KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI

COLLEGE OF ENGINEERING

DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

PERFORMANCE EVALUATION OF A MIXED MODE SOLAR DRYER INCOPORATING A BACKUP HEATER FOR DRYING COCOYAM SLICES

A THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING, IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF SCIENCE DEGREE IN AGRICULTURAL ENGINEERING

BY

DONKOR BENJAMIN

MAY, 2017

DECLARATION

I hereby declare that this work submitted to the Department of Agricultural and Biosystems Engineering is the result of my own investigation which has not been presented anywhere for the award of any other degree of the university and that all references to other people's work have been duly cited.

Benjamin Donkor ……………………… ……………………..

(Student) Signature Date

Certified by:

Prof. Ebenezer Mensah ……………………… ……………………..

(Supervisor) Signature Date

22nd MAY 2017

Dr. George Obeng ………………… ……………………..

(Supervisor) Signature Date

Prof. Ato Bart-Plange ……………………… ……………………..

(Head of Department) Signature Date

DEDICATION

This work is dedicated to my family, Mr. Samuel Donkor, Mrs. Olivia Gyevi, Mr. Emmanuel Siessi and Mr. Evans Donkor and to all my friends for their support throughout my education.

ACKNOWLEDGEMENT

My Sincere gratitude to the ALMIGHTY GOD for his abundant grace, goodness and for His mercy bringing me this far and for guiding me through the entire project and to the completion of this thesis. Special appreciation also goes to my supervisors Prof. Ebenezer Mensah and Dr. George Y. Obeng for their immense support throughout the project.

I wish to express my gratitude to the Technology Consultant Centre (TCC) KNUST, MIT D-Lab IDIN Project and Mr. Joseph O. Akowuah for providing me with the necessary equipment for this project.

Finally, I am thankful to my family, friends and to all those who helped me in diverse ways to make this project a success.

ABSTRACT

A performance evaluation of a mixed mode solar dryer incorporating a backup heater is presented in this thesis. This thesis compares the drying rate, efficiency, the drying time using the solar dryer only and solar dryer with backup heater. The dryer consists of the primary collector, three drying trays enclosed in a drying chamber, the roof (secondary collector) and chimney. The primary collector is made up of a single pass double duct air heating system with a black painted aluminum plate. The roof (secondary collector) and the side walls of the drying chamber are made of transparent glass. The backup heater is made of a charcoal stove "Gyapa" to supply heat to the drying chamber. Different tests were carried out during the performance evaluation of the dryer. The two main tests were no load and load tests. The parameters used for the evaluation were the drying rate, the drying time, moisture content and the drying efficiency. Under no load test, a maximum average temperature of 56.72^{o}C was found in the dryer with an average dryer temperature of 41.91^{o}C. During the evening, the dryer reached a maximum average temperature of 39.6^{o}C after three hours of heat supply from the backup heater. The average collector efficiency was also found to be 25.37%. Under load test, 900g and 7.5kg of sliced cocoyam were used to evaluate the performance of the solar dryer. The first test was done using 900g of sliced cocoyam and was dried from an initial moisture content of 62%wb to a final moisture content of 5.83% within 20 hours of sunshine (almost two days) and 4.89% within 18 hours of sunshine (almost two days) for solar drying only and when the backup heater was used (only in the evening) respectively. The drying rate and drying efficiency were also evaluated to be 25.25g/h and 2.37% respectively for solar drying only; 28.56g/h and 2.62% respectively when the backup heater was used (only in the evening). The second test was also carried out under the load test using 7.5kg of sliced cocoyam and was dried from an initial moisture content of 62%wb

to a final moisture content of 6.26%wb within 37 hours of sunshine (almost four days) and 5.65%wb within 28 hours of sunshine (almost three days) for solar drying only and when the backup heater was used (day and in the evening) respectively. The drying rate and drying efficiency were evaluated to be 113g/h and 10.24% respectively for solar dying only and 151g/h and 13.50% when the backup heater was used (day and in the evening).

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CHAPTER ONE

INTRODUCTION

1.1 Background

Agriculture represents the largest part of the economy in the majority of African countries where about 80-90% of the working population is employed. National food production does not meet the needs of the population despite these large numbers of the population that are employed in agriculture. Considerable losses however occur due to lack of appropriate preservation and storage systems resulting in the reduction of food supply (Weiss and Buchinger, 2002).

MOFA, (2011) reported that agriculture is the largest sector of the economy in Ghana and contributes about 39% of GDP. This sector however faces certain basic problems including high post-harvest losses as a result of poor post-harvest management.

Agriculture product by nature begins to deteriorate immediately after harvest due to the high level of moisture content.

Drying is a mass transfer process consisting of the removal of water or another solvent by evaporation from a solid, semi-solid or liquid (www.en.m.wikipedia.org/wiki/Drying).

FAO, (1994), stated that drying is the phase of the post-harvest system during which the product is rapidly dried until it reaches the safe moisture level. For safe storage or further processing of agricultural products, its moisture content needs to be reduced to prevent the growth of bacteria and mould infestation.

Sun drying is the most common drying method but is only possible in areas where in an average year the weather allows food to be dried immediately after harvest. This was done particularly under the open sky and also the activity of the wind. Thus sun drying is solely dependent on the sun's energy for drying of agricultural produce and hence becomes ineffective where the weather becomes unfavorable. This method of drying however is slow and entails great risk of loss of agricultural produce.

Solar drying has also been in practice since ancient times for drying of agricultural crops by utilizing the sun's radiative energy. This method also depends on the sun's energy but more efficient than the open sun drying. In solar drying, the quality of the product is kept and the drying time is also reduced due to the higher temperature accumulated in the dryer relative to that of the ambient temperature.

1.2 Problem Statement

The reduction of food losses is particularly a problem for small scale farmers in developing countries who produce more than 80% of the national food requirement (Goic et al, 2012). To curb this problem of food losses food have to be dried after harvesting to preserve them so that they can be stored for a longer time.

Agoreyo et al., (2011) reported that tropical food crops such as cocoyam and yam may be in abundance in a particular period of the season. There is the need therefore to dry them after harvest since they are highly perishable.

Due to the high moisture content characteristics of root and tubers which make them difficult to store for any length of time, they have to be dried in order to preserve them for a longer time (FAO, 1998).

Sun drying is one of the oldest methods of drying food crops but has several disadvantages. Even though traditional sun drying is the cheapest method of drying, it is relatively slow and considerable losses can occur. However, there is a reduction in product quality due to insect infestation, enzymatic reactions, micro-organism growth and micotoxin development. There is also spoilage of product due to adverse climatic condition like rain, wind, moisture and dust, loss of material due to birds and animal, theft and fungal growth. The process is also highly labour intensive and requires large area (Goic et al, 2012).

Production of uniform and standard products however is not expected in sun drying of agricultural crops. Improvement in the quality of the dried products and reduction in wastage can be achieved by the introduction of appropriate drying technologies such as the solar dryer which is economical and widely used.

However, most solar dryers that are constructed use only the sun's energy as a heat source for drying of agricultural crops hence dependent on climatic conditions restricting it use in cloudy periods and at night. As a result, agricultural produce that are harvested during the rainy season are still subjected to spoilage.

1.3 Problem Justification

Drying is one of the methods used to preserve food product for longer periods. It is the most efficient preservation technique for most tropical crops.

Solar drying however can be proved to be the best method of food preservation. They have some advantages over sun drying if accurately designed. A faster drying rate is assured which decreases the risk of deterioration; it improves quality of the product and gives a higher rate of production. Moreover the drying area is also reduced.

Solar dryers do not only save energy but also saves enough time and makes the process more efficient. In addition, solar dryers have a high tendency to remove moisture compared to sun and oven drying hence the best alternative for drying (Agoreyo et al., 2011). They have the ability to dry food items faster to a safe moisture level as they ensure a better quality of the dried product.

Since the sun's energy is the main source of energy for drying and drying of crops at night and in rainy season becomes difficult, the need for a backup heater to supply additional heat during these periods is desired

Hence incorporating the backup to the dryer enables its usage during the night and the cloudy or rainy days.

1.4 Objective of Study

1.4.1 Main Objective

The main objective of the study is to evaluate the performance of a mixed-mode solar dyer incorporating a backup heat source for drying of agricultural produce.

1.4.2 Specific Objectives

The specific objectives of the study are;

1. To evaluate the performance of the solar dryer based on parameters such as temperature, moisture content of the produce, drying period, drying rate and efficiency.
2. To compare the performance of the solar dryer with and without the backup heater.

CHAPTER TWO

LITERATURE REVIEW

Drying refers to the process of the removal of moisture due to the simultaneous transfer of heat and mass (Ertekin and Yaldiz, 2004). Drying has become one of the main processing techniques used to preserve food products in sunny areas (Saidur et al., 2014).

Most of the agricultural products contain moisture content of about 25-80% but generally, it is around 70% for agricultural product. This value of moisture content however is much higher than the required value for long preservation. Due to the higher moisture content, bacterial and fungi growth is very fast in the crops (Chaudhari and Salve, 2014). Bacteria and fungi can cause deterioration and loss of quality of agricultural produce.

Moisture content of crops at a certain level slows down the effect of bacteria, enzymes and yeast. Therefore it is very essential to bring the moisture content in the agricultural produce to or near its safe moisture content in order to preserve them for a longer time.

Drying consists of the application of heat to vaporize moisture and some means of removing water vapour after its separation from the food products. It involves a combined and simultaneous heat and mass operation for which energy must be supplied. The removal of moisture prevents the growth and reproduction of bacteria, yeast and moulds (Salve and Santakke, 2015).

Gutti et al., (2012) reported that, agricultural products, especially fruits and vegetables require hot air in the temperature range of 45-60^{o}C for safe drying. Agricultural product drying under controlled condition at specific humidity as well as temperature gives a rapid higher quality of the dried product.

2.1 Sun drying

Sun drying is one of the oldest methods used to keep agricultural produce for a longer time from spoilage. The method however depends entirely on the sun's energy for drying of the agricultural produce. During drying, the crop is placed on the ground and open to the sun, which can reach higher temperatures and left there for some days to dry. This type of drying method is useful for drying grains. In terms of capacity and despite the basic nature of the process, natural drying remains the most common method of solar drying (Hii et al., 2012).

Due to the fact that the sun's energy is the main source for the drying of the crop, drying cannot take place when there is no sunshine of during rainfall. This method also has certain limitations in addition to its inability to dry crops during no sunshine period. Some of which are the re-wetting of the crop, insect infestation which affect the quality of the product and also damage to the crops by birds and animals. Moreover, the process is relatively slow as it takes longer time for the crop to dry.

2.2 Solar drying

Solar drying is the type of drying method that harnesses the sun's energy to dry agricultural produce. It traps the heat in an enclosure to dry the agricultural produce thereby increasing the temperature of the produce. Solar drying helps to correct the disadvantages that results from open sun drying. In the end, the quality of the product is improved to meet economic standard. Although this method is more effective compared to the open sun drying, it use is limited during cloudy and rainy days since its main source of energy is the sun.

Solar drying is often differentiated from “sun drying” by the use of equipment to collect the sun’s radiation in order to harness the radiative energy for drying applications. Sun drying is a common agricultural process in many countries, particularly where the outdoor temperature reaches 30°C or higher.

However, weather conditions often eliminate the use of sun drying because of spoilage due to rehydration during unexpected rainy days.

In addition, any direct exposure to the sun during high temperature days might cause case hardening, where a hard shell develops on the outside of the agricultural products, trapping moisture inside.

Solar dryers therefore are employed to make use of the available sun energy to ensure that the final product after dying is of good quality and of desirable final moisture content.

Sharma et al., (2009) reported that a typical solar dryer improves upon the traditional open-air sun system in five important ways;

1. It is faster: Thus materials can be dried in a shorter period of time. Solar dryers enhance drying times in two ways. Firstly, transparent material over the collection area traps heat inside the dryer, which raise the temperature of the air. Secondly, the flexibility of enlarging the solar collection area allows for greater collection of the sun’s energy.
2. 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 animals and insects since the products are safely enclosed in a chamber.

3. 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.
4. 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. In addition, with solar dryers, products will look better, which enhances their marketability and hence provides better financial returns for the farmers.
5. 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.

To produce a high-quality product economically, food crop or agricultural produce must be dried fast, but without using excessive heat, which could cause product degradation. Moreover drying time can be shortened by two main procedures: one is to raise the product temperature so that the moisture can be readily vaporized, while at the same time the humid air is constantly being removed. The second is to treat the product to be dried so that the moisture barriers, such as dense hydrophobic skin layers or long water migration paths, will be minimized (Boiln and Salunkhe, 1982).

In addition, the drying temperature and method of pretreatment is very essential as it affect the product quality. Certain agricultural produce are pretreated with certain solutions in order to protect their brightness and colour. For instance dipping tomato into 2% sodium metabisulfite ($Na_2S_2O_5$) solution for 3 minute is the best type of pretreatment. Citric acid can be used but it is not as effective as the sodium metabisulfite in the prevention of the growth of moulds and yeasts. Tomatoes can be dried at 55°C in solar tunnel dryer without a darkening in colour. At this temperature the drying takes 4-5 days to a final moisture content of 11%.

Pretreatment with 2% $Na_2S_2O_5$ for one second gives the best colour in the case of Red pepper. Temperatures higher than 60°C results in dark brown colour formation hence drying at low temperatures (45-50°C) for about one day is preferable. Onions can also be dried at 45-50°C for 2-3 days in tunnel solar dryer. Drying temperatures of onions should not exceed 50°C in order to prevent browning of the product. Sodium metabisulfite dipping can be used to preserve the colour. On the basis of colour, flavour and microbiology of the final product, it was observed that high quality dried okra was obtained using 2% $Na_2S_2O_5$ dipping as a pretreatment and drying of okra at 50-55°C in the solar dryer under dark conditions. Drying time was about one day (Kaptan and Seylam, 1996).

2.3 Classifications of solar dryers

Drying systems can be classified primarily according to their operating temperature ranges as high temperature dryers and low temperature dryers. However they are broadly classified according to their source of heating as fossil fuel dryers (for the high temperature dryers) and the solar energy dryers (for the low temperature dryers).

Solar dryers however can also be classified based on their mode of air flow as:

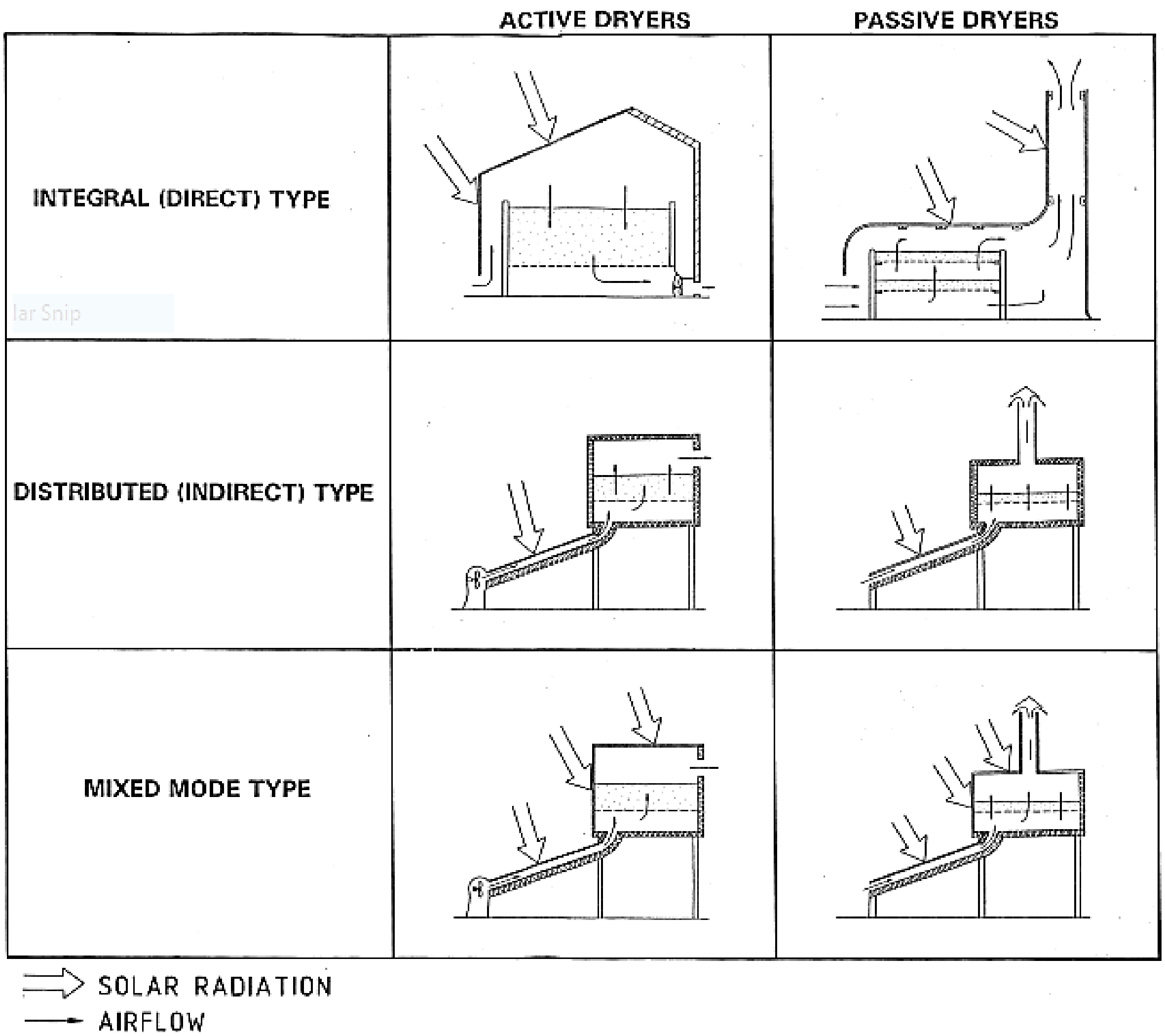
1. Active solar dryer (force convection solar dryer)
2. Passive solar dryer (natural convection solar dryer)

Forced convection solar dryers are the type of dryer in which air is forced through a solar collector and the product bed by a fan or a blower whereas Natural convection solar dryer is the type in which natural movement of air takes place. The heated air flow is induced by thermal gradient (Toshniwal and Karale, 2013). Under the active and passive solar dyers, three sub classes of the dryers can be established which differ in the design arrangement of system components and the mode at which the solar energy is to utilized (Ekechuku, 1987). The sub-classes of solar dryers are;

1. Direct type solar dryers
2. Indirect solar dryers
3. Mixed-mode solar dryers

The main features of typical designs of the direct, indirect and mix-mode types of solar -energy dryers are illustrated in the Table below;

Table 2.1 Typical solar energy dryer designs (Ekechukwu and Norton, 1999).



2.3.1 Direct type solar dryer

It is a type of dryer in which solar radiation is directly absorbed by the product to be dried.it is also called as natural convection cabinet dryer since the solar radiation directly fall on the product and causes a reduction in the quality of the product. Heat is generated by absorbing solar radiation on the product itself and internal surface of drying chamber (Hii et al., 2012).

The direct type of solar dryer is made up of a drying chamber that is covered by a transparent cover made of glass or plastic. The drying chamber is usually a shallow, insulated box with air-holes in it to allow air to enter and exit the box (Toshniwal and Karale, 2013).

Three things happen when sun light is incident on the surface of glass; first, some light is absorbed; second, some is reflected back from the glass and thirdly, some is transmitted.

A direct type of solar dryer is mostly used in areas where direct sunlight is being received for longer periods during the day. The transparent glass cover helps to reduce heat loss from the drying chamber and also protects the product from rain and dust (Saidur et al., 2014).

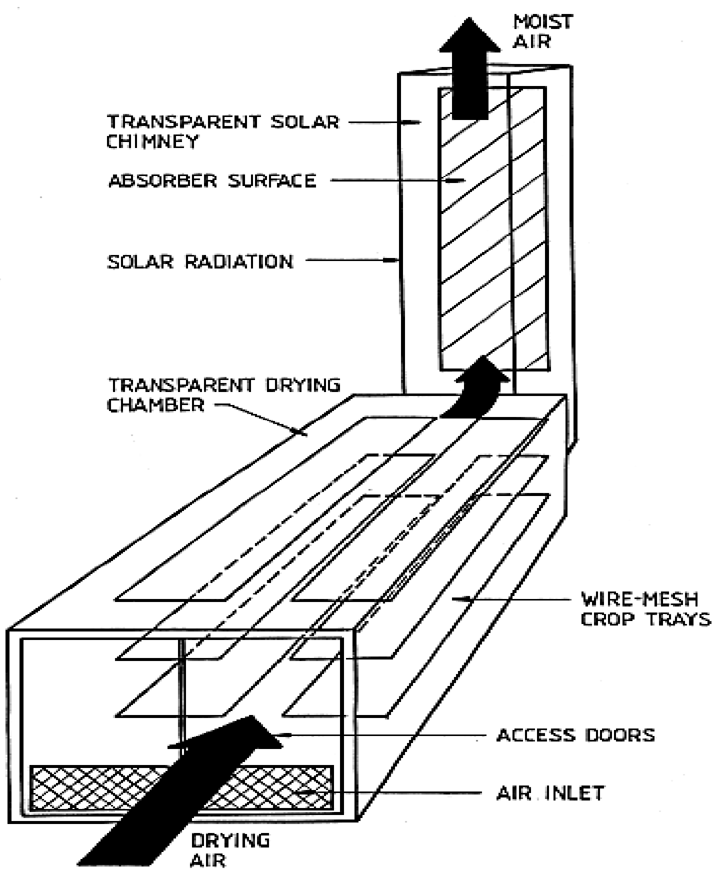


Fig.2.1. A typical direct natural convection solar dryer (Ekechukwu and Norton, 1999)

2.3.2 Indirect type of solar dryer

The indirect type of solar dryer differs from the direct type by the transfer of heat and the removal of vapour. The dryer is made up of a solar collector or the air heater which is connected to a separate drying chamber where the product is kept to be dried. The heated air is allowed to flow through wet material. The heat for the evaporation of moisture is provided by convective heat transfer between the hot air and the wet material. Fundamentally, the drying is the difference in moisture concentration between the drying air and the air in the proximity of product surface. Concentrating collectors can also be used in a similar manner as that of the flat plate collectors for drying application. The temperature obtained from the concentrating collector is however higher than that obtained from the flat plate collector.

Moreover, the solar radiation gained by the indirect type of solar dryer is used to heat the air which flows through the product to be dried. Vents are provided at the top of drying chamber through which moisture can be removed. In addition, a higher drying rate and better control over drying is achieved in the indirect type of solar dryer and therefore proves to be a more efficient method than the direct type of solar dryer (Toshniwal and Karale, 2013).

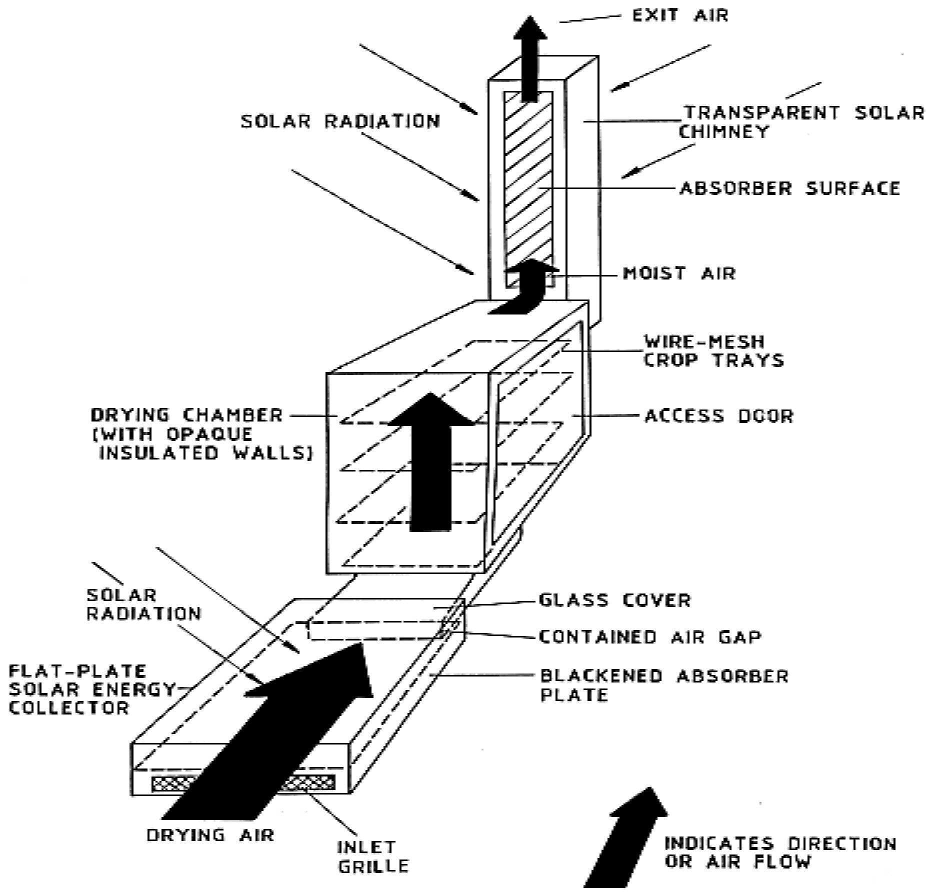


Fig.2.2 Features of a typical indirect passive solar dryer (Ekechukwu and Norton, 1999).

2.3.3 Mixed mode solar dryer

Mixed mode solar dryer is the combination of direct and indirect type of solar dryers. The product is dried by subjecting it directly to the sun's radiation and also by hot air supplied on it. Here, air is heated in a collector and then supplied to the drying chamber. The top of the drying chamber in this type of solar dryer is made up of a glass cover which can directly absorb solar radiation. The temperature thus increases above ambient temperature which in turn causes an increase in the temperature of the product for quick moisture removal, hence reducing the drying time. The drying rate therefore is much higher compared to the direct and indirect types.

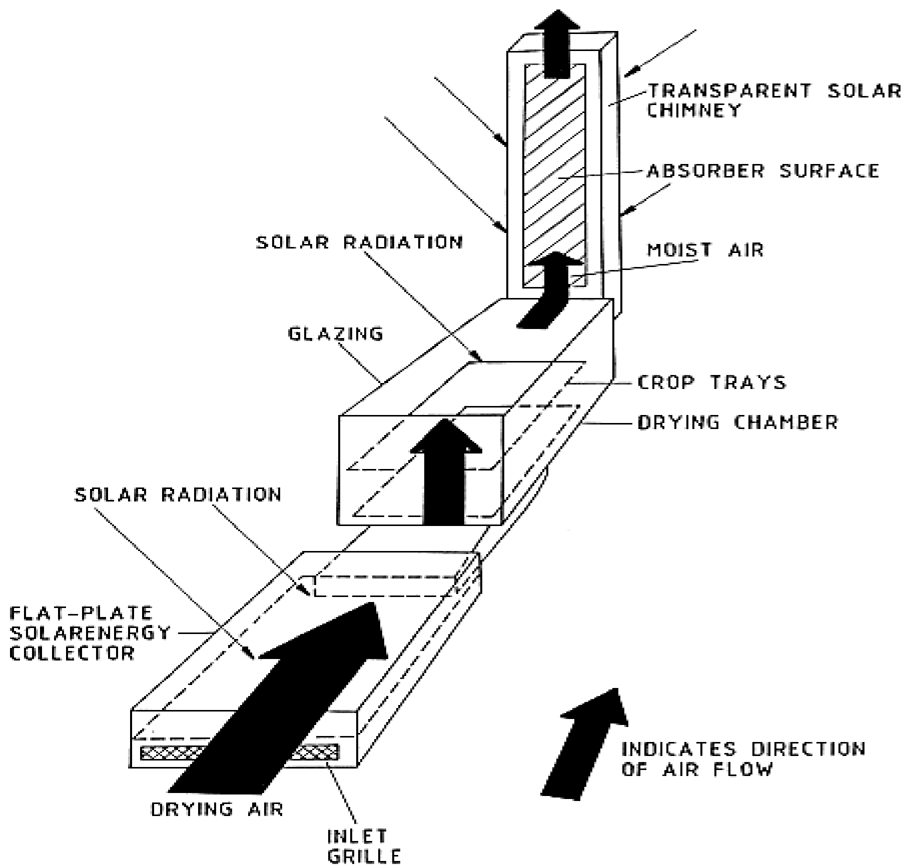


Fig.2.3 Features of a typical mixed mode passive solar dryer (Ekechukwu and Norton, 1999).

2.4.4 Hybrid solar dryers

Certain crops that are harvested during the raining seasons have to be dried in order to prevent their rapid deterioration; hence the use of a hybrid solar dryer plays a major role in preventing the deterioration. A hybrid solar dryer is one which comprises a backup heater incorporated to the solar dryer to enable drying during cloudy and rainy periods as well as night.

An indirect natural convection solar dryer with a backup heater was designed and evaluated by Tibebu (2015) to dry pineapple and mango from an initial moisture content of 87%wb to 16%wb and 85%wb to 13%wb respectively within two to three days. The dryer consisted of the solar collector, drying chamber, chimney and the charcoal stove. The collector was made up of the single layer glass, aluminum absorber plate and fiber glass insulation enclosed in a wooden casing. The backup heater used a stove to burn charcoal for supplying heat into the drying chamber.

Fig.2.4 Pictorial view of the indirect solar dryer with a backup heater (Tibebu, 2015)

Ajala et al., (2014) investigated the effect of temperature on the physical and chemical properties of cocoyam flour with different samples using a tunnel dryer at different temperatures from 50^{o}C to 85^{o}C. They reported that, higher temperature results in a decrease in the proximate composition of cocoyam in terms of moisture content, protein, lipids and ash except carbohydrate and fibre which increase with increase in temperature. From the test, the protein content ranged from 4.340 to 6.960%, lipids ranged from 0.483 to 0.650% that of fibre ranged from 1.923 to 3.220% and carbohydrate ranged from 76.293 to80.713%.

Moreover, it was observed that an increase in temperature resulted in a decrease in thermal conductivity and specific heat capacity but increases in the thermal diffusivity of the cocoyam. In addition, it was observed that the fictional properties of the cocoyam flour increased with temperature (thus; swelling capacity and water absorption except bulk density which decreased with temperature).

Udoye et al., (2014), conducted a study on a thin layer drying characteristics of cocoyam slices using a hot air convective dryer. 3mm thickness of sliced cocoyam was used for the experiment and was performed at five different drying temperatures of 65, 70, 75, 80 and 85 at air velocity of 2m/s with relative humidity of 50, 40, 39.5, 33.8 and 22.2% respectively. They concluded that, the thin layer drying of the cocoyam slice took place in the falling rate period. Moreover, higher temperature increased the drying rate and shortened the drying time. In addition, logarithmic model was used to best describe the drying behavior of the cocoyam slice. They also stated that the moisture diffusivity in cocoyam chips was affected by the drying temperature which in turn affected the internal mass transfer during drying. The test gave a higher moisture diffusivity of cocoyam and this was attributed to the lower moisture content, texture and composition of cocoyam which reduces the transfer of moisture compared to fruits and vegetables.

Agoreyo et al., (2011) investigated the effect of various drying techniques on the nutritional composition of plantain, yam and cocoyam. The drying techniques were oven, sun and solar drying. Analysis of the nutritional composition of the various samples using the different techniques showed that, the moisture content of the solar dried samples reduced significantly compared to that of the sun dried and oven dried samples. Thus the moisture content ranged from 75 to 9.38% with the solar dried sample having the lowest value. Carbohydrate, lipids and fibre contents ranged from 94 - 86.69%, 2.40 - 1.10% and 3.80 - 6.88% respectively with solar dried samples having the lowest value compared to the sun and oven drying. Moreover, the protein and magnesium contents of the soar dried samples were higher than the sun dried samples but lower than that which were oven dried. The protein and magnesium content ranged from 4.00 - 2.84% and 26.12 - 7.90% respectively. In addition, the calcium and ash content of the solar dried samples were higher than the oven dried samples but less than the sun dried samples. The content ranged from 49.37-10.85% and 1.60-4.95% for calcium and ash respectively. From the test, solar dying had a high tendency of moisture removal compared to the oven and sun drying. They concluded that although solar and oven drying were found to be more hygienic and faster than the sun drying, solar drying is more cost effective than the oven drying and maybe the best technique for processing these food crops since it increases the shelf life of the dried sample.

Drying affect the nutritional content of cocoyam as it reduces it to a level but not significantly. This may be due to the presence of oxalate compounds which may be harmful when consumed.

Afoakwa et al., (undated) reported that the presence of oxalate in cocoyam is known to cause acridity, absorption poisoning and binds calcium thereby inhibiting its absorption but this oxalates was less in solar dried samples of cocoyam than oven or sun dried samples. They stated that, one major limiting factor in the utilization of cocoyam (taro) was the presence of oxalates which partly gave an acid taste or caused irritation when consumed.

2.5 Cocoyam

Cocoyam belongs to the family of Araceae and comes in different species such as Xanthosoma Sagittifollium (Red-flesh and White-flesh), Colocasia Esculenta, Colocasia Antiquorum (eddo or eddoe) and Arum. They are mostly cultivated in countries like Nigeria, Asia, pacific island, Ghana and Japan due to their high importance.

It is the fastest growing crop in Africa with the minority from Asia (Okpala, 2015). Nigeria is however the world largest producer of cocoyam accounting for about 37% of total worlds output (FAO, 2006). FAOSTAT (2014),reported that Nigeria produce about 3.3 million metric tons followed by china, Cameroon and Ghana with 1.8, 1.6 and 1.3 million metric tons respectively with a world production of 10.2 million metric tons. They contain low level of carbohydrate and high quality nutritional composition.

It is ranked third after cassava and yam in importance among the root and tuber crops cultivated and consumed in Nigeria and it's also nutritionally higher in quality to cassava and yam (Igbozulike, 2015 quoted from Umudike, 2015).

Cocoyam is a stable crop for many people in the world. It consists of the corm, stem and the leaves. The leaves contain more vitamin content as compared to the corm. Cocoyam however contains high nutritional value when compared with foods like cassava and yam and has substantial vitamins like vitamin B, C and E, minerals such as calcium, magnesium and a high protein content. They also contain dietary fibres which have been proven to help in easy passage of stool (Okpala, 2015).

2.5.1 Processing and utilization of cocoyam

Starchy roots and tuber crops plays an important role in human diet such as the provision of energy. The importance of root and tuber crops is seen in their annual global production of approximately 836 million tons (FAO STAT, 2013). Some of the roots and tuber crops of major importance are; potato, yam, cassava, plantain, sweet potato and aroids (cocoyam and taro).

Many starchy tuber crops are not yet fully explored for their nutritional and health benefits. Tubers have an immense potential to be explored in disease risk reduction and wellness (Chandrasekara and Kumar, 2016).

Tuber crops can be process in different ways; by frying, baking, boiling, roasting or drying before consumption. However, the type of processing chosen has a significant effect on the nutritional composition as reported by several literatures (Udoye et al, 2014, Afoakwa et al, undated and Agoreyo et al, 2011). Some of the processing conditions also change the phytochemical and the bioactivity of the tuber crop (Chandrasekara and Kumar, 2016).

However, processing of cocoyam is hindered by the unavailability of machines and equipment to carry out the various processing tasks (Igbozulike, 2015). Cocoyam can be processed into cocoyam crips, soup thickener, cocoyam fufu flour, cocoyam queen cake doughnut and chips (Igbozulike, 2015, quoted from Umudike, 2015).

Moreover, processing of cocoyam into flour extends its shelf life and makes it available for us all year round. Cocoyam flour can be used in the preparation of soup, biscuits, beverage, bread and puddings.

Dried tuber crops have gain importance now a day with dried cassava produced currently for local animal feed industry in Columbia, Ecuador, Brazil, Panama and Bolivia as reported by Ospina and Wheatley, (undated).

Cocoyam can be utilized in many forms; the corms can be used in the preparation of burger, bread, flakes and pancakes. The processed cocoyam flour can also be mixed in a ratio with cassava flour to form fufu flour for consumption (Oluwaseun et al, 2015). The flours can also be used with other cereals for snack production. The leaves however, can also be used as vegetables for cooking. Moreover, cocoyam is good for diabetic patients due to their low glycemic index which affects blood sugar levels slowly without sudden rise in the blood sugar level. This is also due to its content of loose carbohydrate in the form of starch rather than sugar (Okpala, 2015).

Cocoyam can also be used in the preparation of feeds for weaned pigs (Ajala et al., 2014, quoted from Agwumobi et al, 2012). The utilization of cocoyam is summarized below;

1. Source of animal feed.
2. Process product for human consumption.
3. Manufacturing of starch, alcohol and fermented foods.
4. Used in the treatment of cancer due to the presence of fibre content.
5. Useful for diabetic patients.

Even though cocoyam has several usages, its utilization is however, limited by the presence of oxalate compounds which impart acrid taste and cause irritation when consumed (Afoakwa et al., undated). it is reported that oxalate have caustic effects, exerts irritations to the intestinal tract and cause absorptive poisoning (thus, causes burning sensation in the mouth and throat as well as swelling and construction of the throat, digestive and breathing problems and kidney damage).

Also oxalates interfere with the bio-availability of calcium. Calcium oxalate present in cocoyam corms are insoluble and contributes to kidney stones. Processing methods like sun drying, solar and oven drying help to reduce the oxalate content in cocoyam by 50% but solar drying decreases the oxalate content better than sun or oven drying (Afoakwa et al., undated). It is also recommended that calcium rich foods like milk have to be consumed together with cocoyam to reduce the effect of calcium oxalate (en.m.wikipedia.org/wiki/Taro, quoted from Hossain et al., 2003).

2.5.2 Cocoyam chips

Cocoyam can be processed into chips or in slices form. This is achieved by cutting or slices into very fine thickness with a sharp knife. The thickness of the chips or slices is however determined by the method of processing. Several literatures recommended a slice thickness between 2-5mm when drying to ensure a faster drying of the slices or chips.

Dried chips of root and tubers can be affected by discolouring compounds, except cassava. The discolouring of the dried chips occurs in three (3) ways, (FAO, 1998 quoted from Straw and Booth, undated);

1. Enzymatic darkening
2. After – cooking darkening
3. Browning during drying and storage

Enzymatic darkening is caused by the oxidation of phenolic compounds resulting in a brown to blue black discolouration which affects the quality and the appearance of the final product. Cooking before peeling and slicing will destroy the enzyme and prevent this type of discolouration. Moreover, immersing it in water also helps to slowdown the rate of enzymatic reaction. Adding salt (3% w/w) to water will further slowdown the reaction. In addition, dipping the chips in a 0.1 to 0.2% sodium bisulphite solution for five minutes or in 0.5% sodium metabisulphite solution for 10 minutes is a preferred treatment when freshly cut chips have to be kept for longer period.

After cooking darkening is the result of oxidation of ferrous iron present in the tuber to ferric iron. Roots and tubers chips which are still warm after being boiled or blanched should be cooled as quickly as possible. In addition, dipping the chips in a solution of 0.4% citric acid will help prevent oxidation from occurring.

Browning usually takes place during drying and storage of the chips. This is the result of the combination of reducing sugar with free amino acids. The reaction occurs in a rapid manner at temperatures above 55^{o}C, hence it’s important to keep the drying temperature as low as possible (FAO, 1998).

CHAPTER THREE

3.0 MATERIALS AND METHODS

A mixed mode solar dryer was used in the performance evaluation test. The dryer consisted of three parts; the primary collector, the drying chamber, the roof (secondary collector) and the chimney. The drying chamber was made of wood and painted black to prevent heat loss and designed to hold three trays. The primary collector (Solar collector) consisted of a glass cover, an absorber plate made from aluminum sheet which was painted black to increase its absorptivity and an air vent. The secondary collector was also made of transparent glass to enable direct insolation on the dried produce. The dryer however consisted of a roof made of transparent glass 0.45m in height. The whole dryer was supported on wooden bars.

A backup heater with charcoal as feedstock was incorporated into the dryer to evaluate its performance when used during day time, night and rainy periods.

Table 3.1 Dryer parts and Backup heater dimensions

Parameter	Units	Value
Dryer		
Drying Chamber	m	0.6 x 0.63 x 0.82
Inlet vent area	m^2	0.083
Chimney vent	m	0.1 x 0.63
Chimney height	m	0.31
Roofing height	m	0.45
Trays	m	58 x 60 x 5
Effective area of trays	m^2	0.336
Collector (Primary)	m	1.06 x 0.63
Effective collector area, A_c	m^2	0.611
Collector (Secondary)	m^2	1.06 x 0.53
Collector Area (secondary)	m^2	0.568
Total area receiving insolation, A_T	m^2	1.173
Dryer capacity	Kg/batch	45
Collector tilt angle	^{o}	25
Backup Heater		
Stove Diameter (Medium)	m	0.31
Stove height	m	0.25
Chimney height	m	0.24
Diameter of metal tube	m	0.10

3.1 Experimental Procedures and Dryer Evaluation

3.1.1 Material preparation

Fresh Cocoyam corms were obtained from Ejisu local market. The corms were washed, peeled and sliced (disc shape) of about 3 - 4mm thickness with a stainless steel knife. The peeled corms were immersed in water for some minutes before being sliced. Tissue paper was used to remove excess water. According to Ikejiofor (2010), the slice thickness should be in the range of 2-5mm hence, the thickness of cocoyam slice chosen for the test was in the range. The initial moisture content of the cocoyam was determined by oven drying. The test was carried out from February to April. The temperature, relative humidity, initial and final mass of the cocoyam and the speed of wind were measured at various points during the experiment. The dried cocoyam chips were bagged and sealed.

3.1.2 Instruments used for data collection

Weight, temperature, wind, humidity and solar insolation were some of the parameters measured during the evaluation of the dryer. Initial weight of the cocoyam to be dried was determined with an electronic balance before being placed in the dryer. The weight was determined every two hours interval during the drying process.

Tiny-tag temperature and humidity data loggers TGP-4500 and TY-4500 were calibrated and used to measure and record both temperature and relative humidity in the drying chamber and the collector at every one hour interval. The instrument was then connected to a computer to retrieve the data.

Solar radiation incident on the solar collector was measured with a solar power meter SOLAR-100. Readings were taken at 30 minutes interval from 8:00am until sunset.

Wind vane Anemometer TPI-575C1 was used to measure the speed of the wind passing through the solar collector into the drying chamber. Readings were taken at 30 minutes interval from 8:00am until sunset. The data was then converted to hourly basis and used in evaluating the performance of the dryer based on the drying rates and efficiencies.

3.1.3 Performance evaluation of the solar dryer

3.1.3.1 Collector efficiency

The collector efficiency measures the thermal performance of the dryer. It is defined as the fraction of the useful heat gain by the collector. The steady state efficiency of the solar air collector using Hottel-Whillier-Bliss equation (Forson et al., 2007), is given as:

$$\eta_c = \frac{Q_g}{I_{\mathrm{T}} A_{\mathrm{c}}}$$

Where,

$Q_g = m_a \text{x } C_p \text{x } (T_o - T_i)$

Q_g = Useful heat energy gained by air (kJ)

m_a = Mass flow rate (kg/s)

C_p = Specific heat capacity of dry air (KJ/kgK)

$(T_o - T_i)$ = Average change in temperature (K)

A_c = area of the primary collector (m^2)

I_T = Average solar insolation (W/m^2)

3.1.3.2 Drying efficiency

Drying efficiency is the ratio of the energy utilization for heating the sample for moisture evaporation to the total consumed energy. This measures the overall effectiveness of the dryer (Forson et al., 2007 quoted from Brenndorfer et al, 1987).

$$\eta_d = \frac{M_W L}{I_T A_T t_d}$$

Where;

M_w = Mass of moisture removed by dryer (kg)

A_T = total area of collectors (m^2)

I_T = Average solar insolation (W/m^2)

L = Latent heat of evaporation of water (kJ/kg)

t_d = Overall drying time, (seconds)

- For a dryer assisted with the biomass heater;

$$\eta_d = \frac{M_W L}{I_T A_T t_d + (M_c CV)}$$

Where;

M_c = Mass of biomass (on hourly basis) (kg)

CV = calorific value of biomass (kJ/kg)

3.1.3.3 Average drying rate

Average drying rate, M_{dr} is determined from the mass of moisture removed by dryer, M_w and drying time as given by equation below;

$$M_{dr} = \frac{M_w}{t_d}$$

Where,

M_{dr} = Average drying rate (kg/h)

M_w = Mass of moisture removed by dryer (kg)

t_d = Overall drying time (h)

3.1.3.4 Moisture content

Moisture content is the fraction of the water in the produce. Moisture content of the produce can be calculated in two ways; on wet basis and on dry basis.

- On wet basis

$$M_{wb} = \frac{(m_i - m_f)}{m_i} x100$$

- On dry basis, moisture

$$M_{db} = \frac{(m_i - m_f)}{m_f}\ x\ 100$$

Where,

M_{wb}= moisture content on wet basis (%)

M_{db}= moisture content on dry basis (%)

m_i = Initial mass of the product before drying (kg)

m_f = Final mass of the product after drying (kg)

3.1.3.5 Moisture gain or loss

This is the percentage increase or decrease in moisture during the night period. A negative value indicates further moisture loss while a positive value indicates moisture gain. It can be calculated as;

$$M_n = \frac{M_{sr} - M_{ss}}{M_I}$$

Where;

M_{sr} = Mass at sunrise (kg)

M_{ss} = Mass at sunset (kg)

M_I = Initial mass of sample (kg)

3.1.4 Experimental procedures

The experiment was carried out in Kumasi (Latitude $6^o42'$N and longitude $1^o57'$W). The test was done from February to April, 2017. During the test, tinytag loggers were placed at eight different locations in the dryer. Four of those loggers were placed in the solar collector; one at the collector inlet to measure the inlet temperature and relative humidity of the air entering the collector, one at the middle of the collector to measure the temperature and relative humidity in the collector and one above and below the collector exit to measure the temperature and relative humidity of the air entering the dryer from the collector.

Three of the loggers were also placed in the drying chamber with one over each tray to take readings of the temperature and humidity of the air in the chamber. Lastly, one was placed at the outlet of the chimney air vent to measure the temperature and relative humidity of the exit air from the drying chamber. Another logger was hanged under a tree to measure both the temperature and relative humidity of the surrounding or ambient air. The loggers were calibrated to take reading every hour.

The wind speed and the solar insolation incident on the collector were measured with wind vane anemometer TPI-575C1 and solar power meter SOLAR-100. Readings were taken at 30 minutes interval from 8:00 am until 6:00 pm.

Two tests were done under no load for two days (25th and 26th of February, 2017). Moreover, two tests under load were also done with 900g and 7.5kg from 28th February to 3rd March, 2017 and from 28th march to 7th April, 2017 respectively. The test was done using sliced cocoyam of about 4mm thickness of an average moisture content of 62%wb determined by oven drying. The final moisture content of the cocoyam was in the range of 5 - 7%wb.

The initial weights of the trays without the sliced cocoyam were recorded for subsequent observations. The weight of the sliced cocoyam was determined every two hours interval with an electronic balance and was used to evaluate the moisture loss in the slices from 8:00am to 6:00pm.

Fig.3.1 Arrangements of slices on tray

(a)  (b) 

Fig.3.2 (a) & (b) Measurement of the solar insolation using solar power meter and wind speed using wind vane anemometer respectively.

3.1.5 Parts of the dryer

The mixed mode solar dryer consisted of four parts namely;

- The drying chamber
- The primary collector
- The Chimney and
- The Roof (secondary collector)

Fig.3.3. Front view of the solar dryer with backup heater.

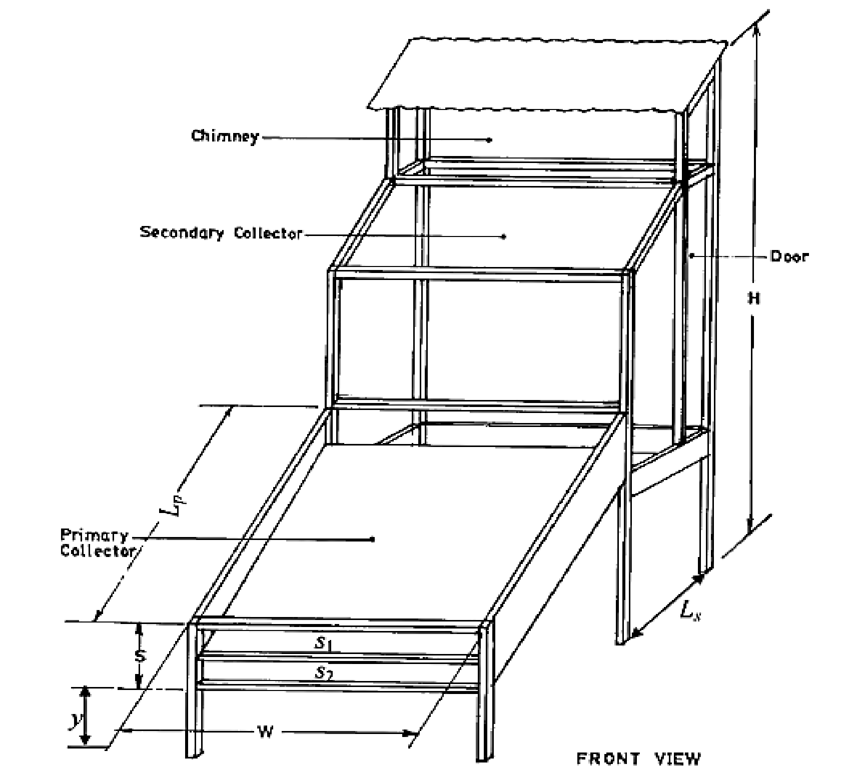


Fig.3.4 Isometric view of the mixed-mode solar dryer

3.1.6 Dryer evaluation test

Three different tests were carried out during the evaluation of the dryer with and without the backup heater.

3.1.6.1 No load test

The No load test was done to know the maximum possible rise in temperature of the collector as compared to that of the ambient. Also this test helped to know the maximum possible rise in temperature of the drying chamber as compared to the ambient. Moreover, a backup heater was used after sunset from 18:00 hours to 21:00 hours. 300g of charcoal was used as the feedstock which was added every one hour interval. Two tests were performed in the month of February. Temperatures, solar radiation and speed of wind were recorded during the test and were used in the calculation of the efficiency of the collector.

3.1.6.2 Load test

3.1.6.2.1 Solar drying test

Two tests were also done under the solar drying test. The first test was carried out using 900g of sliced cocoyam. 300g of the sliced cocoyam were laid on a single layer over each tray. The parameters for evaluation of the dryer were also recorded. 7.5kg mass of sliced cocoyam was used for the evaluation of the dryer during the second test. Each tray contained about 2.5kg of the sliced cocoyam. From different test carried out, it was found out that, cocoyam thickness not more than 9mm with a capacity between 5-18 kg/m^2 could be dried in a single batch for an average solar irradiance in the range 300 to 500 W/m^2 (Forson et al., 2007).

Oven drying was used to determine the initial moisture content of the cocoyam which resulted in an average value of 62%wb. The reduction in weight of the cocoyam slices were recorded and used to calculate the moisture loss of the slices during the period of drying based on the determined initial moisture content. The moisture content at each time during the period of drying was calculated on wet basis.

Drying continued until there was no significant loss of weight or moisture in the cocoyam slices. The performance of the dryer was calculated based on the drying rate and the drying efficiency and compared to the various tests.

3.1.6.2.2 Solar drying in the hybrid mode test (backup heater used only in the evening)

The solar dryer was used during the day and a backup heater was used during the evening from 18:00 hours to 21:00 hours. 900g of sliced cocoyam was used for the test. Various parameters measured in the first test were also done in this test. This was done to ensure that the drying process continued during the night. During the test, 300g of charcoal was fed into the backup heater at every one hour interval from 18:00 to 21:00.

3.1.6.2.3 Solar drying in the hybrid mode test (backup heater used during the daytime and in the evening):

Two tests were also carried out under this hybrid test. The backup was used to supply heat to the drying chamber during the day and in the evening. A mass of 7.5kg of sliced cocoyam was used for test. About 300g of charcoal was fed into the backup heater every two hours during the day and every one hour from18:00 to 21:00.

CHAPTER FOUR

RESULTS AND DISCUSSION

The results of the different tests carried out during the performance evaluation of the solar dryer with and without the backup heater is presented in this chapter. This chapter consists of the results for No load and Load tests presented in tables and in graphs.

4.1. No load test

No load test was performed for two days using the solar dryer only in the daytime and with the backup heater in the evening between the hours of 18:00 and 21:00.

4.1.1 Day 1

A typical no load test for temperature and humidity variation with time over 24 hours are presented in Fig.4.1 and Fig.4.2 respectively.

A GRAPH OF TEMPERATURE AGAINST TIME FOR NO LOAD

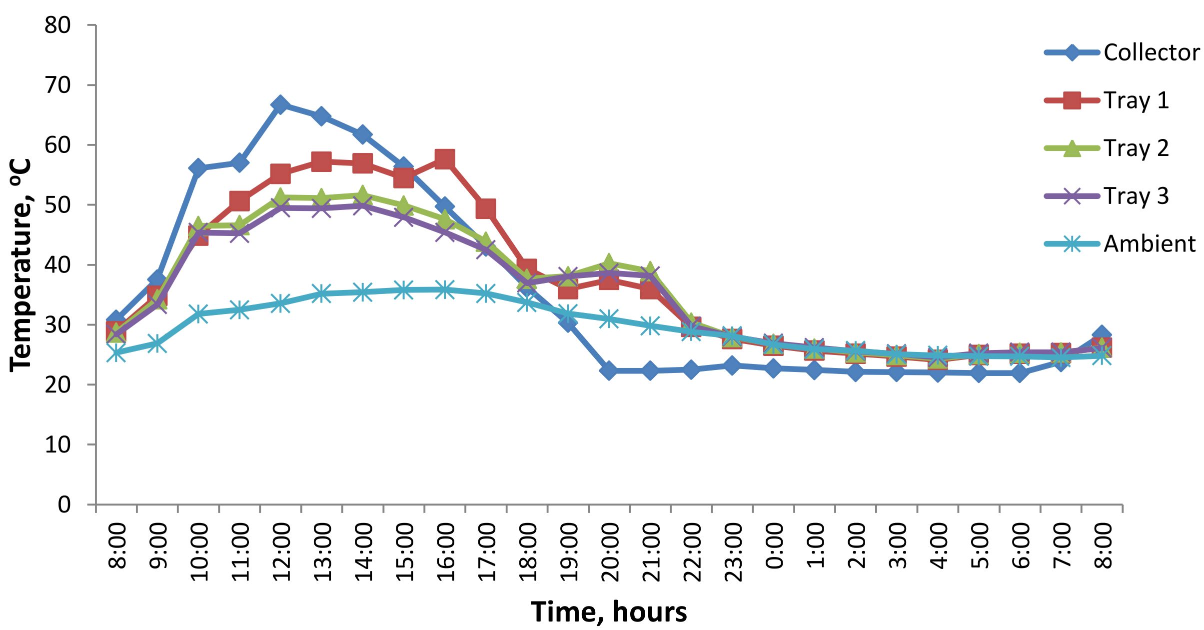


Fig.4.1. Variation of temperature with time for Day 1

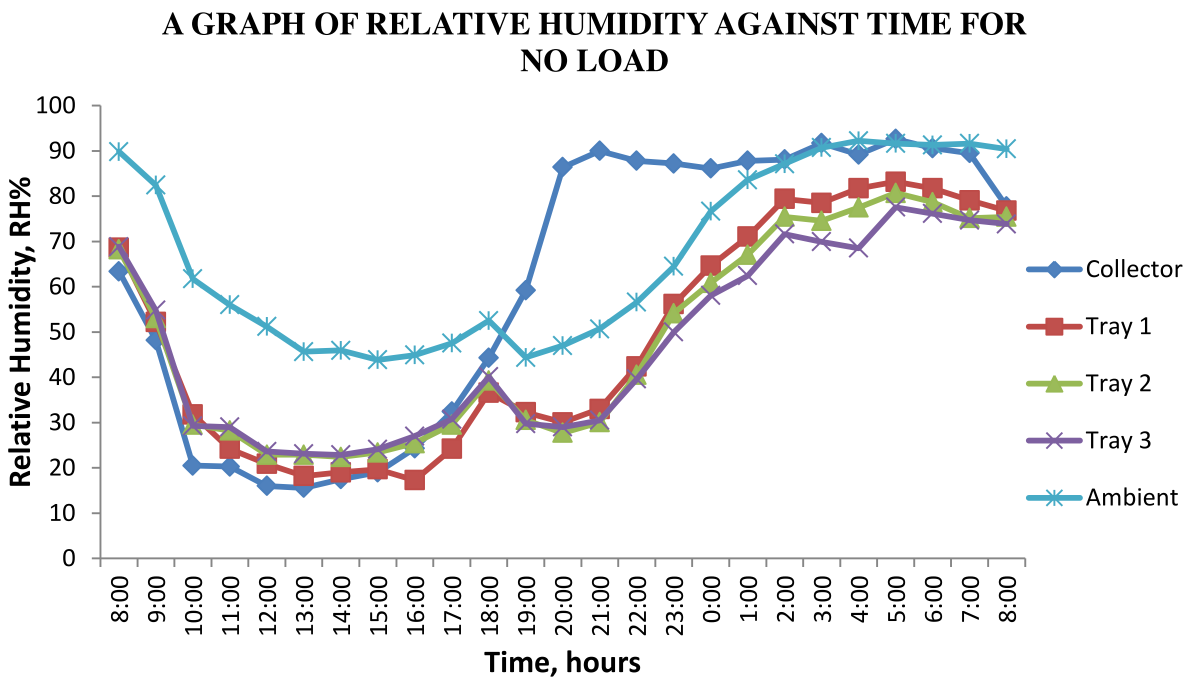


Fig.4.2. Variation of Relative Humidity with time for Day 1.

Figure 4.1 shows the trend of the temperature which increased from morning and attained a peak value in the afternoon where the insolation was the highest and then began to decrease in the evening, but a backup heater was used to keep the temperature in the dryer higher than that of the collector and the ambient.

The maximum temperature at the collector was found to be 66.7^{o}C with an ambient temperature of 33.56^{o}C recorded at 12:00. The maximum temperature in the dryer was found to be 57.19^{o}C at tray 1 with an ambient temperature of 35.18^{o}C. The maximum average temperature in the dryer was 52.77^{o}C with a maximum average ambient temperature of 35.85^{o}C .This gave a temperature increase in the dryer of about 16.92^{o}C more than the ambient temperature.

Also the average temperature in the dryer was 45.22°C and that of the ambient was 32.84°C which gave a temperature increase of about 12.38°C above ambient during the day.

During the evening the temperature in the dryer at tray 2 was found to be 40.25°C when the backup heater was and the ambient temperature was 30.97°C recorded at 20:00. An average maximum temperature of 38.79°C was found in the dryer with an average maximum ambient temperature of 31.84°C, hence a temperature increase in the dryer when the backup heater was used was 6.95°C above ambient.

4.1.2 Day 2

A typical no load test temperature and humidity variation with time over 24 hours are shown in Fig.4.3 and Fig.4.4 respectively.

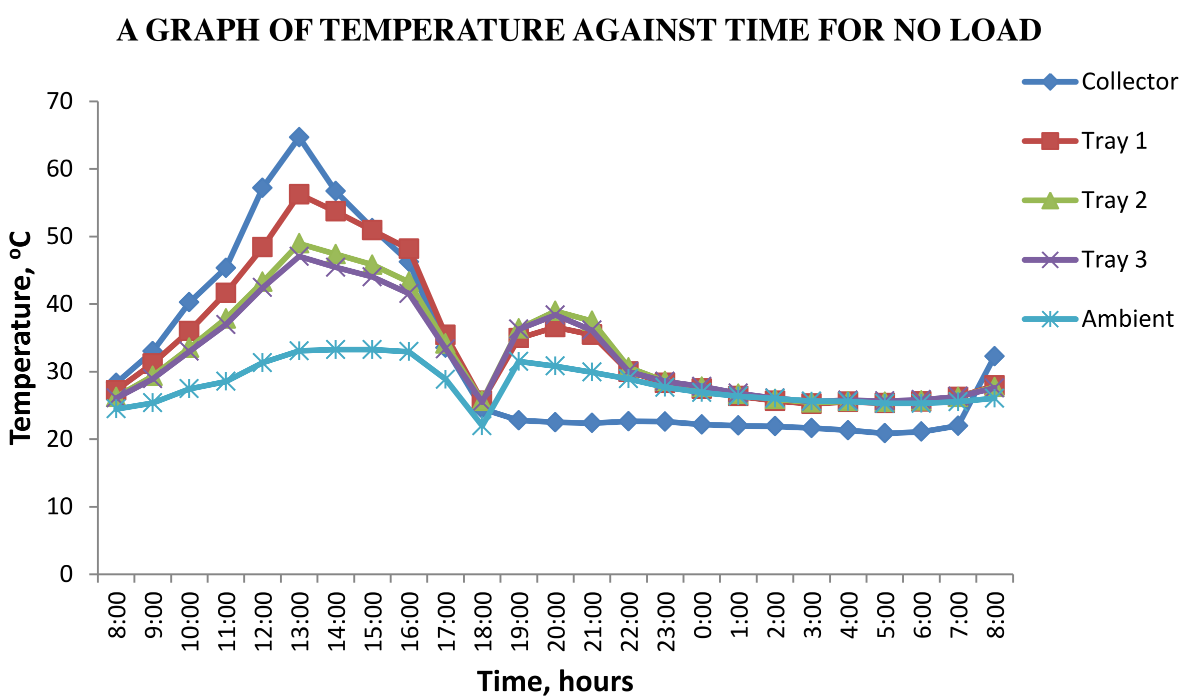


Fig.4.3. Variation of temperature with time for Day 2.

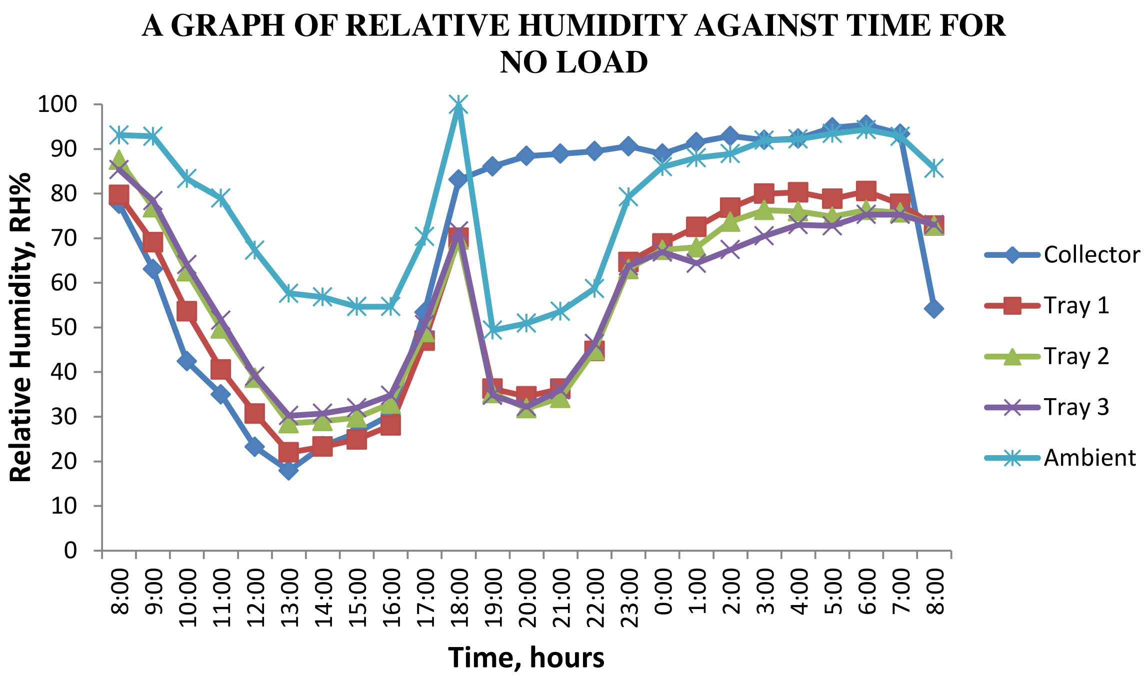


Fig.4.4. Variation of Relative Humidity with time for Day 2.

Figure 4.3 shows the trend of the temperature which increased from morning and attained a peak value in the afternoon where the insolation was the highest and began to decrease again in the evening on the second day of the test, but a backup heater was used to keep the temperature in the dryer higher than that of the collector and the ambient. To maintain a higher temperature in the dryer compared to the ambient, 300g of charcoal as feedstock was burnt in the stove every one hour between the hours of 18:00 and 21:00.

The maximum temperature at the collector was found to be 64.66^{o}C with an ambient temperature of 33.06^{o}C recorded at 13:00. The maximum temperature in the dryer was also found to be 56.24^{o}C recorded at tray 1 at an ambient temperature of 33.06^{o}C. The maximum average temperature in the dryer was 50.74^{o}C with a maximum average ambient temperature of 33.25^{o}C. This gave a temperature increase in the dryer more than the ambient to be 17.49^{o}C.

Also the average temperature in the dryer was 38.6^{o}C and that of the ambient was 29.12^{o}C which gave a temperature increase of about 9.48^{o}C above ambient during the day.

During the evening the dryer reached a maximum temperature of 38.96^{o}C recorded at tray 2 at an ambient temperature of 30.8^{o}C at 20:00 within two hours of backup heat supply. An average maximum temperature of 37.97^{o}C was found in the dryer with a maximum ambient temperature of 31.49^{o}C; hence a temperature increase in the dryer was 6.48^{o}C above the ambient.

In addition, an average dryer temperature of 36.72^{o}C compared to that of the ambient which was 30.79^{o}C for the 24 hours gave a temperature increase in the dryer to be about 5.93^{o}C above ambient.

4.2 Load test

Two different tests were carried out under this load test. First was the use of the solar dryer only and the solar dryer together with the backup heater for drying of the cocoyam slices. Charcoal was used as the feedstock for supplying heat into the drying chamber from the backup heater in the evening from 18:00 to 21:00.

4.2.1 Load test 1

4.2.1.1 Solar dryer only

The solar drying test was carried out from the 28th February to 1st March, 2017 with the solar dryer alone for drying of the cocoyam slices. In this test, 900 g of sliced cocoyam with each tray containing 300 g were dried from an initial moisture content of 62.0%wb to a final moisture content of 5.83%wb within almost two days or 20 sunshine hours.

The moisture loss of the cocoyam slices with the solar dyer only is shown in Fig.4.5 below;

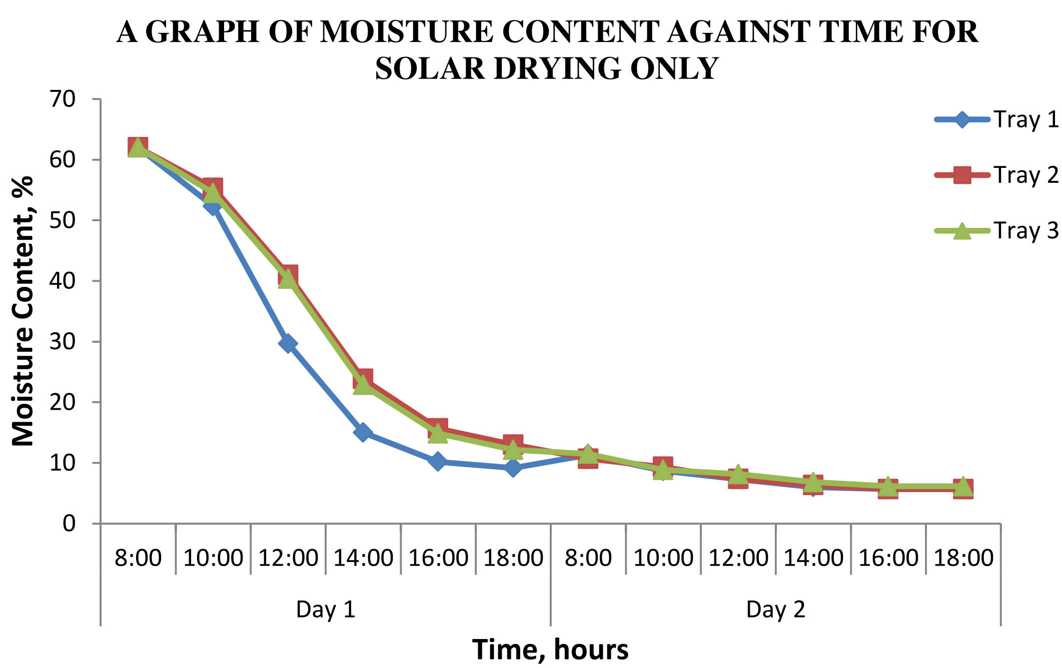


Fig.4.5. Variation of moisture content (%wb) with time of cocoyam slices using only solar dryer.

From graph, it can be seen that the sample in tray 1 lost water faster compared to tray 2 and tray 3.

A maximum temperature of 68.22°C was attained in the collector, 53.61°C in the drying chamber recorded at tray 1 and 33.81°C for that of the ambient temperature during the day recorded at 12:00pm. The average temperature of the dryer and that of the ambient was 33.42°C and 28.53°C respectively. This gave an increase in temperature of 4.89°C above ambient.

The temperature variations with time for Day 1 and Day two are shown in Fig.4.6 and Fig.4.7 respectively.

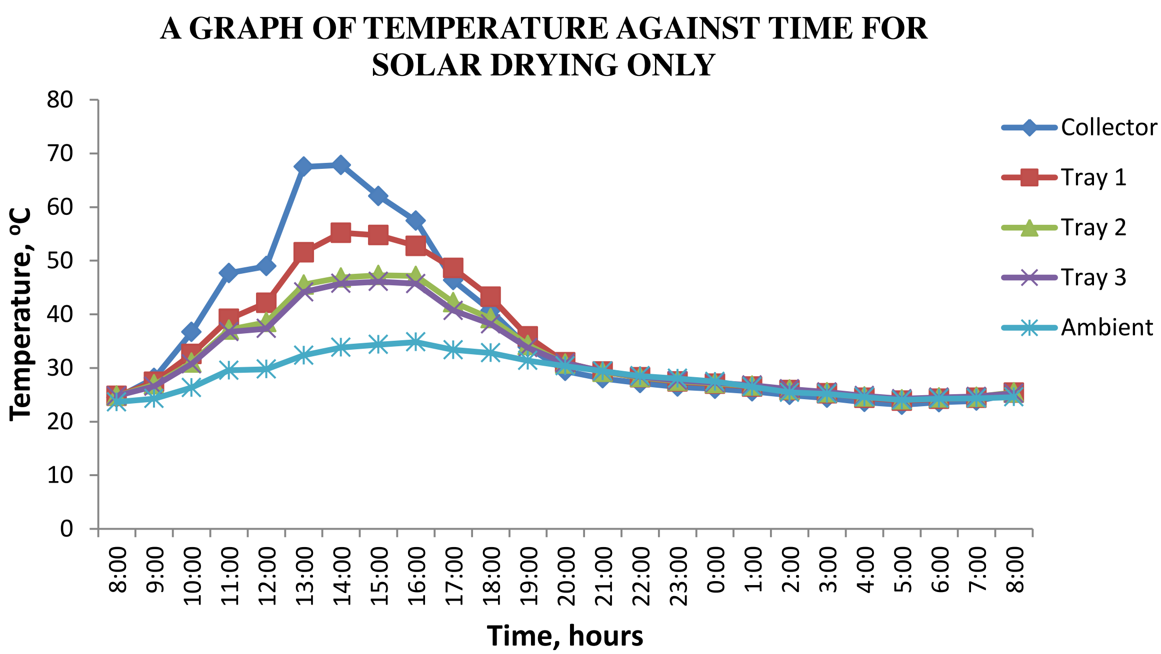


Fig.4.6. Variation of Temperature with time using only solar dryer for Day 1.

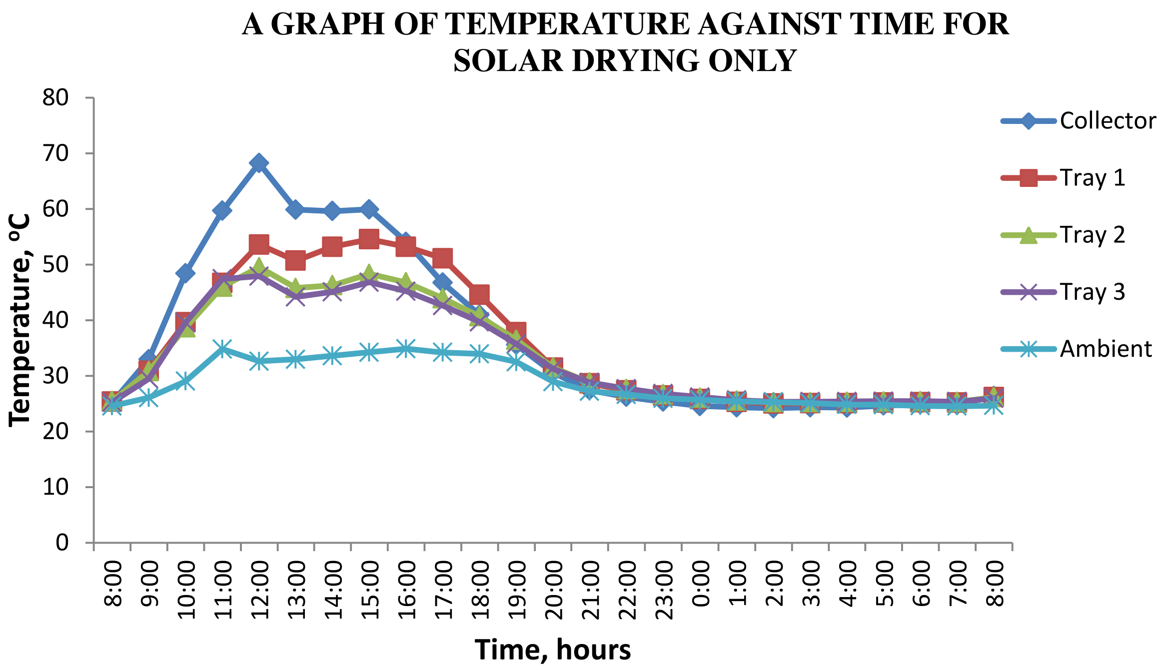


Fig.4.7. Variation of Temperature with time using only solar dryer for Day 2.

4.2.1.2 Solar dryer + backup (only evening)

The test was carried out on the 2nd to 3rd March, 2017 with the solar dryer used during the day and the backup heater during the night for drying of cocoyam slices. In this test, 900 g of cocoyam sliced with each tray containing 300 g were dried from an initial moisture content of 62.0%wb to a final moisture content of about 4.89%wb within almost 2 days or 18 sunshine hours.

The moisture loss of the cocoyam slices with the solar dryer and the backup heater is presented in Fig.4.8 below;

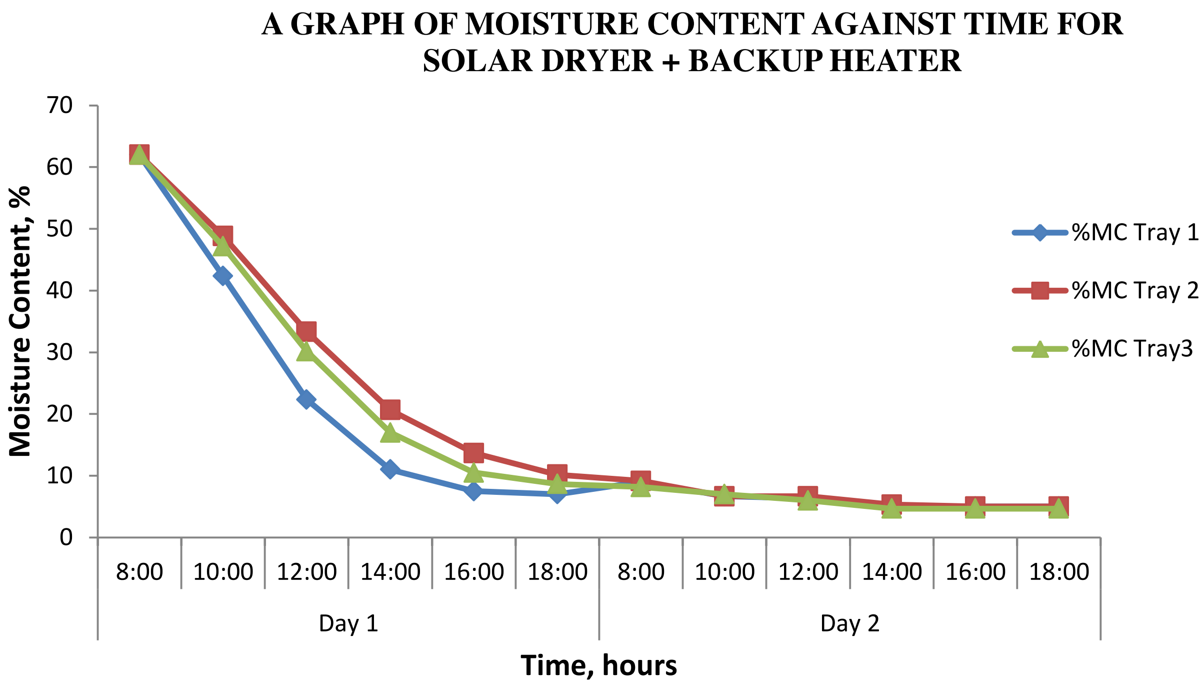


Fig.4.8. Variation of moisture content (%wb) with time of cocoyam slices with the backup heater used only in the evening.

From Fig. 4.8, it can be seen that the sample in tray 1 lost water faster compared to tray 2 and tray 3.

A maximum temperature of 68.83^{o}C was recorded in the collector during the day, 52.74^{o}C at tray 1 and 32.90^{o}C for the ambient temperature recorded at 12:00pm. The average temperature of the dryer and that of the ambient was 33.98^{o}C and 28.53^{o}C respectively. This gave an increase in temperature of 5.45^{o}C above ambient in the dryer.

The temperature variations with time for Day 1 and Day two are shown in Fig.4.9 and Fig.4.10 respectively.

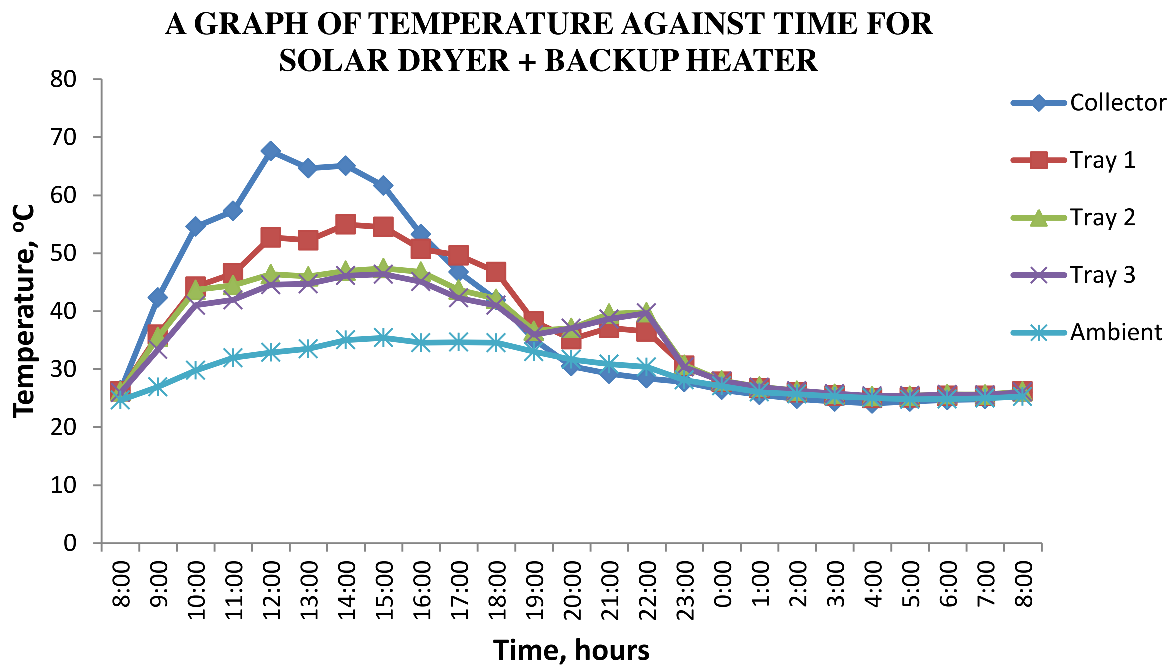


Fig.4.9. Variation of Temperature with time with backup heater used in the evening for Day 1

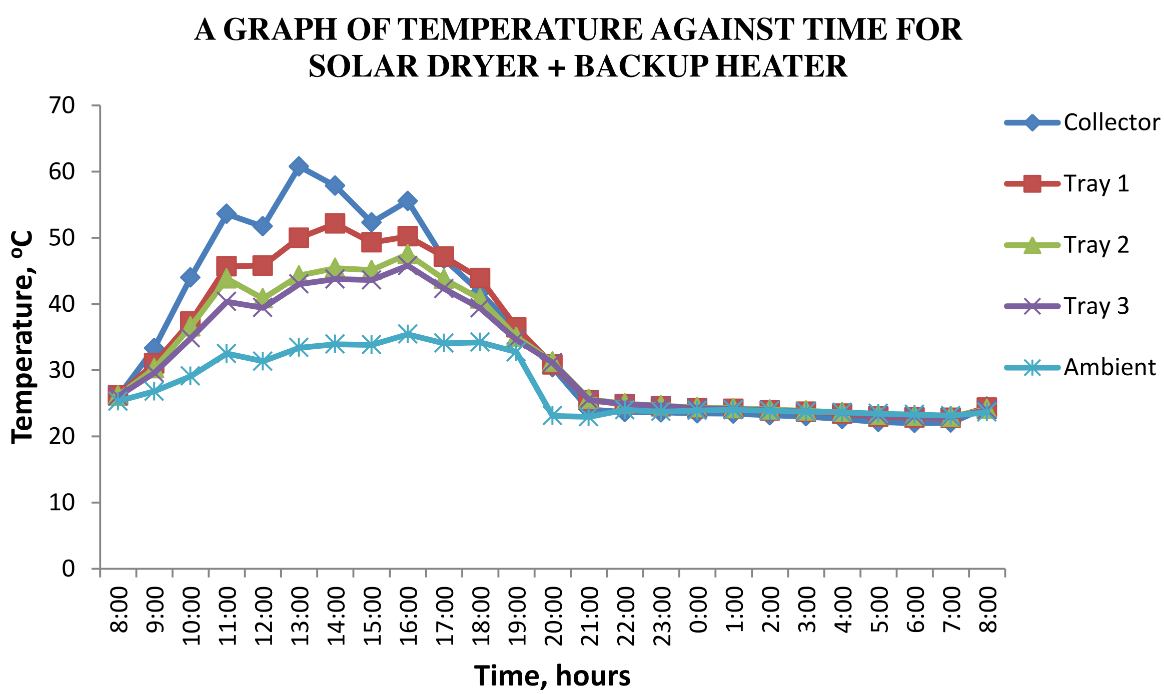


Fig.4.10. Variation of Temperature with time with backup heater used in the evening for Day 2.

The moisture loss of cocoyam slices based on the two drying modes in Fig.4.11 shows that the moisture loss was faster when a backup heater was incorporated into the dryer during the evening as a result the additional heat supplied by the backup heater to the drying chamber to dry the slices in the night.

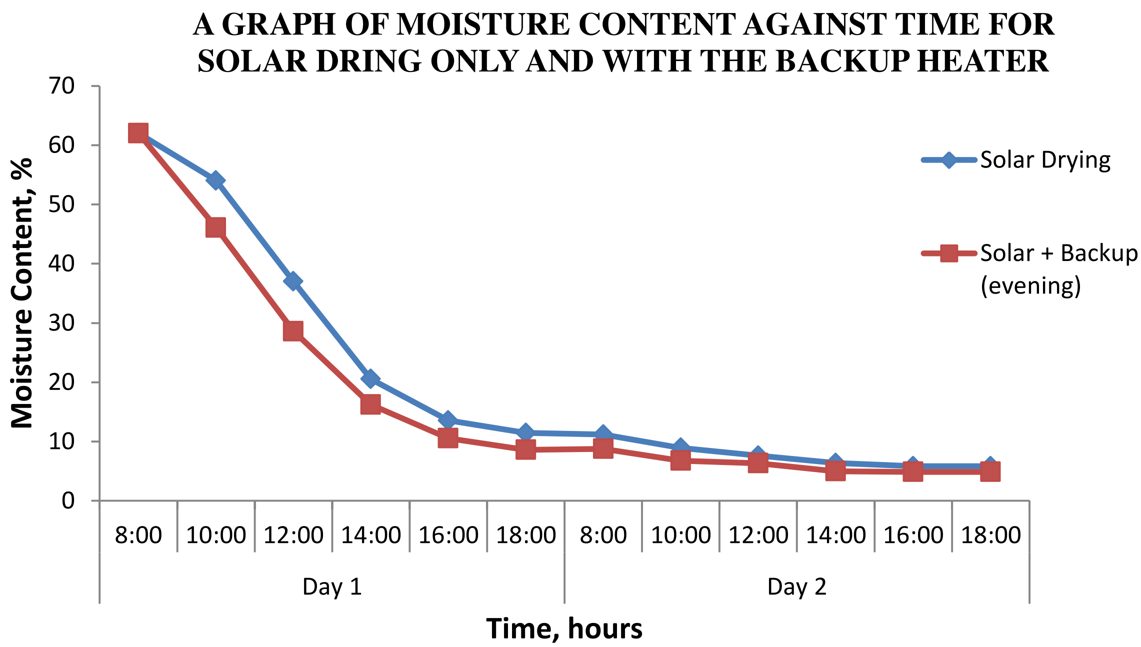


Fig.4.11. Variation of moisture content (%wb) with time for the different drying modes.

4.2.2 Load test 2

Two different tests were also carried out under this load test. First was the use of the solar dryer only and the solar dryer together with the backup heater for drying of the cocoyam slices. Charcoal was used as the feedstock for supplying heat into the drying chamber from the backup heater during the day and in the evening from 8:00 to 21:00.

Upon testing, 7.5kg batch of cocoyam slices of a loading density of 7.44kg/m^2 and an average thickness of 9mm was used. This was done to know the variations of the following parameters with the increase in mass of the sliced cocoyam. The dryer however had a capacity of 45kg/batch with each tray capable of containing about 15kg of the produce per batch.

4.2.2.1 Solar drying only

This test was carried out on the 28th – 31st of March, 2017 with the solar dryer alone for drying the cocoyam slices. During the test 7.5kg batch of cocoyam slices with an average moisture content of 62%wb was used with 2.5kg of the sample placed on each tray and was dried to average final moisture content of 6.26%wb within almost 4 days or 37 hours of sunshine. This indicates that an average moisture content of 55.74%wb was removed from the sample within 37 sunshine hours. Forson et al., (2007) stated that a batch of cocoyam slice can be dried within 3- 5 days for an average solar irradiance in the range of 300-500 W/m^2. The number of days falls within the stated days.

The moisture loss of the cocoyam slices with the solar dyer alone is shown in Fig.4.12 below;

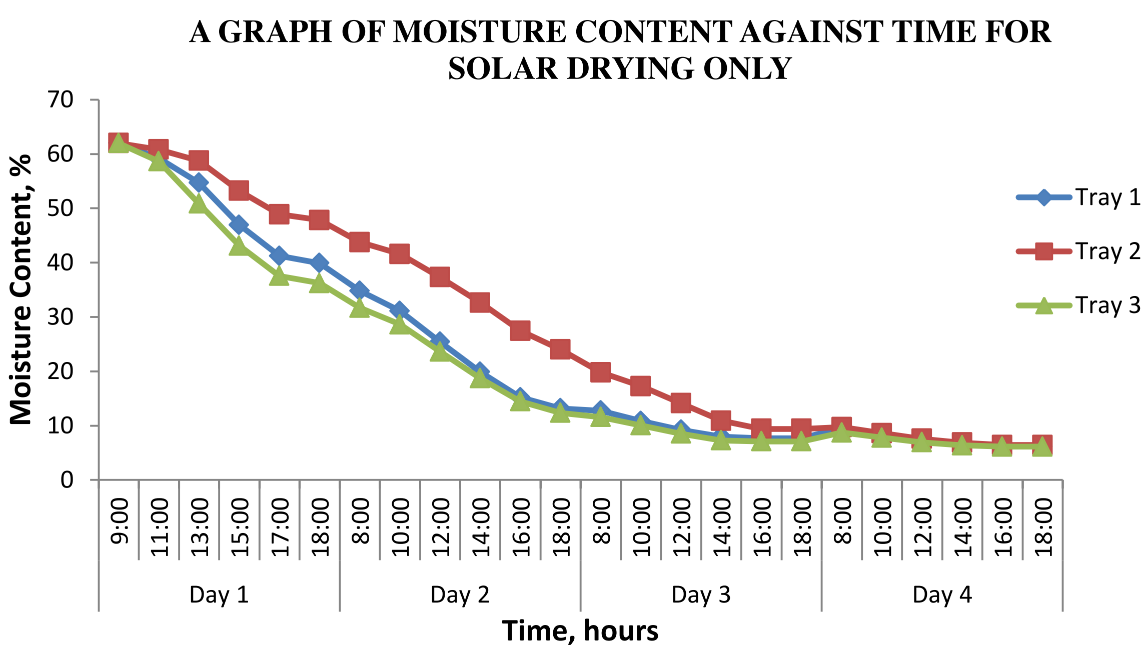


Fig.4.12. Variation of moisture content (%wb) with time of cocoyam slices using the solar dryer.

From Fig.4.12, it can be seen that the sample on the bottom tray (tray 3) dried faster compared to those on tray 1 and 2. This perhaps was due to the heated air coming from the air collector at high temperatures.

The dryer was able to reduce the moisture content of the cocoyam slices to 8.07%wb on the third day (or 27 sunshine hours) of drying at 4.00pm. This moisture content was less than 10%wb which is an accepted value for safe storage of root and tuber. This shows that the moisture removed around 4:00pm on the third day was 53.93%wb. However, drying continued up to the 4^{th} day when there was no significant change in weight of the sliced cocoyam. In addition, there were moisture losses up to the third day of drying during the night which resulted in no moisture re-absorption of the slices.

There was rainfall on the third day of drying round 16:15 pm. The air vents were closed to prevent the rains from falling on the slices so as not to cause rehydration. Even though, the vents were closed, the slices had an average moisture gain of 1.29% on each tray. This caused an increase in moisture content of the slices over the night which resulted in an increase in the drying time.

A maximum temperature of 60.7^{o}C was attained in the collector output during the day. That of the drying chamber was 50.84^{o}C recorded at tray 1 and 35.94^{o}C for the ambient temperature. The average temperature of the dryer was 31.92^{o}C with that of the ambient being 28.57^o C.

4.2.2.2 Solar drying + backup heater (day and evening)

This test was carried out on the 5th – 7th of April, 2017 with the solar dryer together with the backup heater for drying cocoyam slices. About 300g of charcoal was fed into the backup heater to maintain the temperature in the dryer. The charcoal was added at 2 hour interval during the day from the hours of 8:00 to 18:00 and 1 hour interval from 18:00 to 21:00. In the test, 7.5kg of cocoyam slices with an average moisture content of 62%wb was dried to average final moisture content of 5.65%wb within almost 3 days or 28 hours of sunshine. This indicates that an average moisture content of 56.35%wb was removed from the sample within that time period. The dryer assisted by the backup heater reduced the moisture content of the cocoyam slices to 10.72%wb on the second day of drying or 20 sunshine hours. However, drying continued up to the third day when there was no significant change in weight of the cocoyam slices. In addition, there was an average moisture loss of 17% and 4.08% during the nights of day 1 and day 2 respectively when the backup heater was used to continue the drying process in the evening up to the third day of drying.

The moisture loss of the cocoyam slices with the solar dyer and the backup heater used during the day time and in the evening is shown in Fig.4.13 below;

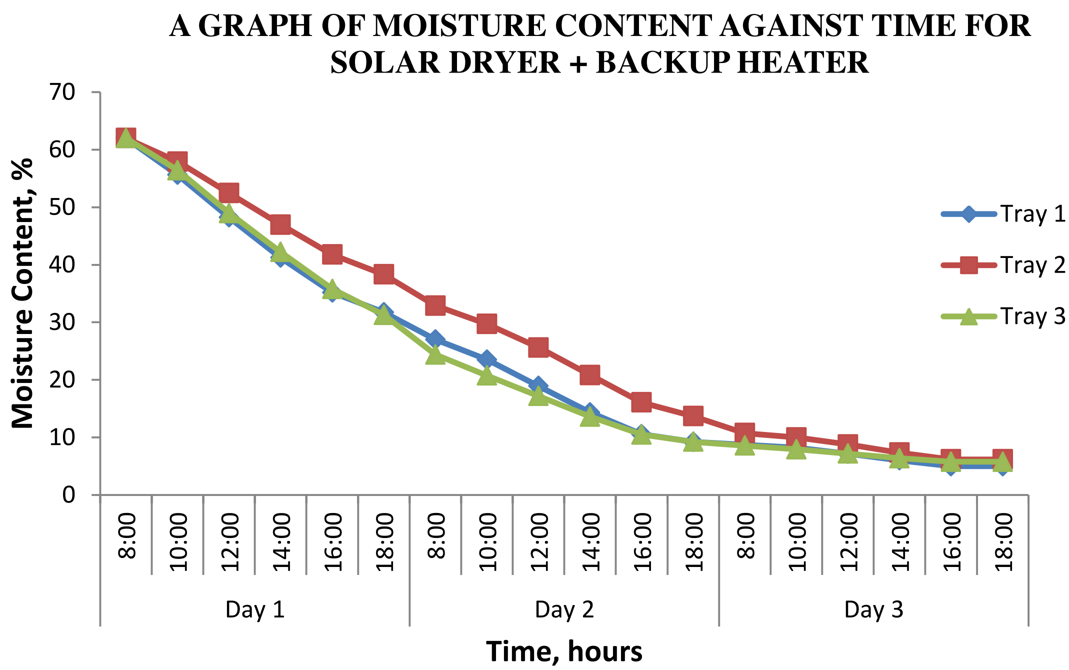


Fig.4.13. Variation of moisture content (%wb) with time of cocoyam slices using the backup heater during the day and in the evening.

The trend of moisture loss of the cocoyam slices on the three trays as shown in Fig.4.13 shows an increase in moisture loss of the slices on tray 1 than tray 2 and tray 3. However the backup heater used during the day and the evening gave a higher moisture loss of the slices on tray 3 than tray 2.

A maximum temperature of 59.7^{o}C was attained in the collector output during the day. That of the drying chamber was 48.25^{o}C recorded at tray 1 and 34.07^{o}C for the ambient temperature. In the evening the dryer attained a maximum temperature of 37.97^{o}C recorded at the bottom tray (tray 3) close to the heat from the backup heater during two hours of heat supply from the backup heater. However, the average temperature in the dryer and the ambient was found to be 32.98°C and 28.09°C respectively.

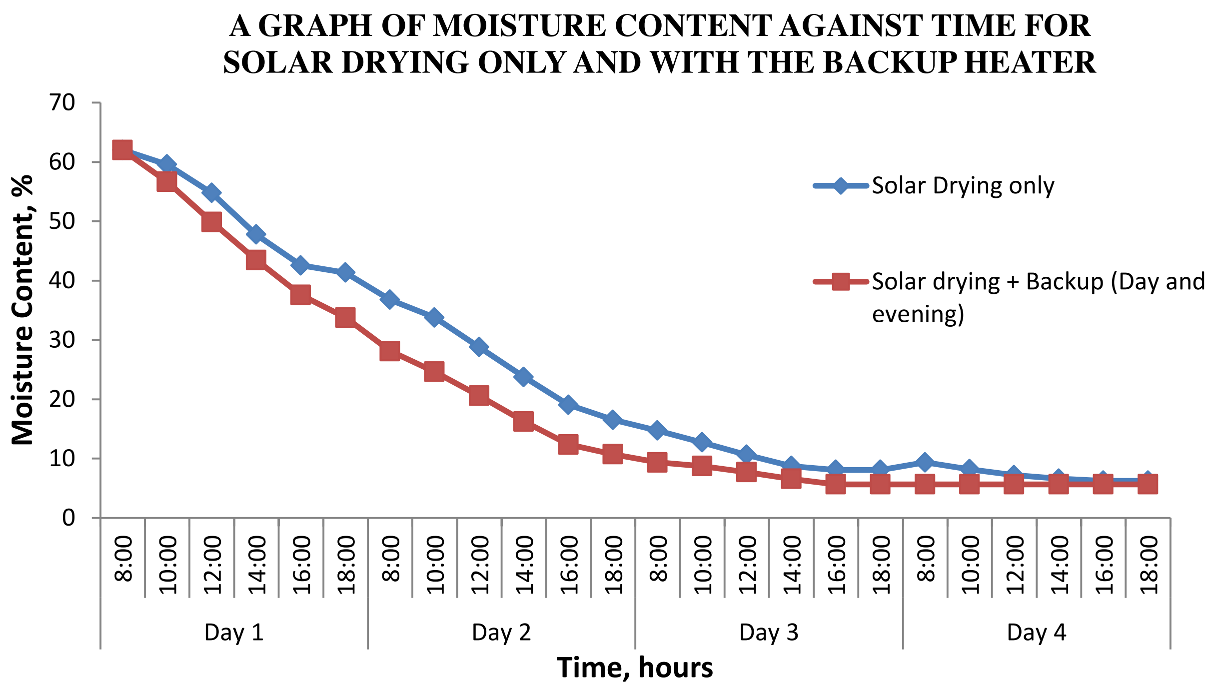


Fig.4.14. Variation of moisture content (%wb) with time for the different drying mode.

The moisture loss of the cocoyam slices based on the two drying modes in Fig.4.14 shows that the moisture loss was faster when a backup heater is incorporated to the dryer during the day and in the evening. This was due to the additional heat supplied by the backup heater to the drying chamber to dry the slices.

Table 4.1 Parameters for evaluating the performance of the dryer on the various tests

No-Load		Load Test 1		Load Test 2	
Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
Insolation, I_T	415.01 W/m^2	Insolation, I_T	571.72 W/m^2	Insolation, I_T	590.29 W/m^2
Air speed, v	0.21 m/s	Air speed, v	0.23 m/s	Air speed, v	0.24 m/s
Mass flow rate, m_a	0.020 kg/s	Mass flow rate, m_a	0.022 kg/s	Mass flow rate, m_a	0.023 kg/s
		Drying time, t_d	18 - 20 h	Drying time, t_d	28 – 37 h
		Latent heat of vaporization, L	2258 kJ/kg	Latent heat of vaporization, L	2258 kJ/kg
		Calorific value, CV	2900 kJ/kg	Calorific value, CV	2900 kJ/kg

4.3 Collector efficiency

The performance of the solar collector was evaluated during no-load and load tests. Under no-load test, collector efficiencies of 26.95% and 23.78% were obtained for day 1 and day 2 respectively. The average collector efficiency during the no-load test was estimated to be 25.37%.

Under the load test, the efficiency of the collector was found to be 24.18% for solar drying only and the backup heater used only in the evening for test 1; 28.71% and 23.84% for solar drying only and the backup heater used during the daytime and in the evening respectively for test 2. This value falls within the range 17% and 30% according to Alfegi et al. (2008) for a single pass double duct solar air heater depending on the mass flow rate of air. However several literature reported higher values of collector efficiency. One such case is collector efficiency of 31.7% reported by Tibebu (2015). Table 4.2 shows the collector efficiencies for the various loaded tests.

Table 4.2 shows the efficiency of the solar collector with and without the backup heater.

Table 4.2 Collector efficiency under the various tests

Type of test	**TEST 1**	**TEST 2**
	Collector Efficiency (%)	**Collector Efficiency (%)**
Solar drying only	24.18	28.71
Solar drying + Backup Heater(Evening)	24.18	-
Solar drying + Backup Heater(Day and Evening)	-	23.84

4.4 Drying efficiency and Drying rate

4.4.1 Drying efficiency

The drying efficiency of the dryer for the load test 1 was evaluated to be 2.37% and 2.62% for the solar drying alone and with the backup heater used in the evening respectively shown in Table 4.3. The value for the drying efficiency of the solar dryer only was less than that with the backup heater used only in the evening. Moreover Tibebu (2015) reported a drying efficiency of 7.5%, when the backup heater was used only in the evening which was less than the dying efficiency of the solar dryer only.

In addition, the drying efficiency for the solar dryer and the backup heater used in the day and in the evening was evaluated to be 10.24% and 13.50% respectively for the load test 2 shown in Table 4.4. The values fall within the range reported by Forson et al., (2007) for a natural convection solar crop dryer which should be between 10% and 15%. However the drying efficiency for the backup heater used throughout the day and in the evening was greater than that of the solar drying only.

4.4.2 Drying rate

The drying rates for the different test are presented in Table 4.3 and Table 4.4. The test gave a drying rate of 25.25 g/h for solar drying only and 28.56 g/h when the backup heater was used only in the evening. It can be seen that the drying rate when the backup heater was used in the evening was higher and 11.59% faster than only the solar drying.

In addition a drying rate for Test 2 was evaluated to be 113g/h and 151g/h for solar drying and with the backup heater used during the day and in the evening respectively. The drying rate is 25.16% faster in the solar dryer with the backup heater compared to that of solar drying only.

Table 4.3 Drying rate and efficiency of the dryer for the different drying modes (load test 1)

LOAD TEST 1 = 900 g		
Type of test	**Drying rate (g/h)**	**Drying Efficiency (%)**
Solar drying only	25.25	2.37
Solar drying + Backup Heater(Evening)	28.56	2.62

Table 4.4 Drying rate and efficiency of the dryer for the different drying modes (load test 2)

LOAD TEST 2 = 7.5kg		
Type of test	**Drying rate (g/h)**	**Drying Efficiency (%)**
Solar drying only	113	10.24
Solar drying + Backup Heater(Day and Evening)	151	13.50

CHAPTER FIVE

CONCLUSION AND RECOMENDATIONS

5.1 Conclusion

A mixed mode solar dryer with a backup heater was evaluated based on its performance during no load and load tests. The backup heater was made up of a charcoal stove to ensure that drying continued at night and in cloudy days. The average temperatures of the dryer and ambient were 45.22^{o}C and 32.84^{o}C; and 38.6^{o}C and 29.12^{o}C for day 1 and day 2 respectively under no load. This shows a temperature increases above ambient providing a suitable condition for drying.

During load tests, sliced cocoyam with an average initial moisture content of 62.0%wb was dried to average moisture content ranging from 4.89% to 6.26%wb within 2-4 days depending on the loading density of the product with the backup heater incorporated having the lowest moisture content value.

The performance of the dryer was evaluated in terms of its efficiency and the drying rate. Results obtained from the tests showed that the collector efficiency ranged from 23.78% to 28.71% with the highest efficiency obtained when the solar insolation was the highest. Moreover, the drying efficiency was found to be 2.37% and 2.62% for solar drying only and with the backup heater used only in the evening respectively for test 1 and 10.24% and 13.50% for solar drying only and with the backup heater used during the day and in the evening for test 2. The drying rate was also found to 25.25g/h and 28.56g/h for test 1 and 113g/h and 151g/h for test 2 with the highest value obtained when the backup heater was incorporated. This gave an increase in drying rate of 11.59% and 25.16% for test 1 and 2 respectively.

From the test it can be said that the performance of the dryer depends on the loading density of the product, hence an increase in density results in an increase in drying rate and drying efficiency.

It can therefore be concluded that the solar dryer has the tendency to dry crops of high moisture contents to a level safe for storage within a short period of time. More so the performance of the dryer is enhanced in terms of its drying rate and efficiency when a backup heater is incorporated to it.

5.2 Recommendations

The performance of the solar dryer can be further improved by the following;

1. The gap between the primary collector and the drying chamber should be sealed properly to avoid heat loss to the surrounding air.
2. The metal tube should be made a little longer to enable uniform heat transfer across the trays when the backup heater is used for supplying heat.
3. The height of the air inlet vent above the ground should be increased to ensure easy flow of air by natural convection.
4. The gaps around the roof of the dryer should be properly sealed as it will contribute to heat loss from the chamber.

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APPENDICES

APPENDIX 1: Sample Analysis of Moisture Content

Day	Time (hrs)	Sunshine hours	Mass Tray1 (g)	M_w Loss Tray1 (g)	% M_w Loss Tray1 (g)	Total % MC Tray1
Day 1	8:00	0	300.0	0.0	0.00	62.00
	10:00	2	271.0	29.0	9.67	52.33
	12:00	4	203.0	68.0	22.67	29.66
	14:00	6	159.0	44.0	14.67	14.99
	16:00	8	144.5	14.5	4.83	10.16
	18:00	10	141.5	3.0	1.00	9.16
Day 2	8:00	0	148.0	-6.5	-2.17	11.33
	10:00	2	140.0	8.0	2.67	8.66
	12:00	4	136.0	4.0	1.33	7.33
	14:00	6	132.0	4.0	1.33	6.0
	16:00	8	131.0	1.0	0.33	5.67
	18:00	10	131.0	0.0	0.00	5.67

Day	Time (hrs)	Sunshine hours	Mass Tray2 (g)	M_w Loss Tray2 (g)	% M_w Loss Tray2 (g)	Total % MC Tray2
	8:00	0	300	0.0	0.00	62.00
	10:00	2	280	20.0	6.67	55.33

Day 1	12:00	4	237	43.0	14.33	41.00
	14:00	6	185.5	51.5	17.17	23.83
	16:00	8	161	24.5	8.17	15.66
	18:00	10	153	8.0	2.67	12.99
Day 2	8:00	0	146	7.0	2.33	10.66
	10:00	2	142	4.0	1.33	9.33
	12:00	4	136	6.0	2.00	7.33
	14:00	6	133	3.0	1.00	6.33
	16:00	8	131	2.0	0.67	5.66
	18:00	10	131	0.0	0.00	5.66

Day	Time (hrs)	Sunshine hours	Mass Tray3 (g)	M_w Loss Tray3 (g)	% M_w Loss Tray3 (g)	Total % MC Tray3
Day 1	8:00	0	300.0	0.0	0.00	62.00
	10:00	2	277.5	22.5	7.50	54.50
	12:00	4	235.5	42.5	14.17	40.33
	14:00	6	183.0	52.5	17.50	22.83
	16:00	8	159.0	24.0	8.00	14.83
	18:00	10	151.0	8.0	2.67	12.16
	8:00	0	149.0	2.0	0.67	11.49
	10:00	2	141.0	8.0	2.67	8.82

Day 2	12:00	4	139.0	2.0	0.67	8.15
	14:00	6	135.0	4.0	1.33	6.82
	16:00	8	133.0	2.0	0.67	6.15
	18:00	10	133.0	0.0	0.00	6.15

APPENDIX 2: Typical Solar Insolation, W/m^2 (Solar Power meter) under Load Test

Time, hours	Day 1	Day2	Day 3	Day 4	Day 5	Day 6	Day 7
8:00	N/A	385	294	434	484	178.6	121.7
9:00	343	255	330.5	608.5	660.5	468.5	142.4
10:00	1049.5	659.5	757	898	930	504	216
11:00	1061	766.5	261.5	980	938	645.5	287.5
12:00	1090	1203	833	1039.5	1098.5	1120.5	433
13:00	1062	1139.5	992	1054.5	1064	916	451
14:00	904.5	644.5	677	961.5	887	848.5	421.5
15:00	459.5	556	246	806	421.5	662	708
16:00	411.5	436	137.9	450	311.5	367	283
17:00	184.6	189	14.6	139.9	151.65	150.6	166.75
18:00	37.1	50.8	0	0	38.6	33.95	28.45

An average solar insolation = 590.29 W/m^2

APPENDIX 3: Typical Wind Speed, m/s (Wind vane anemometer) under Load Test

Time, hours	Day 1	Day2	Day 3	Day 4	Day 5	Day 6	Day 7
8:00	N/A	0.1	0.1	0.1	0	0	0
9:00	0.4	0.2	0	0.15	0.2	0.3	0.05
10:00	0.3	0.3	0.55	0.45	0.5	0.15	0
11:00	0.3	0.3	0.2	0.55	0.25	0.15	0.25
12:00	0.4	0.25	0.25	0.35	0.1	0.4	0.25
13:00	0.3	0.1	0.2	0.15	0.4	0.55	0.2
14:00	0.3	0.15	0.1	0.8	0.15	0.3	0.3
15:00	0.5	0.15	0.1	0.4	0.25	0.15	0.35
16:00	0.15	0.05	0	0.1	0.15	0.25	0.25
17:00	0.05	0.05	0.25	0.45	0.25	0.3	0.3
18:00	0	0	0	0	0	0.05	0

An average wind speed = 0.24 m/s

APPENDIX 4: Dried cocoyam chips

APPENDIX 5: The Backup Heater