar driers

There are different types of solar dryers and literature classifies them based on various criteria. Accordingly, solar dryers can be classified as direct or indirect based on whether the material to be dried is exposed to direct insolation or not. Based upon the mechanism of air flow through the dryer, solar dryers can be either natural convection solar dryers or forced convection solar dryers (Brenndorfer et al., 1987). Natural convection solar drying also called passive solar-energy drying system utilizes the natural principle that hot air rises (Green and Schwarz, 2001). The flow of air through such dryers is based on thermally induced density gradient. On the other hand, forced convection dryers or active solar dryers force the flow of air through the drying chamber using a pressure difference generated by a fan (Brenndorfer et al., 1987).

2.4.1. Direct Solar Dryers

In direct solar dryer a structure with transparent covers and side panels is used to keep the agricultural produce to be dried. Solar radiation absorbed by the product and the internal surfaces of the drying chamber generate heat thus increasing the temperature of the crop and its enclosure (El-Sebaii and

Shalaby, 2012). These types of dryers are suitable for places where direct sunlight can be received for longer periods during the day (Mustayen et al., 2014).

Brenndorfer et al. (1987) classifies direct solar dryers using natural convection with combined drying and collector chamber as cabinet dryer and tent dryer. Figure 2.5 shows sample of cabinet dryer. It can be made from wooden box insulated at its base and side. The material to be dried is kept on a perforated tray. Air coming from the lower part of the cabinet flows through the holes and leave through the upper ventilation holes maintaining a natural air circulation (Mujumdar, 2006).

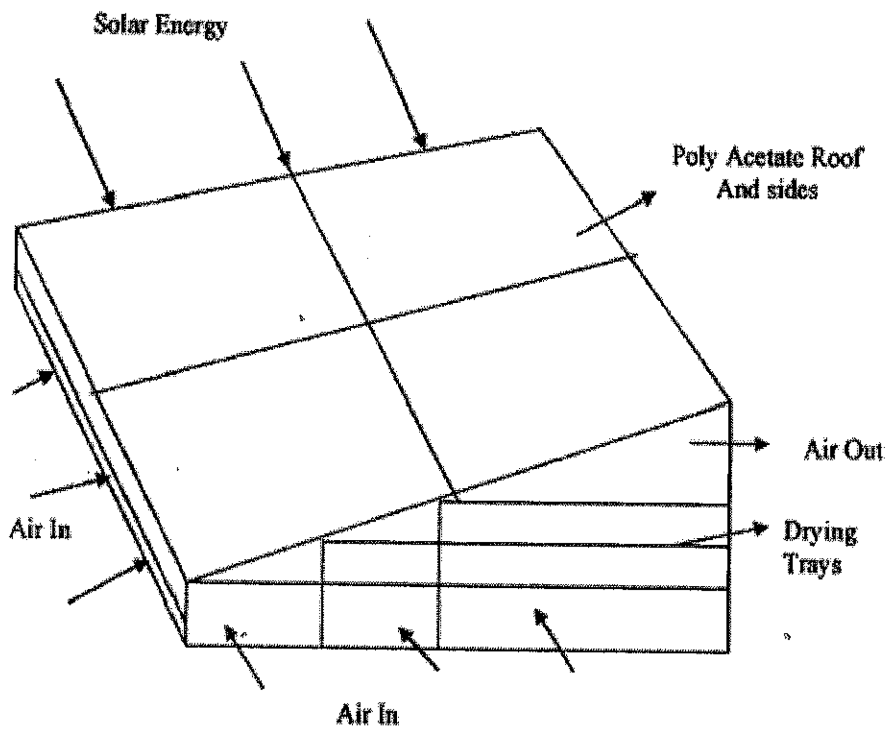

Figure 2.5 Direct solar drying (Natural convection type cabinet drier)

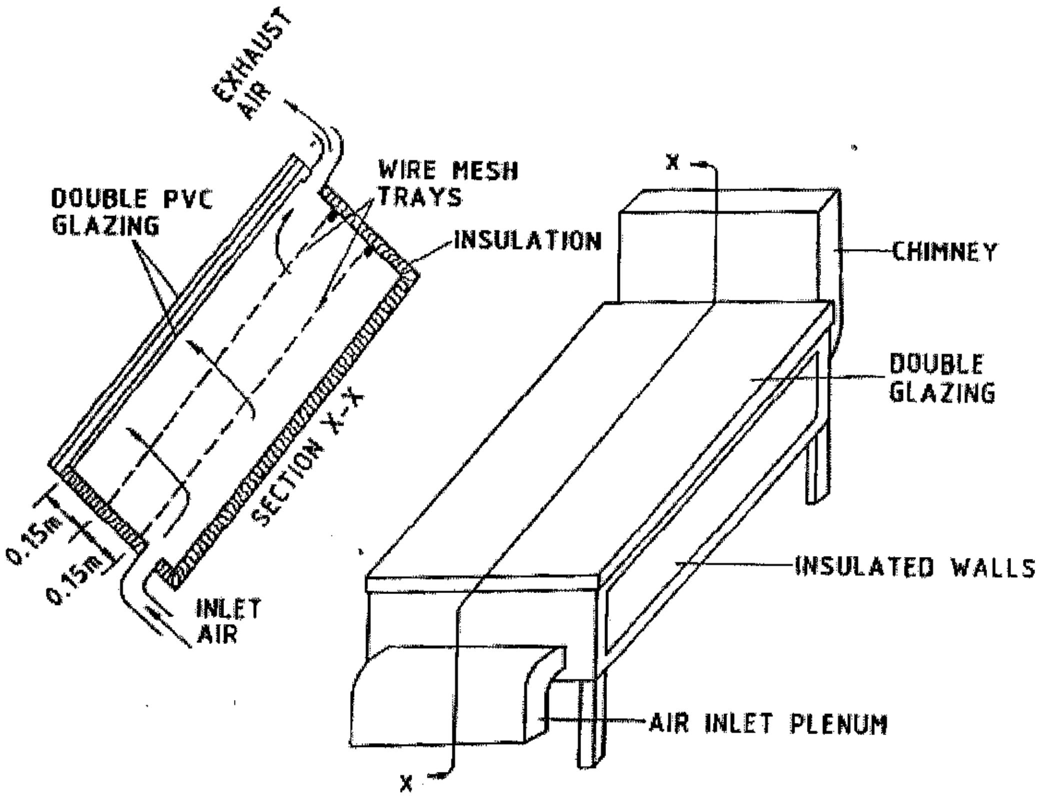

Figure 2.6 A modified natural-circulation solar-energy cabinet dryer

2.4.2 Open Sun Drying (OSD)

The working principle of open sun drying by using only the solar energy, the crops are generally spread on the ground, mat, cement floor where they receive short wavelength solar energy during a major part of the day and also natural air circulation. A part of the energy is reflected back and the remaining is absorbed by the surface depending upon the colour of the crops. The absorbed radiation is converted into thermal energy and the temperature of the material starts to increase. However there are losses like the long wavelength radiation loss from the surface of crop to ambient air through moist air and also convective heat loss due to the blowing wind through moist air over the crop surface. This causes a rise in temperature and formation of water vapor inside the material and then diffuses towards the surface of the and finally losses thermal energy in the end then diffuses towards the surface of the and finally losses the thermal energy in the form of evaporation. In the initial stages, the moisture removal is rapid since the excess moisture on the surface of the product presents a wet surface to the drying air

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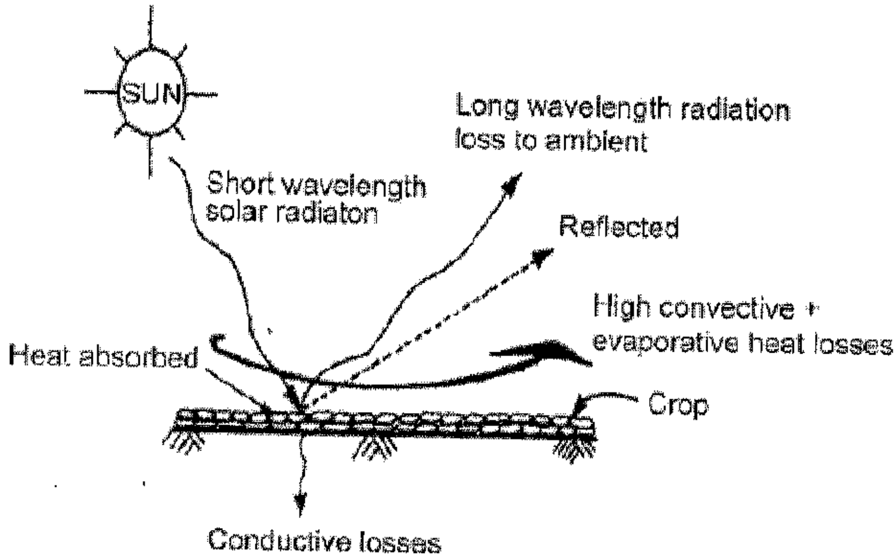
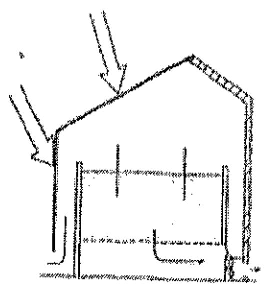
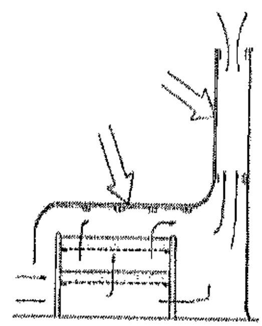
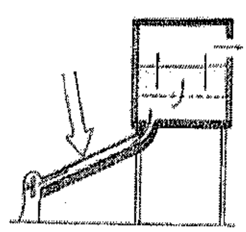
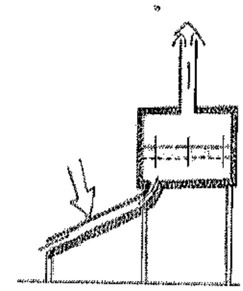


Figure 2.7 The working principle of open sun drying

In general, the open sun drying method does not fulfill the required quality standards and sometimes the products cannot be sold in the International market. With the awareness of inadequacies involved in open sun drying, a more scientific method of solar-energy utilization for crop drying has emerged termed as solar drying. With the awareness of inadequacies involved in open sun drying, a more scientific method of solar-energy utilization for drying has emerged termed as controlled drying or solar drying. The main features of typical designs of the direct and of indirect types solar -energy dryers are illustrated in Table 2.1.

Table 2.1 Typical solar energy dryer designs

	ACTIVE DRYERS	PASSIVE DRYERS
INTEGRAL (DIRECT) TYPE		
DISTRIBUTED (INDIRECT) TYPE		

2.4.3 Indirect Solar Drying (ISD)

The crops in these indirect solar dryers are located in trays or shelves inside an opaque drying cabinet and a separate unit termed as solar collector is used for heating of the entering air into the cabinet. The heated air is allowed to flow through/over the wet crop that provides the heat for moisture evaporation by convective heat transfer between the hot air and the wet crop (Hii *et al.*, 2012).

Drying takes place due to the difference in moisture concentration between the drying air and the air in the vicinity of crop surface. The drying chamber is used for keeping the in wire mesh tray. A downward facing absorber is fixed below the drying chamber at a sufficient distance from the bottom of the drying chamber. A cylindrical reflector is placed under the absorber fitted with the glass cover on its aperture to minimize convective heat losses from the absorber. The absorber can be selectively coated. The inclination of the glass cover is taken as 45° from horizontal to receive maximum radiation. The area of absorber and glass cover are taken equal to the area of bottom of drying chamber. Solar radiation after passing through the glass cover is reflected by cylindrical reflector toward an absorber. After absorber, a part of this is lost to ambient through a glass cover and remaining is transferred to the flowing air above it by convection. The flowing air is thus heated and passes through the placed in the drying chamber. The exhaust air and moisture is removed through a vent provided at the top of drying chamber.

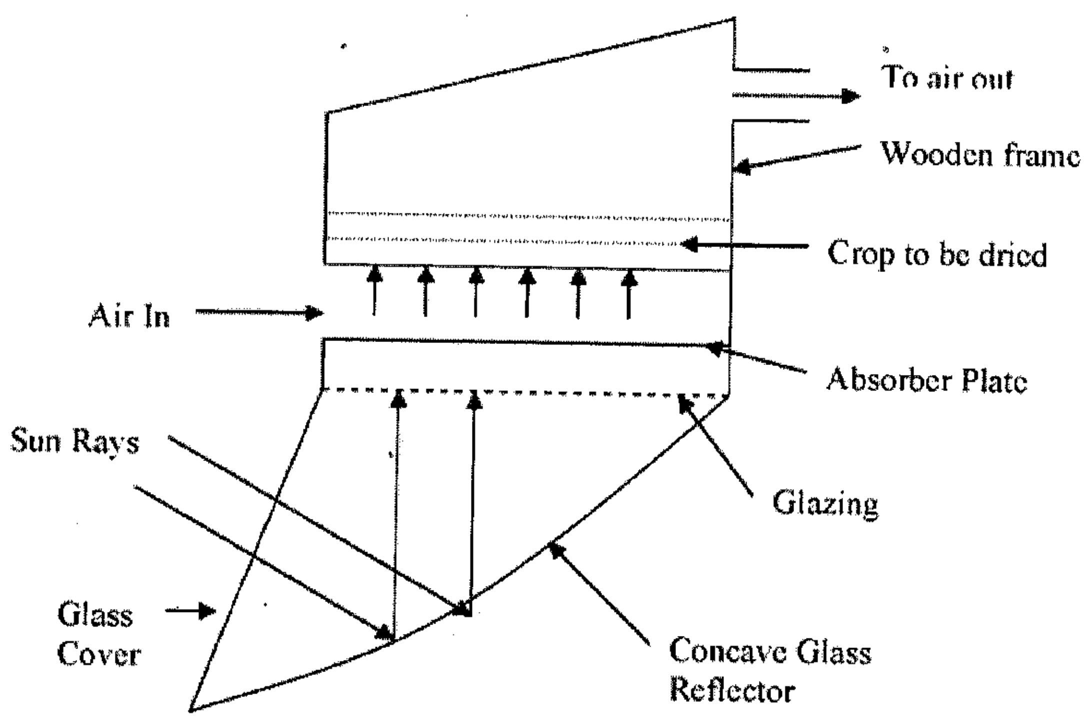


Figure 2.8 Reverse absorber cabinet drier

Describes another principle of indirect solar drying which is generally known as conventional dryer. In this case, a separate unit termed as solar air heater is used for solar energy collection for heating of entering air into this unit. The air heater is connected to a separate drying chamber where the product is kept. The heated air is allowed to flow through wet material. Here, the heat from moisture evaporation is provided by convective heat transfer between the hot air and the wet material. The drying is basically by the difference in moisture concentration between the drying air and the air in the vicinity of product surface. A better control over drying is achieved in indirect type of solar drying systems and the product obtained is good quality.

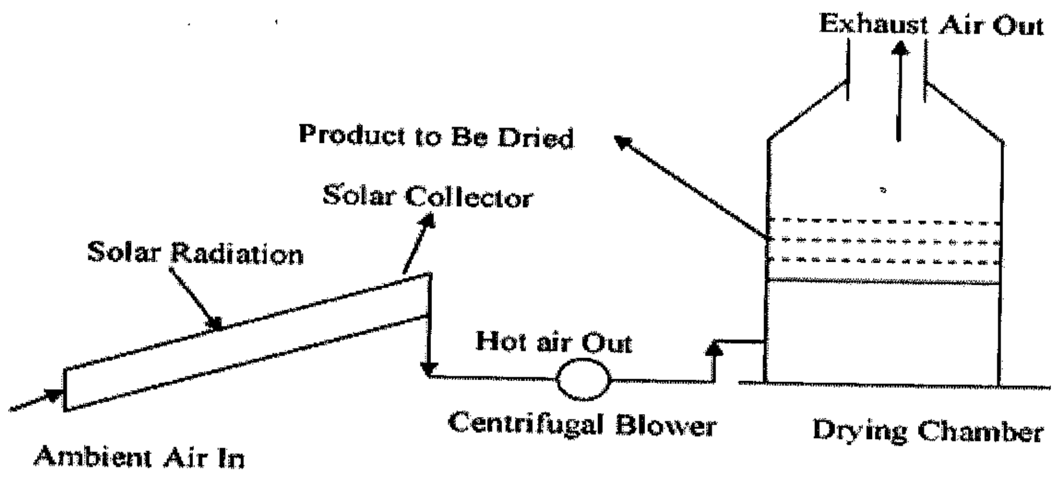


Figure 2.9 Indirect solar drier (Forced convection solar drier)

There are several types of driers developed to serve the various purposes of drying products as per local need and available technology. The best potential and popular ones are natural convection cabinet type, forced convection indirect type and green house type. Apart from the above three, as seen from the literature, tent drier and solar tunnel drier is also found to be popular

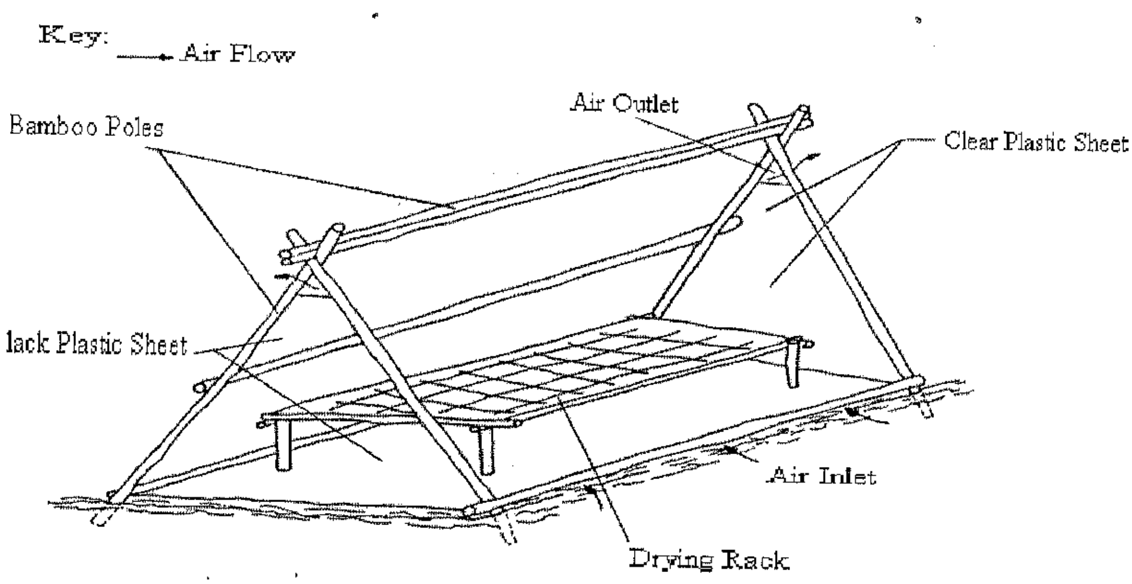


Figure 2.10 Tent Dryer

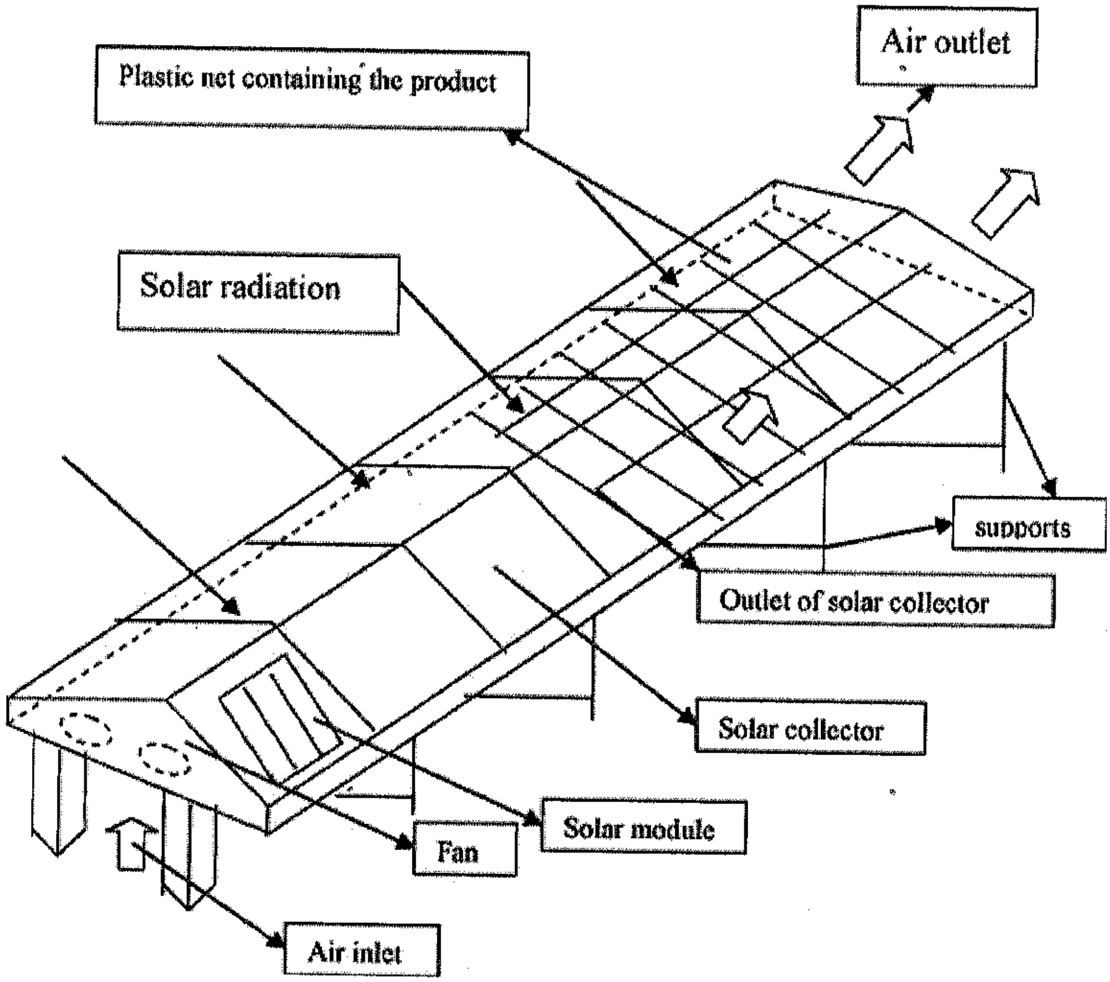


Figure 2.11 Solar tunnel drier

Apart from the obvious advantages of passive solar-energy dryers over the active types (for applications in rural farm locations in developing countries), the advantages of the natural circulation solar-energy "ventilated greenhouse dryer" over other passive solar-energy dryer designs include its low cost and its simplicity in both on-the-site construction and operation. Its major drawback is its susceptibility to damage under very high wind speeds.

Table 2 gives a concise comparison of the integral and distributed natural-circulation solar energy dryers. A multi-shelf portable solar dryer is developed. It has four main parts, i.e., multi-tray rack, trays, movable glazing and shading plate (see Fig. 2.13). The ambient air enters from the bottom and moves up through the material loaded in different trays. After passing through the trays, the air leaves from the top. The multirack is inclined depending upon the latitude of the location. Four layers of black HDP sheet are wrapped around the multi-rack such that heat losses are reduced to ambient air from back and sides. There are seven perforated trays, which are arranged at seven different levels one above the other. The product to be dried is loaded in these trays. To facilitate loading and unloading, a new concept of movable glazing has been developed. It consists of a movable frame (on castor wheels) and UV stabilized plastic sheet. After loading the product, the movable glazing is fixed with the ulti-tray rack so as to avoid any air leakage.

Table 2.2 Comparisons of natural-circulation solar-energy dryers

	Type	
	Integral	Distributed
Principal modes of heat transfer to crop	Radiation (ie. By direct absorption of solar radiation) and convection (ie. from heated surrounding air).	Convection from pre-heated air in an air-heating solar-energy collector.
Components	Glazed drying chamber and chimney.	Air-heating solar-energy collector, ducting, drying chamber and chimney.
Initial cost	Increasing cost ⟶	
Construction, operation and maintenance	Simplicity in both construction (ie. On-the-site construction) and operation. Requires little maintenance.	Consists of comparatively elaborate structures, thus requires more capital investment in materials and large running costs. More operational difficulties of loading and occasional stirring of the crop (since crops are usually dried in relatively deep layers).
Efficiency	Little information on comparison of performance with distributed-type dryers. Likely to operate at lower efficiencies due to its simplicity and less controllability of drying operations.	Have a tendency to higher efficiency since individual components can be designed to optimal performance.

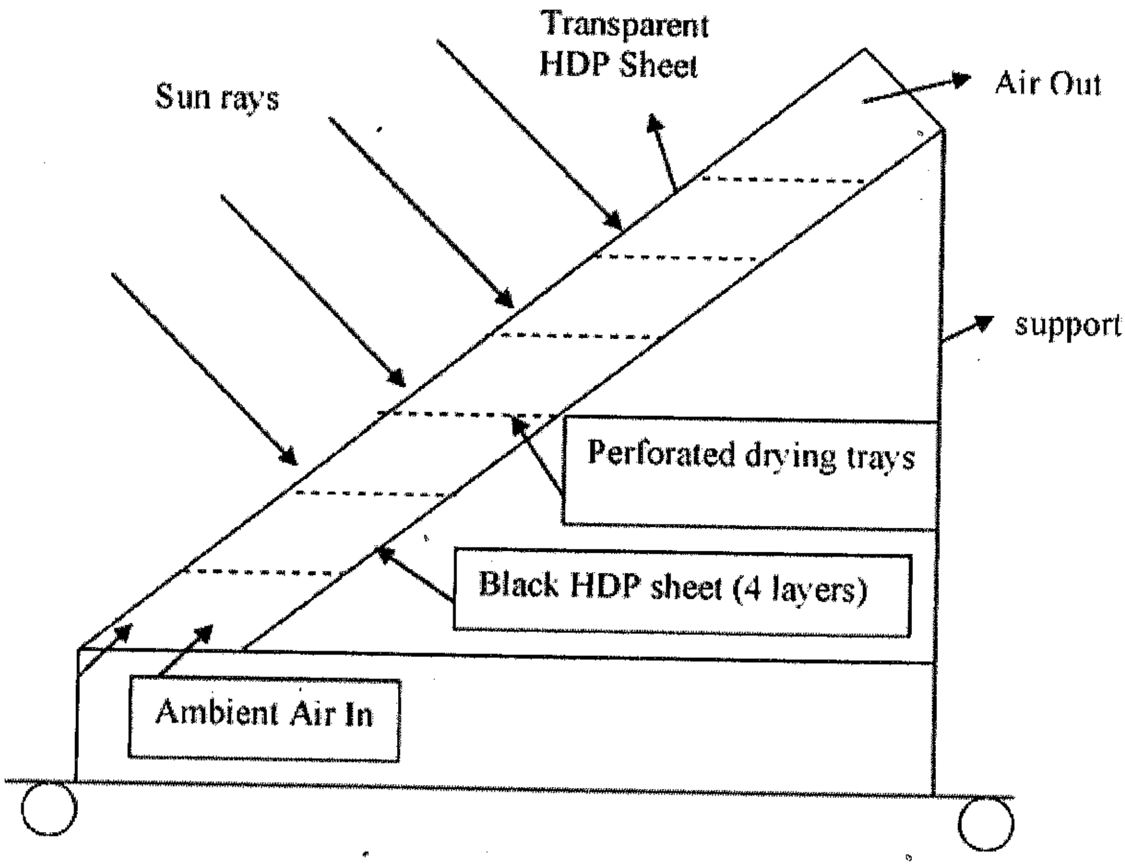


Figure 2.12 Multiple-shelf portable solar drier

A staircase type dryer is developed which is in the shape of a metal staircase with its base and sides covered with double walled galvanized metal sheets with a cavity filled with no degradable thermal insulation (see Fig.2.13). The upper surface is covered with transparent polycarbon sheet to allow the sun's rays to pass through and be trapped. The upper polycarbon glazed surface is divided into three equal parts which can swing open, to provide access to the three compartment inside the dryer. The base of the dryer has four entry points. The partition walls between the compartments also have four port holes for easy airflow. Air moves by natural convection as it enters through the bottom and leaves from the top.

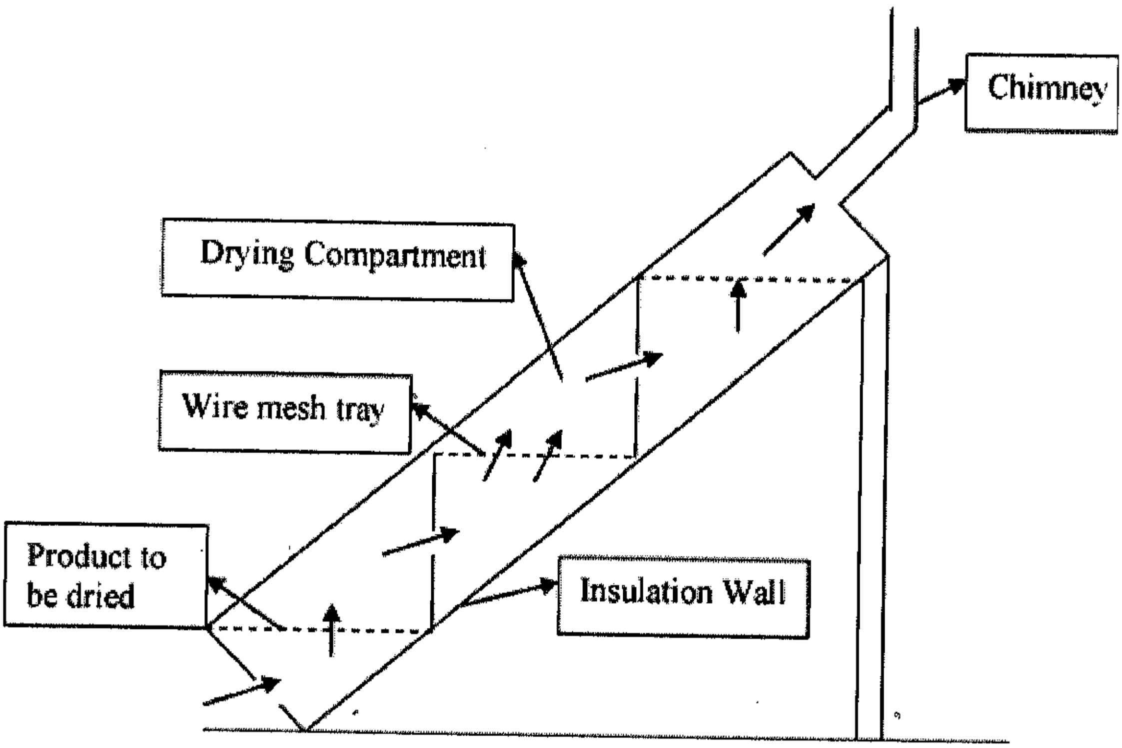


Figure 2.13 Staircase solar drier

In all the types of driers stated above, the hot air enters the drying chamber and leaves to the atmosphere. But the hot air can be recirculated to save the energy. The drying of coconut and cocoa in a scaled down drier of a large scale drier is considered in which the recirculation of hot air yields 31 and 29% of energy saving, respectively. The recirculation of exhaust hot air is also applied to hay driers. Lack of uniform drying and inability to accurately predict drying times are some of the existing problems. A new drier is developed which uses forced heated-air circulation through hay stacks. A drying rate difference of 7% is observed due to recirculation of hot air. By recirculating all of the exhaust air, the previous driers either increased drying time or proved to be uneconomical, so only30% of the hot air is recirculated in the present case. The favorable conditions to recirculate the exhaust air are presented.

A drier called FASD (Foldable Agro Solar Dryer) is developed which is a foldable type that can be stored and transported as desired. The performance of the drier is tested to find that the inner temperature is about 8 oC higher than ambient and humidity is lesser by 6% inside. Out of all types, the well-known heat pump principle has been used to dry the products and this has been found to be excellent alternative to the solar drying.

2.4.4 Applications of solar driers

Solar drying methods as applied to foods have earlier been reviewed by Bolin and Salunkhe (1980, 1982). The former surveyed methods of solar drying having varying levels of technological sophistication and compared the thermodynamics of conventional dehydration with those of solar drying. It has been exhaustively reviewed the drying methods using only solar energy, as well as those using solar plus and auxiliary energy source, besides discussing the quality and economic aspects, suggesting that to produce a high quality product economically it must be dried fast without excessive heat (Singh et al., 2011; Jangam et al., 2011)

Imre (2004) described in detail the construction principles of solar dryers and flat plate collectors along with their economics and performance evaluation. Several authors have studied the usability and performance of various types of solar dryers, energy storage systems (Kalra et al., 1981; Miller, 1985) and pretreatment techniques (Islamet al., 1982; Moyls, 1986; Vaghani, 1986). Cheema and Ribero (1978) studied the comparative performance of three dryers for the drying of cashew, banana and pineapple and found that optimum combination of solar and conventional drying is more suitable. To shorten the drying time Wagner et al. (*1979*) utilized the principles of parabolic reflector to increase the radiation on the product.

Bolin et al. (1980) discussed the relative merits of five experimental methods for the solar dehydration of fruits, namely: black wooden tray, solar troughs of various materials designed to reflect radiant energy onto bottom of black metal drying trays, cabinet dryers with slanted plate heat collectors with natural convection, utilizing inflated Polyethylene (PE) tubes as solar collectors with and without partial air recirculation; and PE semi cylinder with a fan blower to be used in inflated hemispheres or as a solar collector, to blow air over the fruit in a cabinet dryer. They reported that utilizing inflated PE tubes method was cheap, 38% faster than sun drying for apricots and could be used as supplementary heat source for conventional dryer.

Kalra and Bhardwaj (1981) described two simple models of solar dehydrator with the functions of direct and indirect dryers for mango products and vegetables which are well suited to rural conditions and small scale industries. Sun drying of grapes requires longer time to dry and also there is a browning, contamination and spoilage of the product when exposed to the open atmosphere (*Pangavhane et al.,1999, 2002; El- Sebaii et al., 2002*).

Natural convection solar dryers have been the subject of investigation by many workers for studying the drying behavior of several fruits and vegetables. Islam and Flink (*1982*), conducted experiments on potato at low air velocities as encountered in solar dryers and found that due to extensive external mass transport resistance in deep bed drying, the air flow behavior of the bed was more important than drying behavior of the pieces. Drying time increased less rapidly than increase in bed depth. On the basis of simulated solar drying experiments, Shakya and Flink (1986), concluded that drying rate of potato increased with increased inlet air temperature and/or air flow potential and overall productivity increased with increasing bed depth.

CHAPTER THREE

MATERIALS AND METHOD

3.1. Method

3.1.1. Construction of the solar dryer

The materials used for the construction of the mixed-mode solar dryer are cheap and easily obtainable in the local market. The solar dryer consists of the solar collector (air heater), the drying cabinet, drying trays, fans and solar panel.

3.1.2. Solar Dryer Components

Solar Collector

Solar collectors are used to convert direct and diffuse radiation from the sun into thermal energy (*Jercan, 2006*). It is a special kind of heat exchanger that transforms solar energy to heat. Energy is transferred from a distant source of radiant energy to a fluid (*Duffie and Beckman, 1980*). For applications requiring less than 80oC, flat plate collectors are widely used (*Struckmann, 2008*). Flat plate collectors are mechanically simpler and require little maintenance than concentrating type of collectors (*Duffie and Beckman, 1980*).Generally, flat plate collector designs consist of three major parts. These are transparent cover, absorber plate and insulation.

Cover plate: It is transparent sheet is made of 4 mm thick glass used to cover the absorber, thereby preventing dust and rain from coming in contact with the absorber. It also retards the heat from escaping (i.e . forming a confinement for heated air) It is placed about 2.54 cm above the absorber.

Absorber plate: It is a metal painted black to absorb the incident solar radiation transmitted by the cover thereby heating the air between it and the cover. Here aluminum is chosen because it's quick response in absorption of solar radiation.

Insulation: It is used to minimize heat loss from the system. It is placed under the absorber plate. The insulator can withstand stagnation temperature, it is fire resistant and not subject to out-going gassing; and it should not be damageable by moisture or insect. Insulating materials are usually fiberglass, mineral wool, Styrofoam and urethanes, with at least 5 cm thickness

Drying Trays: The drying trays are contained inside the drying chamber and were constructed from a double layer of fine chicken wire mesh with a fairly open structure to allow drying air to pass through the food items.

Drying chamber/ Compartment: Products are located on trays or shelves, normally it is made of opaque materials in the case of indirect or hybrid system of dryer. Solar radiation is thus not incident directly on the crop. Preheated air is warmed during its flow through the solar thermal collector; it is ducted to this chamber to dry the products. Because the products are not subjected to direct sunshine, localized heat damage, do not occur. This chamber sometimes is made of highly polished metal materials because of its good conductor of heat characteristic and smooth surface finish.

Fan system

Fan or blower can be installed before the collector or after the collector. In the systems, where it is connected between the collectors and the drying chamber, the collector works under slight negative pressure hence minimizing the effect of minor leaks if any developed with time. Positive pressure is maintained inside the dryer to avoid entry of dust and cold air into the dryer. Normally, fans may be powered with utility electricity if it is available, or with a solar photovoltaic cell.

. **Turbo-ventilator**

This create a draught that enables heated air to flow upward in the solar collector, pass through the food stuffs arranged in trays taking out the moisture from the food. Wind driven turbo ventilators are used all over the world because of their low capital and installed cost, adaptability, high capacity per vent, and overall reliability. Operation is simplicity in itself. As the vent hood is rotated by the wind, the saturated inside air is exhausted through the vanes and the natural inward flow of heated air from the collector is boosted.

Chimney

This provides a means through which the dry heated air that has passed through materials being dried and exits the dryer are recirculated and heated further. Chimney has to have overhung in order to prevent rains or any insects from interfering with drying materials. Besides, turbo-ventilator can be fixed on top of it to aid draught built up.

3.1.3 The orientation of the solar collector: The Plat plate 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 and due north in southern hemisphere. Therefore, solar collector in this work is oriented facing south and tilted at 17.7983°N to the horizontal. This is approximately 10° more than the local geographical latitude (Ikole-Ekiti a location in Nigeria, 17.7983°N), which according to Adegoke and Bolaji (2000), is the best recommended orientation for stationary absorber. This inclination is also to allow easy run off of water and enhance air circulation.

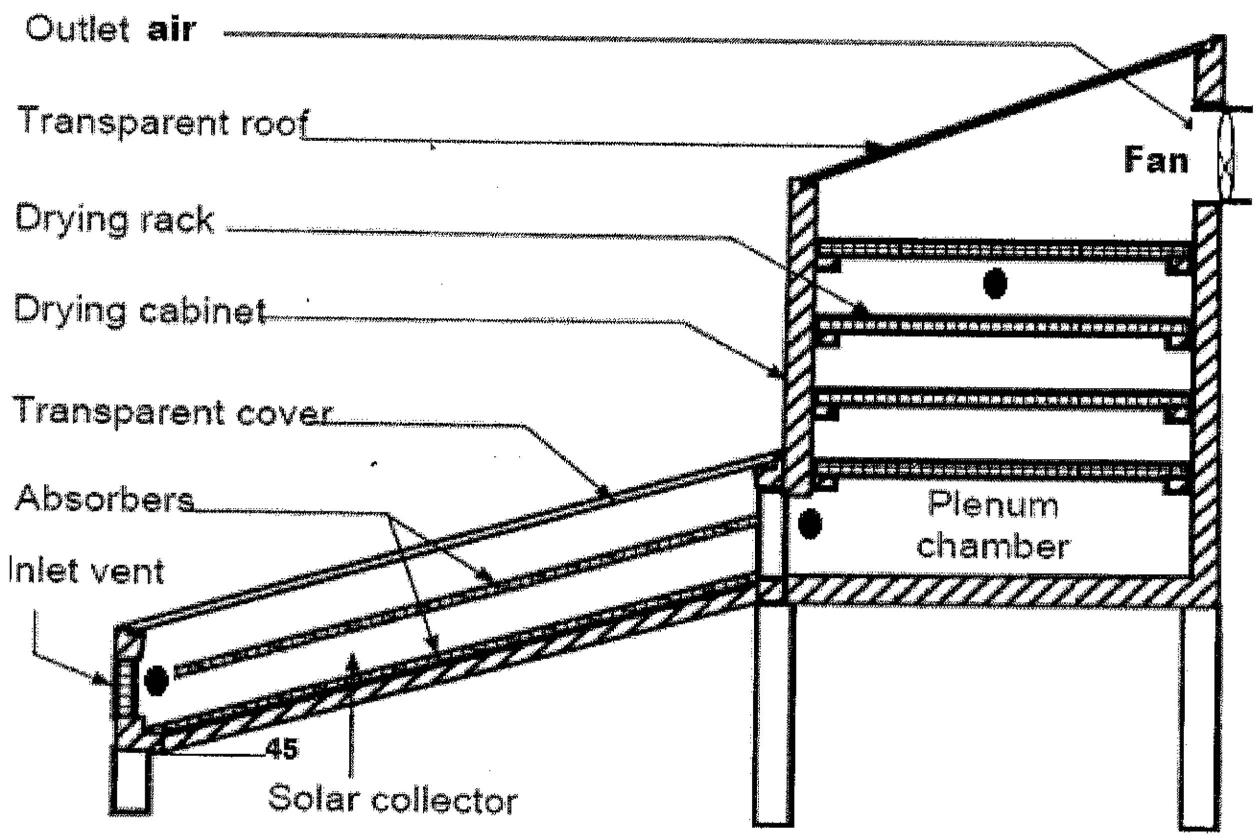


Fig. 3.1 Sectional view of the mixed-mode solar dryer

3.1.4. Operation of the dryer

The dryer is active system in the sense that it has moving parts. It is energized by a fan powered by photovoltaic source assisted the airflow through the drying system in the collector glazing. The solar dryer also includes two 12 V, 3.3 A D.C.-fan attached to the intake of collector. The trapping of the rays is enhanced by the inside surfaces of the collector that were painted black and the trapped energy heats the air inside the collector. The green-house effect achieved within the collector drives the air current through the drying chamber. If the vents are open, the hot air rises and escapes through the upper vent in the drying chamber while cooler air at ambient temperature enters through the lower vent in the collector. Therefore, an air current is maintained, as cooler air at a temperature enters through the lower vents and hot air at a temperature leaves through the upper vent.

When the dryer contains no items to be dried, the incoming air at a temperature '' has relative humidity '' and the out-going air at a temperature '', has a relative humidity ''. Because >and the dryer contains no item, > . Thus there is tendency for the out-going hot air to pick more moisture within the dryer as a result of the difference between and therefore, insulation received is principally used in increasing the affinity of the air in the dryer to pick moisture.

3.1.5. Design calculations

3.1.5.1. Collector Efficiency

Collector efficiency measures the thermal performance, i.e. the useful energy gains of the collector. Not all of the solar radiation from the sun incident on the collector surface is converted to heat. Part of the radiation is reflected back to the sky and the other component is absorbed by the glazing. Once the collector absorbs heat and as a result temperature gets higher than the surrounding, there will also be a heat loss to the atmosphere by convection and radiation (Struckmann, 2008).

Collector efficiency, 퀣 = $\frac{□퐸Δ□□□}{퐼□□}$ x 100 (3.2)

Where; V = Volumetric flow rate of air, 퓜□/ 큰

Q = air density, 퓛퓚/ 퓜□

Δ퓣= Air temperature elevation, °C

퓒퓟 = air specific capacity, 퓙/퓚퓚°C

퓘 = Insolation on collector surface 퓦/ 퓜^2

퓐□ = Collector area 퓜□

퀣 = $\frac{□.□□2□ \times 2 \times □□ \times □□□□}{□□□2 \times □.□□}$ x 100

$$\frac{75978}{1086.156} = 70\%$$

3.1.5.2. Drying Efficiency

Drying efficiency is the ratio of the energy needed to evaporate moisture from the material to the heat supplied to the dryer. This term is used to measure the overall effectiveness of a drying system (Dhanushkodi *et al.*, 2014). But it may not be used for comparing one dryer with another due to different factors such as the particular material being dried, the air temperature and mode of air flow may differ for various dryers (Brenndorfe *et al.*, 1987).

$$\text{Drying Efficiency} = \frac{□\,□}{□_{□\,□_{□}}}, \qquad (3.3)$$

M_w – Weight of moisture evaporated, kg

L – Latent heat of evaporation of water (at temperature of dryer), kJ/kg

$$\text{Drying Efficiency} = \frac{□.□□□ \times 22□□}{□□□2 \times □.□□}$$

$$= 12.8\%$$

3.1.5.3. Drying Rate

Drying rate is the amount of evaporated moisture over time (Dhanushkodi *et al.*, 2014).

$$DR = \frac{M_i - M_d}{t} \qquad (3.4)$$

M_i = mass of sample before drying

M_d = mass of sample after drying

t = drying period

$$DR = \frac{□□□ - □□□}{□2} = 19.2 g/h$$

3.1.5.4. Moisture Content

Moisture content is one of the important parameters that is taken to evaluate the performance of a dryer. Moisture content of a material can be given either on the basis of total weight of the material to be dried or the amount of solid weight present in the material. The moisture content on wet basis is given by the following equation (Fudholi*e t al.*, 2011):

$$MC(w.b), \% = \frac{w-d}{w} * 100 \qquad (3.5)$$

w = weight of wet material

d = weight of dry material

Dry basis moisture content is given by (Mercer, 2007):

$$MC\ (d.b.)\ g\ water\ /\ g\ dry\ solids = \frac{w-d}{d}$$

(3.5a)

Nocturnal moisture re-absorption or loss, Rn, is the ratio of the increase in moisture content during the night period to the moisture content value at the sunset of the previous day. If the value of R_n is positive, it indicates moisture re-absorption, but negative value implies further moisture loss (Medugu, 2010).

$$R_n = \frac{M_{sr} - M_{ss}}{M_{ss}} * 100$$

(3.5b)

M_{sr} = moisture content at sunrise (%)

M_{ss} = moisture content at sunset (%)

3.1.5.5. Sizing of the dryer chamber

The breadth of the drying chamber, B, is made equal to the width (W) of the air-heater. Thus, the length of the drying chamber, L_{dc}, is determined from the relation

$$L_{dc} = \frac{A_{dc}}{W}$$

(3.6)

3.1.5.6. Average drying rate

Average drying rate, m_{dr}, would be determined from the mass of moisture to be removed by solar heater and drying time by the following equation.

$$m_{dr} = \frac{m_w}{t_d}$$

(3.7)

3.1.5.7. Solar collector/ Air heater angle of tilt (β)

The angle of tilt (β) of the solar collector is given by the formula below:

$$\beta = 10^{□} + 퓛퓪퓽퓪 \quad (3.8)$$

Where Lat ϕ is the latitude of the collector location, the latitude of Ikole-Ekiti were the dryer was designed is latitude 7.7983□퓝, hence, the suitable value of β use for the collector:

$$\beta = 10^{□} + 7.7983^{□}$$

$$\beta = 17.7983^{□}$$

3.1.5.8. Insolation on the collector surface area.

A research obtained that the value of insolation for Ikole – Ekiti i.e. average daily radiation H on horizontal surface as;

H = 600 W/퓶^2

and average effective ratio of solar energy on tilted surface to that on the horizontal surface R as;

R = 1.017

Thus, insulation on the collector surface was obtained as

퓘 = 퓗□ = 퓗퓡 = 600 x 1.017= 610.2 W/ 퓶^2 (3. 9)

3.1.5.9. Determinations of collector Area and Dimension.

The mass flow rate of air 퓶̇□ was determined by taken the average air speed 퓥 = 0.2 m/s

The air gap height was taken as 9cm = 0.09m and the width of the collection assumed to be 90 cm = 0.9 m

Thus, Volumetric flow rate of air

퓥퓪 = 퓥 x 0.09 x 0.9

퓥퓪 = 0.2 x 0.09 x 0.9 = 0.0126 퓶□/s

Thus, mass flow rate of air

퓶̇□ = 퓥퓪퓹 (3.10)

Density of air ρ_a should be taken as 2 kg/m□

퓶̇□ = 0.0162 x 2 = 0.0324 kg/s

Therefore, area of the collector 퍪□

퍪□ = □□ □□ Δ□ / □□□ (3.11)

퍪□ = □.□□24 퍪□□□□x □□ / □□□.2 퍪□.□ = □□□.□□ / □4□.□□

퍪□ = 1.78퍪²

Length of the solar collector (L) was taken as;

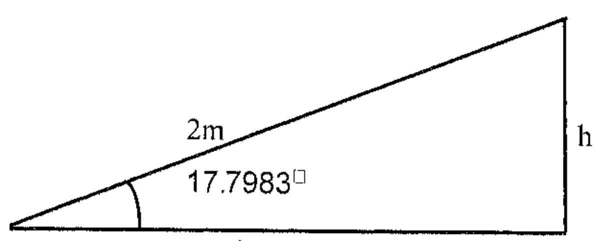
L = □□ / 퍪 = □.□□ / □.□ = 2.0 m (3.12)

Therefore, collector area was taken as (2 x 0.9) = 1.8퍪²

Vent area = Width of collector x Air gap height (3.13)

= 0.9 x 0.09 = 0.081퍪²

3.1.5.10. Height of the solar collector



sin 퍪 = □ / 퍪 (3.24)

sin 17.7983□ = □ / 2

H= sin 17.7983□ 퍪2

H =0.61m

3.1.6. Backup Heater

The backup heater used bed rock as a source of energy. The bed rock was painted with black plaint to enhance the store of heat during the day time. For this project, the medium type of bed rock was used. It had a height of 25 cm and diameter of 10 cm. The heat from the bed rock used for drying was collected indirectly. The hot air from the bed rock escaped through a chimney which was connected at the top of the cover. At the top of the chimney was a cylindrical surface metal sheet cover.

3.1.6.1. Drawing of the Dryer

The dryer was designed using a software called AutoCAD. The drawing of the design and the corresponding side views with dimensions are shown in Figure 3.2 and Figure 3.3

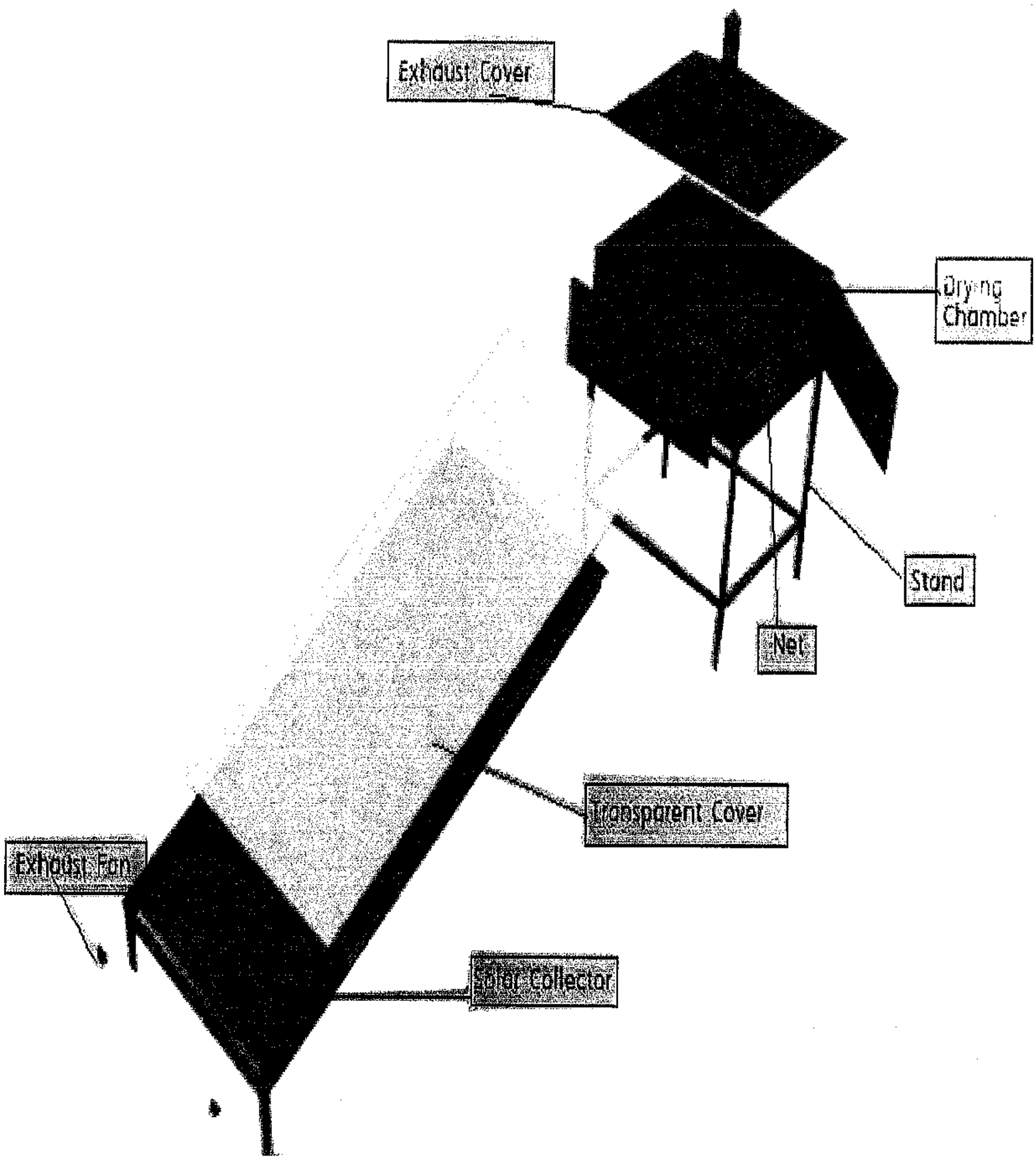


Fig. 3.2. Dryer drawing

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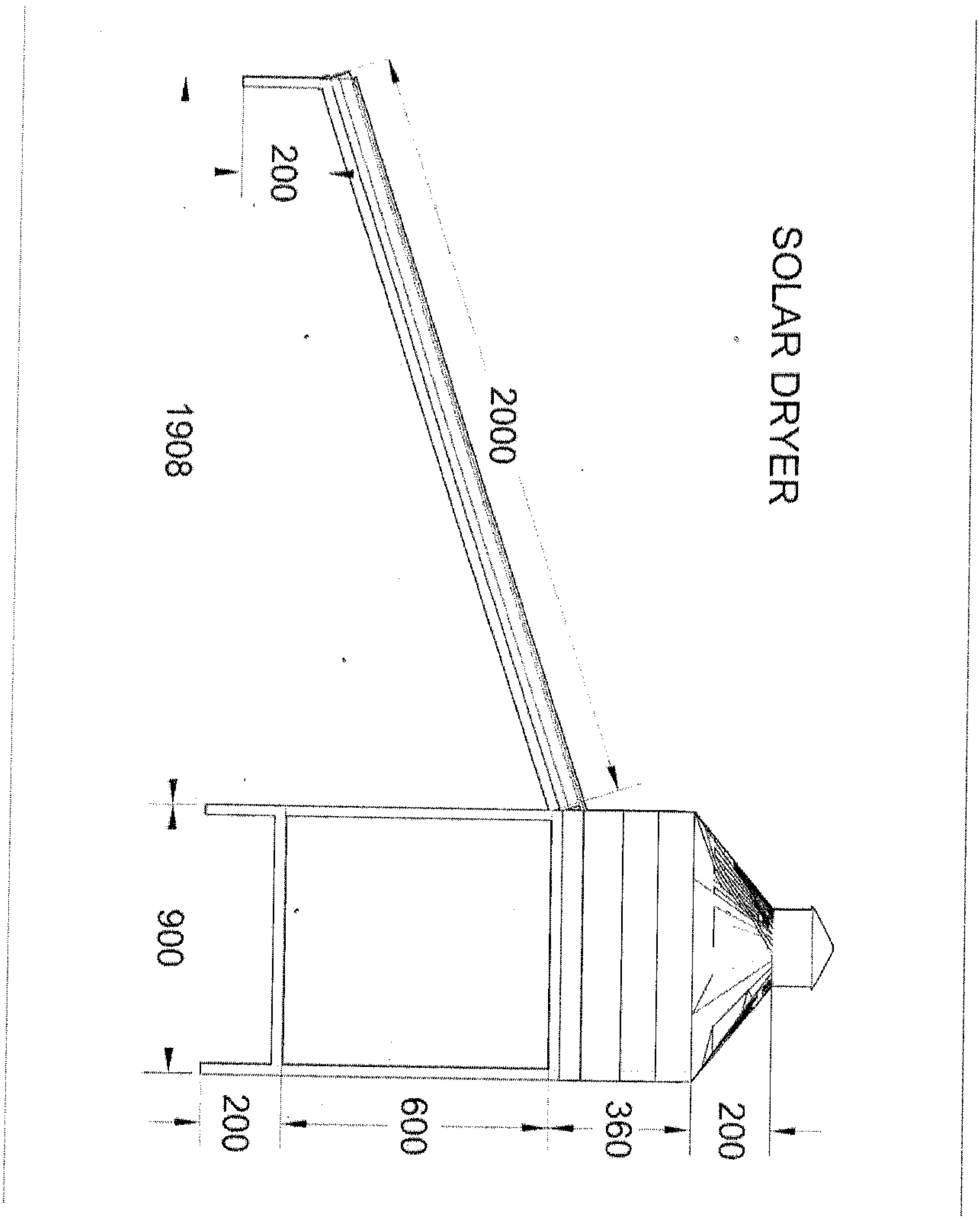

Fig. 3.3. Side view of the dryer

All dimensions are in mm

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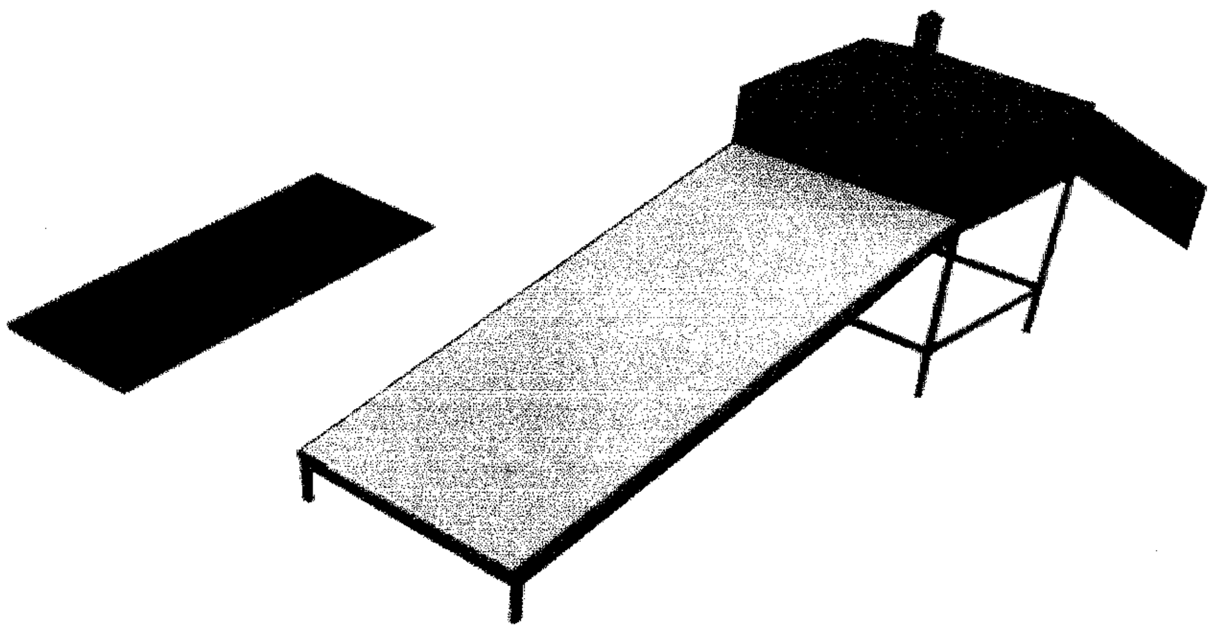


Fig 3.4. Pictorial view of the assembled tomatoes dryer

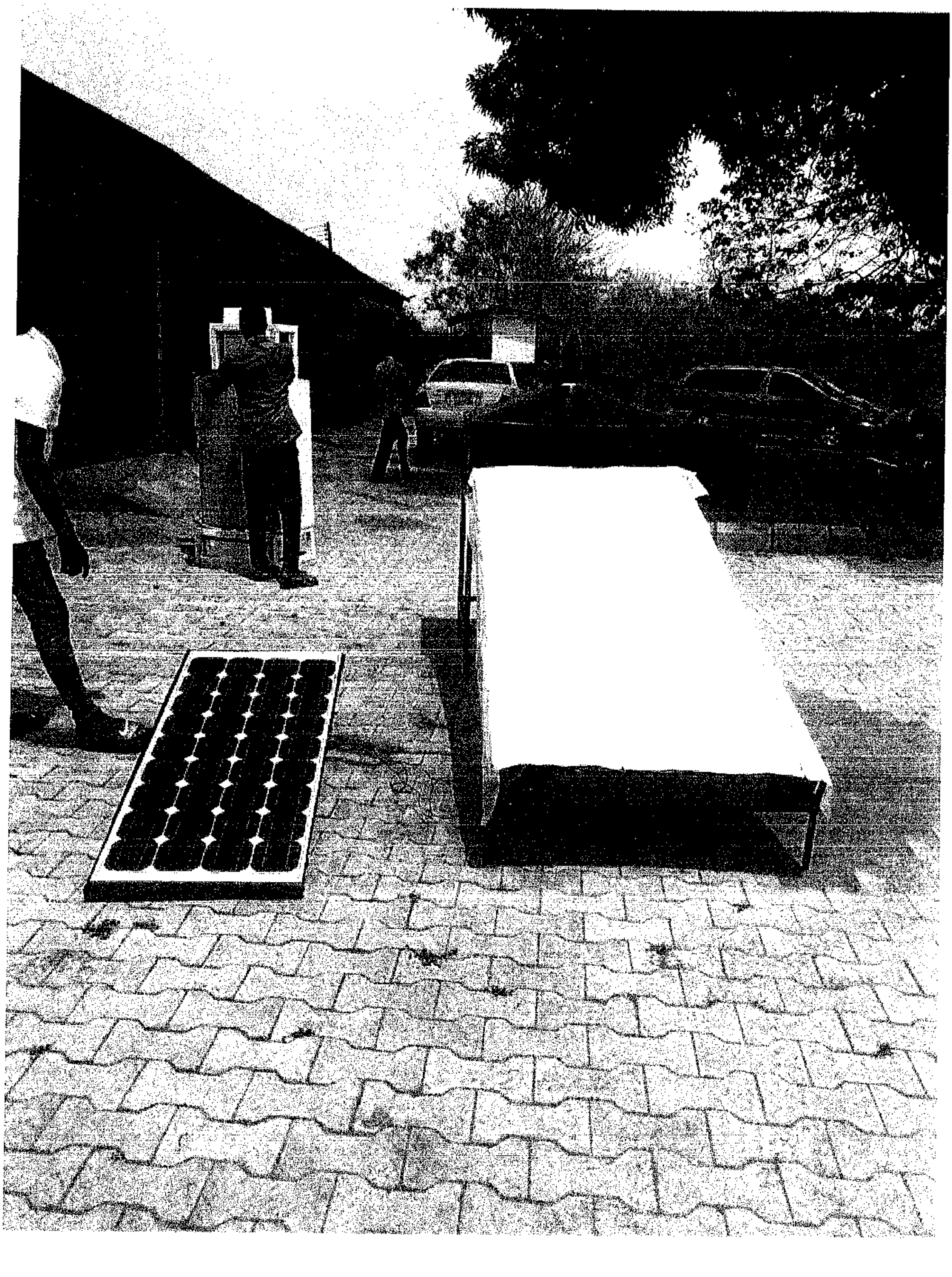


Fig. 3.5. Pictorial view of the constructed solar dryer

3.1.7. General description of the solar dryer

The designed and constructed solar dryer consists of two major compartments or chambers being integrated together, the solar collector compartment, which can also be referred to as the air heater, and the drying chamber, designed to accommodate three layers of drying trays on which the produces (or food) are placed for drying.

In this solar dryer constructed, the greenhouse effect and thermo siphon principles are the theoretical basis. There is an air vent (or inlet) to the solar collector where air enters and is heated up by the greenhouse effect, the hot air rises through the drying chamber passing through the trays and around the food, removing the moisture content and exits through the air vent (or outlet) near the top of the shadowed side. The hot air acts as the drying medium, it extracts and conveys the moisture from the produce (or food) to the atmosphere under artificial convection, thus the system is active solar system and a mechanical device is required to control the intake of air into the dryer.

3.1.8. Solar Drying Test

The testing of the solar dryer was done in the month of November – December (2018), the dryer was placed outside with the collector facing the sun. The collector has been rigidly fixed to the dryer at an angle of 17.7983° to the horizontal to obtain approximately perpendicular beam of sun rays. The loaded test of the solar dryer was carried out using 1 kg of fresh slices of tomatoes and pepper. The slices were laid on a single layer over each tray. This helped to avoid overlapping and ensure uniform drying. From the different tests carried out it was found that 2 – 2.5 kg of tomatoes each with about 5 – 8 mm diameter and 1.5 – 2 kg of tomatoes can be dried in a single batch. Only solar energy was used as heat source for drying during this test. Ambient temperature and humidity, dryer temperature and collector output temperature were recorded every one-hour interval while the weight of the produce kept in the dryer was measured every three-hour interval. Oven drying was used to determine the initial moisture content of tomatoes and pepper as 87.0 % and 81.0 %, respectively. Using these values of initial moisture contents and measuring the weight at regular interval enabled the determination of the moisture loss of the produce during the course of the drying. Wet basis moisture tells the weight of water as a percentage of total weight of a sample and dry basis indicates the weight of water contained in a given weight of dry solids (*Mercer,2014*). As a result, moisture content was determined in terms of both wet basis and dry basis. Drying was continued until no further weight reduction was recorded.

The performance of the dryer was also evaluated using drying efficiency and drying rate. These values are used to compare the different loaded tests carried out.

CHAPTER FOUR
RESULTS AND DISCUSSION

After completing the construction of the dryer, different tests were performed in order to evaluate its performance. Tomatoes and peppers were dried during the test period. The results of different tests performed are presented below.

4.1. No Load Test

A typical no-load test temperature variation is shown in Fig. 4.1.

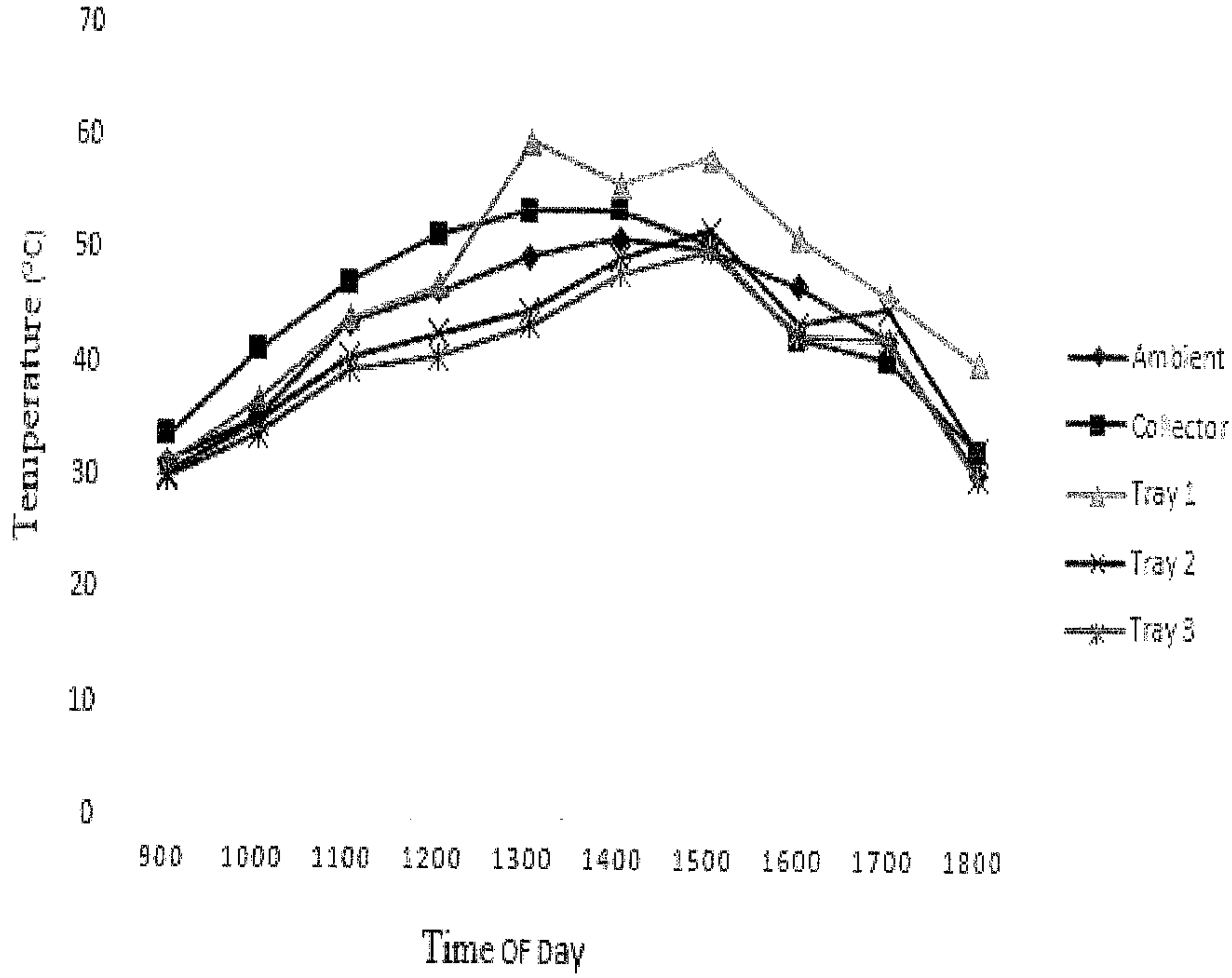


Fig. 4.1. Day time temperature variation for no load test

Figure 4.1 shows that during the day time when the sun was the only source of heat supply, a maximum temperature of 53.7°C was attained by the collector output after six hours while the average collector temperature from 09:00 to 17:00 Hour was 44.6°C. The collector reached its peak temperature value at 53.7⁰C when the ambient temperature was 31.3°C. The maximum average temperature increase on the trays was about 58.3°C. This indicates that the maximum increase in temperature of the dryer was about 7.2°C more as compared with the ambient temperature. A similar no-load indirect type dryer test performed by Alonge and Adeboye (2012) resulted in a maximum temperature elevation of 48°C when the ambient temperature was 39°C. In addition, a higher drying chamber was reported by (Bolaji, 2005) who designed a box type indirect crop dryer where the maximum average temperature obtained in the drying chamber was 57.0°C, while the ambient temperature was 33.5°C.

From Figure 4.1, the trend of the graph shows that the temperature starts to increase from morning and reaches its peak value in the afternoon, when the sun insolation is highest at 13:00 and starts to decline at 16:00 in the evening when the sun sets. A higher temperature was recorded on the top tray due to incident solar radiation coming in contact with the top drying chamber than the bottom and middle tray

4.2. **Solar Drying Test**

The moisture content wet basis and dry basis with time for tomatoes when the sun was used as the only source of heat supply, are shown in Fig. 4.2 and Fig 4.3

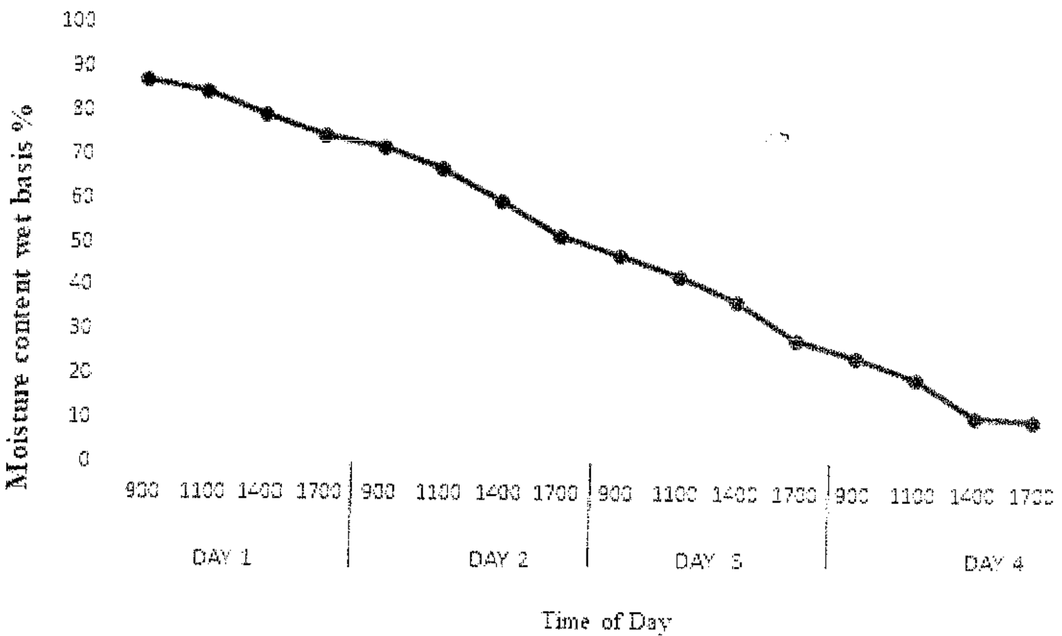


Fig. 4.2. Moisture content (wet basis) by tomatoes with time

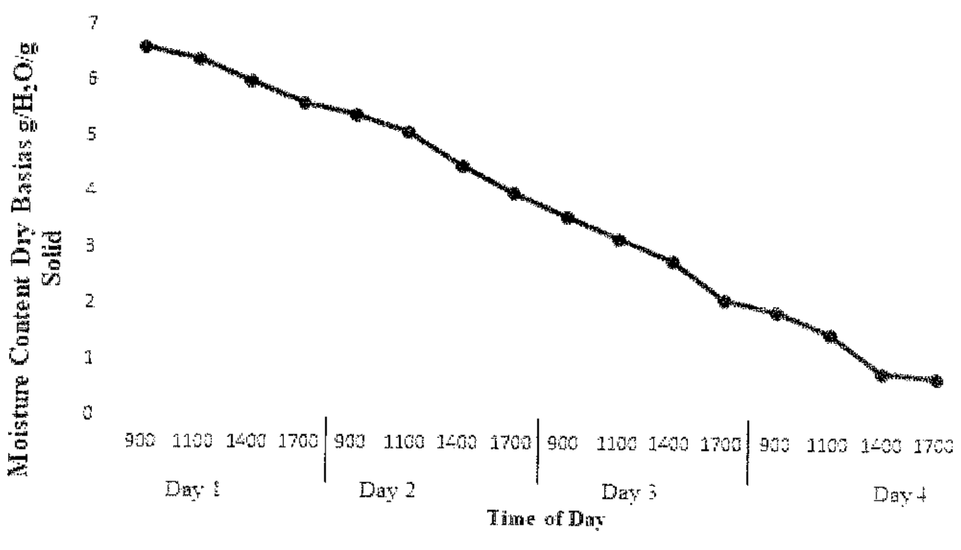


Fig. 4.3. Moisture content (dry basis) by tomatoes with time

As the inlet air passes through the collector and enters the dryer, it will have higher temperature and lower humidity. As the hot air rises in the drying chamber, it picks up moisture from the vegetable kept on the trays. This results in reduction of weight or moisture loss of the tomatoes. The moisture content of tomatoes was reduced from 87.9 % (w.b.) to 10.1 % (w.b.) or 6.6 g H2O/g solids (d.b.) to 0.7 g H2O/g solids (d.b) within three to four days.

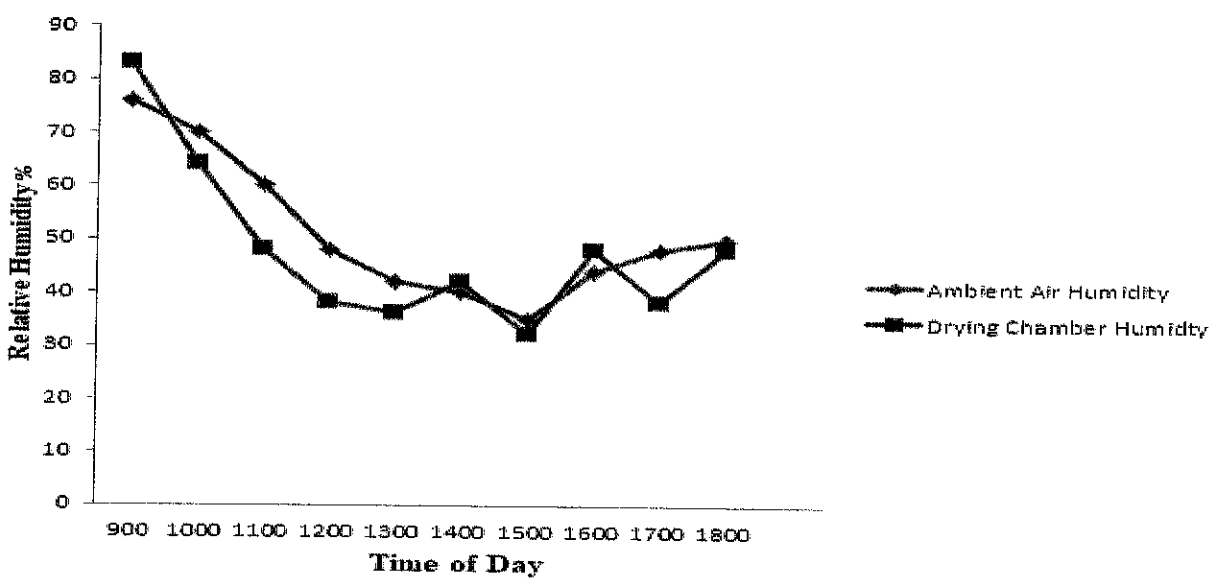


Fig 4.4. Variation of the relative humidity of the ambient air and drying chamber

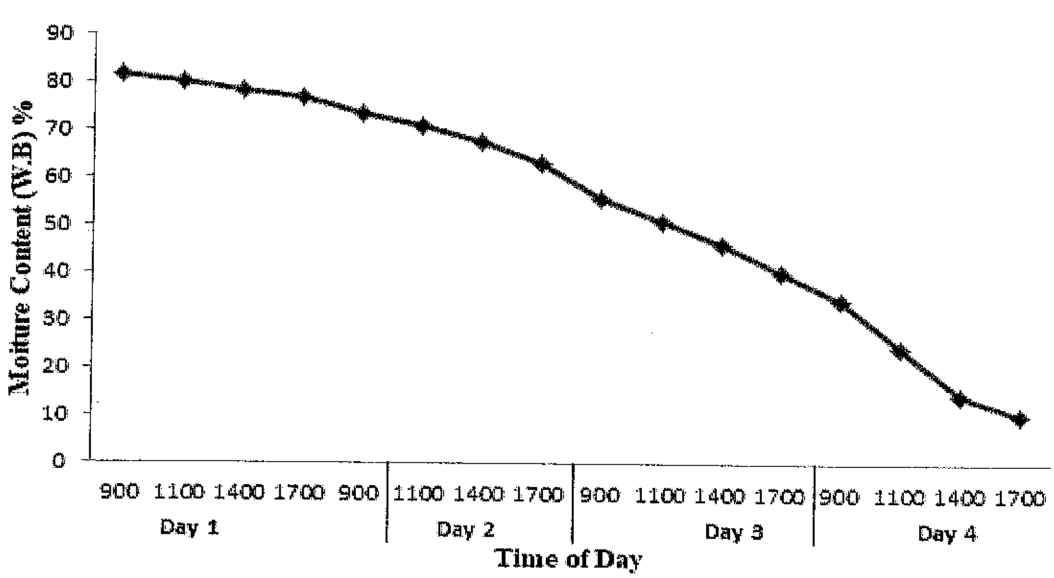


Fig 4.5. Moisture content (wet basis) by Pepper with time

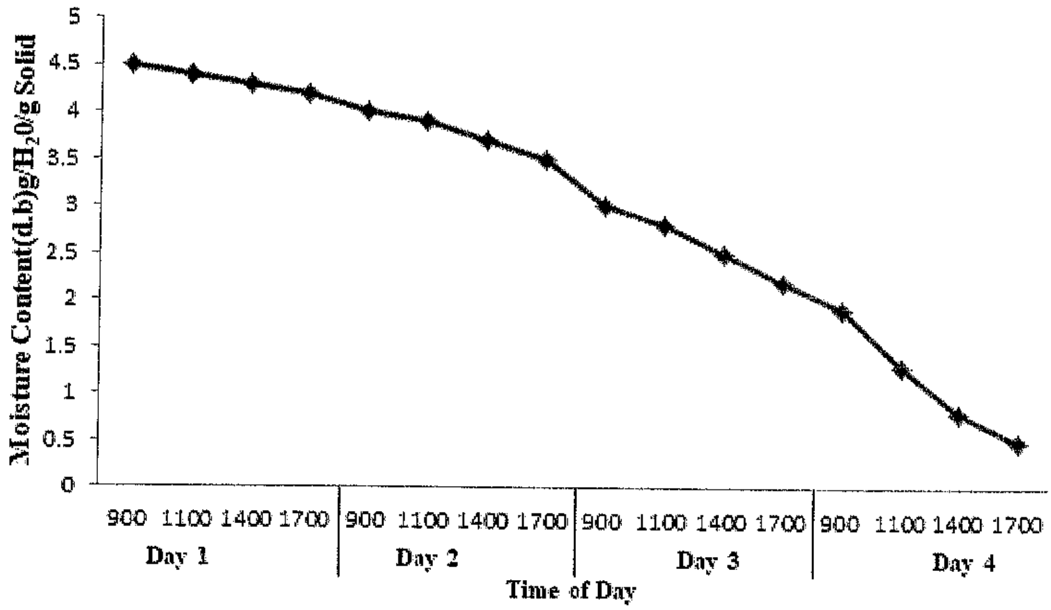


Fig 4.5. Moisture content (dry basis) by Pepper with time

In solar drying of pepper, the moisture content of the fruit was reduced from initial moisture content 81.7 % (w.b.) to 10% (w.b) or 4.45 g H_2O/g solids (d.b.) to 0.55 g H_2O/g solids (d.b.) after drying for four days. The value was well in range with the one stated by Economic Commission for Europe (2012) that sets the final moisture content for a dried pepper to be not more than 15 % (wet basis). For solar dryer, the drying rate for tomatoes was found to be 19.2g/h whereas for pepper it was 15.3 g/h.

A natural convection direct type solar dryer constructed and tested by Akoy *et al.* (2004) reported a moisture reduction from 81.7% to 10 % w.b. in four days when drying pepper. Lower moisture content, i.e. 10 % was achieved within the same drying period as compared to the current dryer constructed. This can be attributed to the fact that a higher drying temperature was recorded in the dryer as a result of direct exposure to the sunlight or direct type of solar dryer.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

An indirect type solar dryer with a photovoltaic (PV) solar panel to power the fans and backup heater was designed and constructed with materials readily available in the market which had a storage energy system was developed; to study the drying behavior of tomato slices and peppers. The dryer is easy to operate and handle. An additional system, backup heater consisting of a bed rock, was included in order to make drying continuous throughout the night and cloudy periods.

Under no-load condition, the average collector temperature reached 56.4°C and that of the dryer reached 45.1°C while the average ambient temperature was 34.6°C.When only the backup heater was used in the evening by bed rock a temperature as high as 50.8°C was recorded on the bottom tray. This indicated that the temperature in the dryer was raised above the ambient temperature creating a suitable condition for drying.

The performance of the dryer was evaluated using tomatoes and peppers in which the initial moisture contents were reduced from 86.9 % and 84.4 % to 79.4 % and 10.1 %, respectively, within three to four days. A better dryer performance in terms of drying rate was obtained when the dryer was operated in a hybrid mode, i.e. when heat was supplied by bed rock as a backup system. The collector efficiency obtained from no load test was 70%. The drying efficiencies was 12.8% for solar drying, backup heater used throughout the drying period and backup heater used only in the evening.

It was found that the solar dryer can dry high initial moisture content vegetable such as tomatoes and peppers to the recommended value of moisture content for safe storage within three to four days. The solar dryer can be used during any time and season as a result of the heat provided using the backup bed rock. Hence, it can provide a means of preserving agricultural produce that are harvested in the rainy season.

5.2. Recommendations

The performance of the dryer can further be enhanced by making modifications and following the recommendations given below:

1. The gap between the collector and drying chamber should be covered with permanent insulation that can withstand rain.

2. insulating the drying chamber will help to attain a higher drying temperature, especially at night when the backup heater is the only source of heat supply.

3. Design modifications are required to maintain the same amount of drying temperature in the dryer when the backup heater is used. One such suggestion would be to internally extend the metal tube to the adjacent sides of the drying chamber. This would help to minimize the non-uniformity of heat transfer on a tray.

REFERENCES

Adegoke, C.O.; and Bolaji, B.O. 2000. Performance evaluation of solar-operated thermosyphon hot water system in Akure. *International Journal Engineering.* Engin. Technol. 2(1): 35-40.

Alonge, A. F. and Adeboye, O. A. (2012). Drying Rates of Some Fruits and Vegetables with Passive Solar Dryers. *International Journal of Agricultural and Biological Engineering*, *5*(4): 83–90. DOI: 10.3965/j.ijabe.20120504.0010

Bolaji, B. O. (2005). Development and Performance Evaluation of a Box-type Absorber Solar Air Collector for Crop Drying. *Journal of Food Technology*, *3*(4): 595–600.

Bolin, H.R., Huxsoll, C.C., Salunkhe, D.K., 1980, Fruit drying by solar energy, Confructa, 25, 147-160.

Bolin, H.R., Salunkhe, D.K., 1982, Food dehydration by solar energy, Crit. Rev. Food Sci.Nutri,16,pp. 327-354.

Brenndorfer, B., Kennedy, L., Oswin Bateman, C. O., Trim, D. S., Mrema, G. C. and Wereko Brommy, C. (1987). Solar Dryers - Their Role in Post-Harvest Processing (2nd edition), The Commonwealth Secretariat, London. ISBN 0 85092 282 8, 298 p.

Cheema, L.S., Robeiro, C. M., 1978, Solar dryers of cashew, banana, and pineapple, *Sun*, 3, pp. 2075- 2079.

Dhanushkodi, S., Wilson, V. H. and Sudhakar, K. (2014). Thermal Performance Evaluation of Indirect Forced Cabinet Solar Dryer for Cashew Drying. *American-Eurasian J. Agric. & Environ. Sci.*, *14*(11): 1248–1254.

Duffie, J. A. and Beckman, W. A. (1980). Solar Energy of Thermal Processes (2nd edn.). John Wiley & Sons, Inc, New York, 919 p.

El-Sebaii, A. A. and Shalaby, S. M. (2012). Solar drying of agricultural products: A Review. Journal of Renewable and Sustainable Energy Reviews, 16(1): 37–43.

Hii, C.L., Jangam, S.V., Ong, S.P. and Mujumdar, A. S. (Ed.). Solar Drying: Fundamentals, Applications and Innovations. Transport Phenomena Group, Singapore, 2012, ISBN 978981-07-3336-0. p 150

Imre, L., 2004, Solar drying, In: Mujumdar, A.S., (Ed.), Handbook of Industrial Drying, vol. 1. second ed, pp. 373–451.

Islam, M.N., Flink, J. M., 1982, Dehydration of potato- II, Osmotic concentration and its effect on air drying behaviour, *Journal of Food Technology*, 17, pp. 387- 403.

Jangam, S.V., Visavale, G.L., Mujumdar, A. S., 2011, Use of renewable source of energy for drying of FVF, In Dry foods, vegetables and fruits – Vol 3, Chapter 6, pp. 103-126

Jercan, A. S. (2006). The Simplified Calculus of the Flat Plate Solar Collector, *Anals of the University of Craiova, Electrical Engineering Series*. (30): 302–306.

Kalra, S.K., Bhardwaj, K. C., 1981, Use of simple solar dehydrator for drying fruit and vegetable, *Journal of Food Science Technology*, 18, pp. 23- 26.

Mercer, D. G. (2014). An Introduction to the Dehydration and Drying of Fruits and Vegetables. Department of Food Science, University of Guelph. Ontario, Canada. ISBN 978-0-88955-621-8

Miller, W.M., 1985, Solar drying coupled with solid desiccant energy storage, *Trans. ASAE,* 1985, 28, pp. 649- 656.

Moyls, A.L., 1986, Evaluation of a solar fruit dryer, *Canadian Agricultural Engineering*, 28, pp. 137- 144.

Mustayen, A. G. M. B., Mekhilef, S. and Saidur, R. (2014). Performance Study of Different Solar Dryers: A Review. Journal of Renewable and Sustainable Energy Reviews, 34(1): 463–470.

Mujumdar, A.S., 2006, *Handbook of Industrial drying*, Taylor and Francis group, U.K.

Pangavhane, D. R., Sawhney, R. L., Sarsavadia, P. N., 2002, Design, development and performance testing of a new natural convection solar dryer, *Energy*, 27, pp. 579- 590.

Raju, R. V. S., Reddy, R. M. and Reddy, E. S. (2013). Design and Fabrication of Efficient Solar Dryer. Journal of Engineering Research and Applications, 3(6): 1445–1458.

Sanni, L. O., Onadipe-Phorbee, O. and Alenkhe, E. B. (2012). Low-cost Sustainable Cassava Drying Technologies in West Africa: A Compendium of Inforation, Design, Fabrication and Pilot Testing. IITA/CFC-WA Project Report, Nigeria. 28 p.

Seveda, M. S. (2013). Design of a Photovoltaic Powered Forced Convection Solar Dryer in NEH Region of India, International Journal of Renewable Energy Research, 3(4): 1–7.

Shakya, B.R., Flink, J.M., 1986, Dehydration of potato III, Influence of process parameters on drying behavior for natural convection solar drying conditions, *Journal of Food Processing and Engineering*, 10, pp. 127- 143.

Struckmann, F. (2008). Analysis of a Flat-plate Solar Collector. Project Report: 2008 MVK 160 Heat and Mass Transport. Lund University, Lund, Sweden.

Vaghani, S.N., Chundawat, B. S., 1986, Sun drying of Sapota fruits (Achras sapota L.). *Indian Food Packer*, 40, pp. 23- 28.

Wagner, C. J., Coleman, R.L., Berry, R. E., 1979, A low cost small scale solar dryer for Florida fruits and vegetables, *Proc. Florida State Horticultural Society*, 92, pp. 180- 183.

Weiss, W. and Buchinger, J (2002). Solar Drying. Austrian Development Cooperation, Austria. Available from <http://t.aee-intec.at/0uploads/dateien553.pdf>. [17 June 2014]

APPENDIX 1

Typical temperature variation with time during No- load test

			Dryer Temperature ^0C		
Time of Day	Ambient Temperature	Collector temperature	Tray 1 Top	Tray 2 Middle	Tray 3 Bottom
0900	31.3	33.6	31.2	30.2	30.0
1000	35.1	41.1	36.8	34.7	33.7
1100	43.6	47.1	44.0	40.5	39.5
1200	46.4	51.3	46.9	42.6	40.6
1300	49.5	53.5	59.9	44.7	43.5
1400	51.1	53.7	55.9	49.4	48.0
1500	50.1	50.6	58.3	51.9	50.1
1600	46.9	42.3	51.2	43.6	42.7
1700	42.3	40.4	46.1	44.9	42.2
1800	30.5	32.3	40.2	32.5	30.1

APPENDIX 2

Ambient Air Humidity

Time of Day	Dry Bulb temperature (^OC).	Wet Bulb Temperature (^OC)	Relative Humidity %
0900	28	25	76
1000	31	26	70
1100	35	28	60
1200	39	29	48
1300	41	29	42
1400	37	26	40
1500	38	25	35
1600	40	28	44
1700	35	25	48
1800	35	26	50

Drying Chamber Humidity

Time of Day	Dry Bulb temperature (^{o}C)	Wet Bulb Temperature (^{o}C)	Relative Humidity %
0900	25	23	83
1000	32	26	64
1100	37	27	48
1200	42	29	38
1300	43	29	36
1400	41	29	42
1500	42	27	32
1600	40	27	48
1700	39	26	38
1800	36	26	48

APPENDIX 3

Sample Analysis of Moisture Content

Day	Time of Day	Tomatoes Slice weight and Sample holder(g)	Weight of Sample holder (g)	Tomatoes weight (g)	Moisture loss	Cumulative moisture loss	Moisture content Wet Basis %	Moisture content Dry Basis g/H_2O/g Solid
Day 1	0900	2000	1200	800	0	0	86.875	6.6
	1100	1980	1200	780	20	20	84.375	6.4
	1400	1940	1200	740	40	60	79.375	6.0
	1700	1900	1200	700	40	100	74.375	5.6
Day 2	900	1880	1200	680	20	120	71.875	5.4
	1100	1840	1200	640	40	160	66.875	5.1
	1400	1780	1200	580	60	220	59.375	4.5
	1700	1720	1200	520	60	280	51.875	4.0
Day 3	0900	1685	1200	485	35	315	47.5	3.6
	1100	1645	1200	445	40	355	42.5	3.2
	1400	1600	1200	400	45	400	36.875	2.8
	1700	1530	1200	330	70	470	28.125	2.1
Day 4	0900	1500	1200	300	30	500	24.375	1.9
	1100	1450	1200	260	40	540	19.375	1.5
	1400	1390	1200	190	70	610	10.625	0.8
	1700	1340	1200	185	5	615	10.1	0.7

APPENDIX 4

Sample Analysis of Moisture Content for Pepper

Day	Time of Day	pepper weight and Sample holder(g)	Weight of Sample holder (g)	Pepper weight (g)	Moisture loss	Cumulative moisture loss	Moisture content Wet Basis %	Moisture content Dry Basis $g/H_2O/g$ Solid
Day 1	0900	1800	1200	600	0	0	81.7	4.5
	1100	1790	1200	590	10	10	80.0	4.4
	1400	1780	1200	580	10	20	78.3	4.3
	1700	1770	1200	570	10	30	76.7	4.2
Day 2	0900	1750	1200	550	20	50	73.3	4.0
	1100	1735	1200	535	15	65	70.7	3.9
	1400	1715	1200	515	20	85	67.5	3.7
	1700	1685	1200	485	30	115	63.2	3.5
Day 3	0900	1645	1200	445	40	155	55.8	3.0
	1100	1615	1200	415	30	185	50.8	2.8
	1400	1585	1200	385	30	215	45.8	2.5
	1700	1555	1200	355	30	245	40.0	2.2
Day 4	0900	1520	1200	320	35	280	34.2	1.9
	1100	1460	1200	260	60	340	24.2	1.3
	1400	1400	1200	200	60	400	14.2	0.8
	1700	1375	1200	175	25	425	10.0	0.5

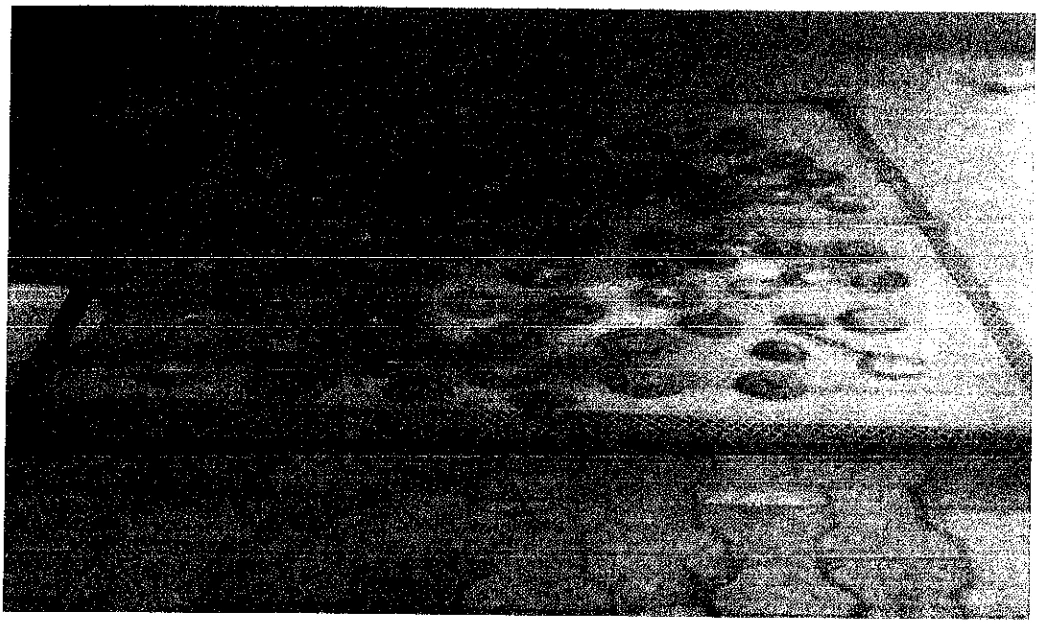
APPENDIX 5

Cost of the solar dryer

No	Name of part	Materials and dimension	Quality	Unit price	Amount
1	Metal Sheet	0.5 x 4ft x 8ft 1.2 x 4ft x 8ft	2	18000	36000
2	Flat bar	1 inch	9	2200	19800
3	Angle iron	1 inch	8	1700	14600
4	Square pipe	1 inch	2	2200	4400
5	Riveting pin	Riveting pin	1	2700	2700
6	Wire mesh	30x 90(m)	3	900	2700
7	Metal rod	10mm, 18ft	1	1800	1800
8	Solar panel		1	18000	18000
9	Electrode	Oelikon 2.50x350(SWG 12)	2	6000	12000
10	Cutting disc	9"x5/64" x7/8	2	5000	10000
11	Grinding disc	9"x1/4" x7/8"	2	5000	10000
12	Nylon		1	1500	1500
13	Black tube		4	2000	8000
14	Fan	12v, 3.3dc	2	6000	12000
15	Filler		1	2000	2000
16	Gum	Resin gum	4	500	2000
17	Black paint		10	700	7000
18	Miscellaneous			23800	23800
		TOTAL			# 188,300.00

APPENDIX 6

Samples of the sliced tomatoes before and after drying



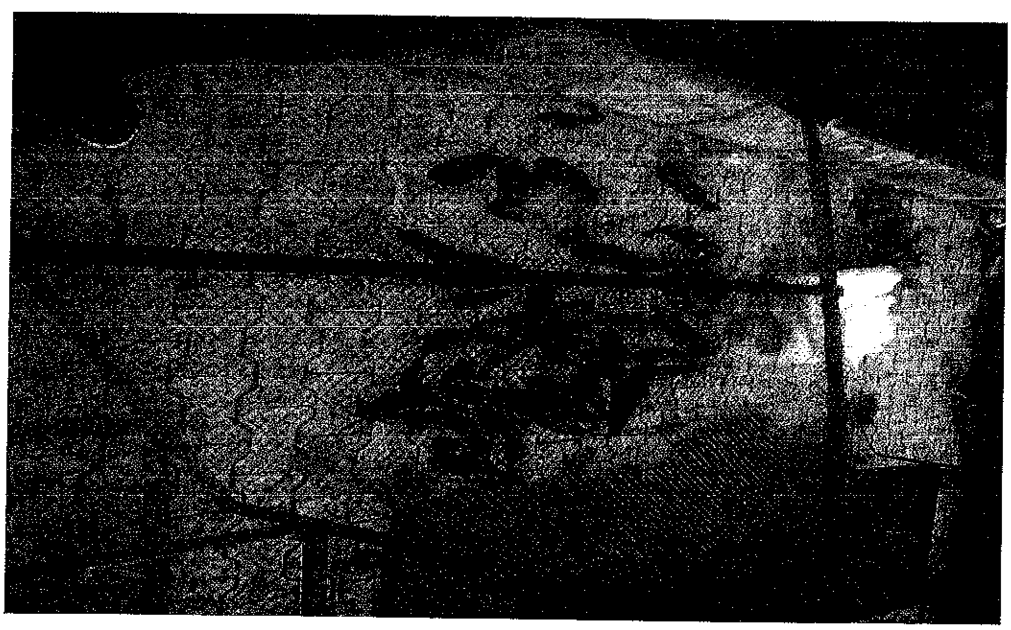
Before drying

After drying

APPENDIX 7

Samples of the Pepper before and after drying

Before drying



After drying