DEVELOPMENT OF A PARABOLIC SOLAR DRYER FOR EFFICIENT SOLAR ENERGY USE IN THE RURAL AREAS IN GHANA

By

Maame Tabuah Duah, Bsc. Civil Engineering

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of

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DECLARATION

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

Maame Tabuah Duah-20256197	-----------------------	----------------------
	Signature	Date

Certified by:

Mr. Emmanuel W. Ramde	-----------------------	----------------------
(Supervisor)	Signature	Date

Certified by:

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Dr. S. M Sackey	Signature	Date
(Head of Department)		

DEDICATION

This thesis is dedicated to my beloved Ato Kwamina Ankoh and Fiifi Adom Ankoh. Love you all.

ACKNOWLEDGEMENT

I would like to acknowledge the invaluable comments and much appreciated direction given to me by my supervisor Mr. Emmanuel W. Ramde. Thank you for the ample time you dedicated in reviewing the final report given the short amount of time you had available.

Much appreciation is also given to my dear Peter Ankoh for assisting me to acquire the necessary instrument for the experiment. You always respond when your services are needed, you are truly a blessing.

ABSTRACT

The use of the solar resource for food drying has always been a food preservation technique which is widely practised in this part of the world but unfortunately some of the methods practised in the rural areas, have been wrought with many disadvantages one of which is the poor quality of food derived. There have been much research into developing more enhanced and more efficient means of drying but unfortunately much still remains to be done in this area.

The thesis looked at bringing out a new design of the parabolic solar dryer, which combined the concept of the parabolic concentrator and the flat plat collector system with the aim of increasing the overall drying efficiency of the dryer. The dryer was designed primarily as a mixed mode passive dryer.

A prototype was built and tested, with the test spanning a period of three days. A control test using the open sun drying method was conducted at the same time and under the same weather conditions as the prototype dryer. The test crop used was Okra with recorded initial moisture content on wet basis (w.b.) of 90.7%. The overall performance of the dryer after the assessment of the drying data was not satisfactory with the open sun drying method recording final moisture content about 9.7% w.b. lower than that of the solar dryer. The estimated average drying efficiency for one of the typical testing days was about 8.1%.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A_s	Collector aperture area (m^2)
A_s	Collector reflective area (m^2)
A_c	area of the glazing (m^2)
A_1	area of inlet of the dryer (m^2)
A_2	area of outlet of the dryer (m^2)
C_2	air velocity in the upper opening of naturally ventilated solar dryer (m^3/s)
CR	Concentration Ratio
C_p	specific heat capacity of air (J/kgK)
D	Aperture diameter (mm)
d_e	Drying efficiency (%)
f	Focal length (mm)
G_{sc}	Solar Constant (1367W/m^2)
h	depth of a parabola(mm)
h_f	final humidity ratio
h_i	initial humidity ratio
H	height difference from the inlet and outlet (mm)
I_b	Beam irradiance (W/m^2)
$I_{b,n}$	Beam normal irradiance (W/m^2)
I_d	Diffuse irradiance (W/m^2)
I_o	Hourly extraterrestrial irradiance (W/m^2)

$I_{t,a}$	Total irradiance (W/m^2)
m_{dr}	average drying rate (kg/s)
$\dot{m}$	mass flow rate(kg/s)
RH	Relative Humidity (%)
s	arc length of the parabolic curve(mm)
T_{in}	internal temperature in the dryer (^oC)
T_{amb}	ambient temperature of the dryer (^oC)
θ	Angle of incidence
ω	Hour angle
Φ	Latitude
δ	Angle of declination

CHAPTER 1: INTRODUCTION

1.1 Background

Drying is the process of removing moisture and in the case of drying of food, it is either to prevent the activities of microorganism for efficient storage or to reduce the bulk weight for easy transportation. It can sometimes be even a step in the food preparation process. Thermal food drying using the sun's energy is a very simple and ancient skill which has been practised for many years. Open sun drying is a form of drying where the food crops are directly exposed to the sun's radiation whereas a more advanced method, solar drying, houses the food in drying chambers and is directly or indirectly heated by the sun. Despite the numerous advantages of the solar drying over the open sun drying, the latter is the most preferred method in the rural areas particularly due to that fact that it is easy to execute and does not require great skill. Unfortunately this mode of drying has been wrought with many disadvantages one of which is the poor quality of food derived (Ekechukwu and Norton 1998).

However, various researchers have found ways of improving upon this ancient method of drying in the form of the solar dryer. The solar dryer still harnesses the sun's energy but utilises it more efficiently and subsequently results in better final products. Various forms of solar dryers exist and they vary from very simple direct dryers to more complex indirect designs (Practical Action 2008).

Properly designed solar dryers have the advantage of giving faster drying rates by heating the air to about 10-15^{0}C above room temperatures (Practical Action 2008), which reduces the relative humidity and causes the air to move faster through the dryer. The faster drying time of the solar dryer reduces the risk of spoilage, improves quality of the product and gives a higher throughput. Improvement of the efficiencies of these solar dryers and developing cheaper dryers that are more easily adaptable by rural folks is still a working progress that can ultimately be achieved if research and development tend to focus more in that area. It has therefore become necessary to continue to find workable and adaptable designs which can easily be replicated and used in the rural areas without the need to procure expensive construction materials. These solar dryers should ultimately be able to cause a reduction in energy costs and also speed up drying, while still turning out good quality final dried produce. The aim of this thesis is therefore to introduce a new design of solar dryer which explores the possibility of incorporating the parabolic collector in a solar dryer.

1.2 Justification

Given that most staple foods in Ghana are seasonal and mostly perishable, it has become imperative to salvage some of these food crops which cannot all be consumed within the season they are produced. In most rural areas in Ghana, sun drying of food crops is seen as the best method of food preservation because it has a low initial setup cost and requires very little skill. Unfortunately this very simple technique leaves the crop susceptible to rain, contamination by dirt and animals and also usually takes a much longer time to dry resulting in a final produce with very poor quality.

In addition, ingenuity towards food preservation in Ghana has been directed more towards fish preservation as was mentioned by Pace et al (1989) and is still the case in present day Ghana. This has left a gap in the innovation of drying techniques for other types of food like major roots crops, most especially vegetables and fruits.

These issues have therefore given rise to the need to design effective solar dryers which are easy to construct and whose materials can easily be attained to promote faster, more efficient and cost effective drying process and ultimately promote the need to preserve more agriculture produce during the glut season.

The parabolic trough or collector has been widely adopted in the solar energy field because of its unique ability to focus high amount of energy to its focal point. This characteristic although explored in the design of solar cookers and other solar thermal systems, has not been wholly explored as a means of increasing the efficiencies of solar dryers.

This thesis therefore seeks to bring out a new design of solar dryer, which combines the flat plate collector concept and the parabolic trough collector termed the ‘parabolic solar dryer’. It is the intention that the dryer becomes a more efficient method of drying of agricultural products with reduced drying time and cost of drying operations.

1.3 Objectives

This study will aim to:

a) Bring out a new design of solar dryer which utilises both the parabolic trough and flat plate collector system.
b) Assess the performance of this new design of solar dryer from a constructed prototype.
c) Obtain experimental data that can be used in the future development of the dryer.

1.4 Scope

The scope of this thesis is limited to initial developing and testing phase of the dryer. Performance assessment of the dryer is also limited to the testing location (Bui Power Resettlement Township), a couple of days in the month of July and testing results of okra.

1.5 Methodology

The methodology which was adopted in carrying out the studies is as follows:

a) A desk study was conducted on the different modes of drying in the rural areas in Ghana and also on existing solar dryers which have been designed for use in food drying.

b) The Parabolic solar dryer was then developed on paper using the parabolic collector concept.

c) A prototype parabolic dryer was then constructed based on the design concept.

d) The prototype dryer was subsequently tested by using it to dry Okra while at the same time a control test using open sun drying was performed on the same batch of Okra.

e) The ambient and internal temperature and relative humidity during operation of the dryer was measured. A handheld pyranometer was also used in measuring instantaneous solar irradiance on the horizontal surface of the dryer. A weighing balance and an oven were used in testing the moisture content of the initial mass of samples whilst the balance was used during the drying process to check the varying mass of the produce being dried.

f) Results were then compiled and analysed.

CHAPTER 2: LITERATURE REVIEW

The utilisation of sun for drying of food has been practised since ancient times and to date it is still being used as the preferred method in developing countries like Ghana because this source of energy is freely available and is very economical. In a tropical continent like Africa, where solar energy is widely abundant it will be prudent to take advantage of this form of energy which is highly abundant and very environmentally friendly and does not pose adverse environmental impacts like other forms of non-renewable energy. There have been numerous studies in the domain of harnessing the sun's energy in the drying process worldwide. Researchers like Fagunwa et al (2009) and other researchers alike have been designing solar dryers for cocoa beans and other food crops usually produced in Africa. However there seems to be more room for improvement so as to efficiently and effectively harness the maximum of the solar resource available. This will also help us avoid the need for non-conventional modes of drying which are not only costly but often cannot be replicated in the rural areas, where they are most needed.

This chapter aims to review the different modes of drying using the sun's energy for both traditional and progressive methods and look at examples of some of the existing solar dryers and the working principles behind them. The review will also touch on the principle behind the parabolic solar collector. When these are juxtaposed with the new solar dryer the design concept governing the Parabolic Solar dryer will be better appreciated.

2.1 Drying

2.1.1 Principle of Drying

There are various types of drying; however this thesis concentrates on thermal drying using the sun's power. As mentioned in the earlier chapter, drying is usually done for three main purposes; for easier transportation, storage and also as a food preparation process. The main function of the sun's energy is to heat the air surrounding the food and the food itself. The relative humidity of the heated air surrounding the food during the drying process, increases in absorptivity and hence its ability to absorb more moisture. It then carries with it, the moisture that has migrated to the surface of the food as a result of an increased temperature. This cycle continues when new dry air takes the place of the hot humid one and eventually renders the food less moist (drier). Solar thermal drying has been categorised into two main groups; open sun drying and the solar drying.

2.1.2 Open Sun Drying

Open sun drying is the means of drying where the food product is laid out in open air to have direct exposure to the sun. This is a very simple method of drying and is the most adopted drying method in the rural areas in Ghana. During drying, solar radiation direct from the sun's incident rays warms up the immediate environment of the crop and its surface. This causes the evaporation of moisture from the produce into the atmosphere. Unfortunately not all the incident rays are converted to the latent heat of vaporisation. Some are reflected from the surface, carried away by wind and some lost through conduction to the ground surface (Figure 2- 1).

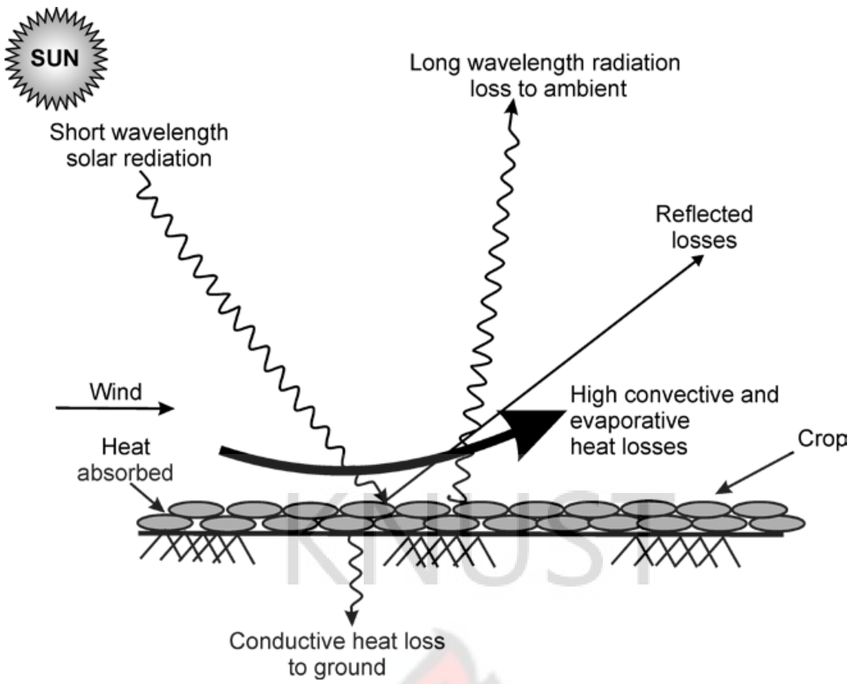

Figure 2- 1: Working principle of Open sun drying

Source: Seveda et al, 2011

Traditionally in Ghana, food produce are usually laid on any flat surface such as raised wooden table, tarred roads, concrete slabs etc. A typical example can be seen in Figure 2- 2. The figure shows chips of cassava being dried in open air along a tarred road.

The main advantages of sun drying are the low capital requirement and the fact that little or no skill is needed. However this type of drying has lots of disadvantages, some of which are the easy contamination of produce by insects, dusts and volatile chemicals from the tar (in cases where they are dried on tarred roads). This makes the produce very unhealthy to consume. It also leads to longer drying time since the sun's radiations are not efficiently utilised in the drying process. In addition to the above disadvantages, the produce which are directly exposed to the atmosphere are usually subjected to intermittent moistening by rain and dew which increases the moisture content of the produce and therefore results in longer drying times. Most often, due to the distance of the roads from the residences, the rural folks cannot get back in time to take the produce from the road when it starts raining. There is also the likelihood of domestic animals feeding on the drying products. The final quality of produce is therefore very poor because of the contamination by foreign materials from the atmosphere and the presence of moulds.

Figure 2- 2: Open Sun drying of Cassava along the road in the Northern region

2.1.3 Solar Drying

Solar drying is the drying of products in enclosed structures where the temperature of air surrounding the produce is usually higher than the ambient temperature of the dryer. It is a better means of increasing the quality of final dried product, reducing post harvest losses and generally reduces the drying times as compared to open sun drying. (Zobaa and Bansal 2011).

The energy requirement for drying different products in solar dryers varies from the types of dryers, to the type of product being dried and also to the type of climate. It is usually determined from the initial and final moisture content of each product. Different types of food crops have different drying rates and maximum allowable temperatures. In many cases, only a small temperature rise in the air is necessary to achieve proper drying conditions (Zobaa and Bansal 2011).

In dealing with solar dryers, it is often useful to investigate some two key characteristic of the dryer before use. These are the drying rate and the drying efficiency. These indicators give an overall assessment of the dryer in relation to their performance.

The drying efficiency of a dryer can be estimated from Equation 2- 1. It can be a used to effectively compare different types of solar dryers to be selected for use. The factors which have said to influence the drying efficiency are basically (Green and Schwarz 2001):

a) Factors pertaining to the crop like the size, type of crop, the moisture content etc.
b) Factors relating to the peculiar characteristics of the dryer in question and
c) Factors relating to the environmental conditions such as the climate.

The drying efficiency (d_e) is given by:

$$d_e = \frac{\text{Heat utilised for moisture removal}}{\text{Heat available for moisture removal}}$$ *Equation 2- 1*

The drying rate is defined as the rate at which moisture is removed from a material. The shorter the drying rate the better it is. The drying rate (d_r) have also been said to have an effect on the quality of the final product (Practical Action 2008).It is usually determined by the equation:

$$d_r = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Duration of drying}}$$ *Equation 2- 2*

Seveda and Rathore (2007) highlighted that the drying rate is essentially affected by some critical climatic factors such as the temperature, relative humidity, sunshine hours, available solar irradiation, wind velocity, frequency and duration of rain showers during the drying period. However other factors which have also been identified to have some extent of influence on the drying process are the particle size of the product being dried, the type of solar dryer being used, the initial moisture content of the crop, air flow rate, crop absorptivity (Seveda et al, 2011, Mohanraj and Chandrasekar 2009).

2.1.3.1 Major Factors Affecting Solar Drying

2.1.3.1.1 Temperature

Temperature has been defined by Seveda et al (2011), as one of the main factors which affect the drying process most specifically the drying rate. Solar radiation received by a solar dryer is converted to heat which increases the temperature of the air in the drying chamber. This increase in temperature of the air in turn heats up the crop surface which causes the moisture in the crop to migrate to the surface and is vaporised. It is then carried away through vents holes. Usually, the higher the temperatures in the chamber, the higher the drying rates however, some crops have a maximum temperature under which they can be dried and if exceeded might lead to their deterioration. High temperatures in the drying chamber can only be effective, if it is relatively higher than the ambient temperature surrounding the dryer. Temperatures are often measured using a thermometer.

2.1.3.1.2 Solar Irradiation

Solar irradiance can be referred to as the "the rate at which solar energy reaches a unit area on the earth" (Stine and Geyer 2001). It is composed of three components; the direct normal, indirect and reflected solar irradiance. The component that is directly incident and normal to a surface without its being diffused or changed in direction by the atmosphere is termed as the direct normal irradiance and is usually measured by a pyrheliometer. Indirect irradiance is the irradiance which is scattered by the atmosphere before being received on a surface. This component can only be utilised by flat plate collectors and some low type concentrators (Stine and Geyer 2001). Some component of the irradiance which has been reflected off the earth's surface might be received for an inclined surface, and this part is called the reflected irradiance. However, for a horizontal surface the reflected irradiance is usually zero.

These components of the global solar irradiance in all determine the total amount of energy that will be received on a collector's surface and can be measured by a pyranometer. It varies depending on the geographic location, climatic conditions, the clearness of the sky, position of the sun, and the day of the year. Higher readings can be recorded on a clear and sunny day than on cloudy day or when the sun is down. The higher the available solar irradiance, the higher the temperature and therefore the higher the drying rate.

2.1.3.1.3 Relative Humidity

The relative humidity is defined as "the ratio of the amount of water vapour in the air at a given temperature to the maximum amount of air at the same temperature" (Encarta Dictionary 2008) . The propensity for a crop to dry is dependent on the ratio of the amount of moisture in the crop to that of the immediate surrounding air. If the surrounding air has a lower relative humidity the drier surrounding air can accommodate moisture migrating from the crop. Therefore the lower the relative humidity (RH) entering the dryer, the higher the drying rate and vice versa. It is usually measured by a hygrometer.

2.1.3.1.4 Moisture content

Most agricultural food products which require drying contain some amount of water in their fresh state. This water which is also termed moisture, when present might render the products unsafe for storage as it might lead to deterioration. The moisture content of most food products can range from 20 to 90% (Green and Schwarz 2001) and depending on the type of product, the safe moisture content for storage might vary. The moisture content of any product being dried has the potential of directly affecting the drying time. The amount of moisture content in the product is likely to determine the type of solar dryer to be selected.

Two phases have been identified to characterise the drying process and they are the constant rate and the falling rate phase. The initial phase where water is evaporated directly from the produce surface is the constant rate. As the drying progresses it requires more energy to evaporate the water that is embedded in the produce. This phase is called the falling rate and the final moisture content of produce usually falls within this phase of the drying process.

The moisture content of food is determined by taking the initial mass before drying in an oven at about 100^{o}C for 24hours (Practical Action 2008). The final mass of the oven dried product is acceptable if the mass after measuring over a period of time (when in the oven) continues to remains constant.

Moisture content can be determined on the wet or dry basis as indicated in the Equation 2- 3 and Equation 2- 4 below (Practical Action 2008):

$$\text{Moisture Content(dry basis)}, MC_d = \frac{(W_i - W_f) \times 100}{W_f} \qquad \textit{Equation 2- 3}$$

$$\text{Moisture Content(wet basis)}, MC_w = \frac{(W_i - W_f) \times 100}{W_i} \qquad \textit{Equation 2- 4}$$

The final mass of water lost can then be determined by:

$$M_w = \frac{(MC_{wi} - MC_{wf}) \times W_i}{1 - MC_{wf}} \qquad \textit{Equation 2- 5}$$

where:

MC_{wi}	Initial moisture content on a wet basis before drying (%)
MC_{wf}	Final moisture content on a wet basis after drying (%)
MC_d	Moisture content on dry basis (%)
MC_w	Moisture content on wet basis (%)
W_i	Initial mass before drying (g)
W_f	Final mass after drying (g)

2.1.3.1.5 Air Mass Flow Rate

In as much as heat is important in the drying of produce, the characteristics of air flowing in and out of the drying chamber of a dryer is equally important. The air flow rate through a dryer is generally a measure of the quantity of air that has passed through a dryer within a specified time. The quantity which is usually measured is mass (kg). Therefore the air mass flow rate is the mass of air flowing through dyer in a unit time. Higher mass flow rates which denotes good ventilation, increases the drying efficiency of the dryer.

2.1.3.2 Types of Solar Dryers

Solar dryers have been categorised into two main groups based on the mode of air flow through the dryer (passive and active). However there are other sub categories under these main groups which are defined based on whether the drying commodity is exposed to direct solar radiation or not (direct or indirect) or a constitution of both modes (mixed mode).

2.1.3.2.1 Direct, Indirect and Mixed Mode Dryers

Direct mode of drying usually consists of the drying chamber covered by a transparent material. This transparent material acting as the glazing, allows solar radiation into the chamber to heat up and increase the temperature of the air and the crop being dried. The main disadvantage of this type of dryer is its inability to control the crop temperature because of the direct absorption of radiation by the crop, which might cause some crops sensitive to sunlight to lose some of its nutrients e.g. Moringa.

With the indirect mode dryer, the crop is placed in an opaque enclosed chamber and thus shielded from direct solar radiation and therefore the heat transfer mode for drying is by convection only. The incident radiation is absorbed by another surface and converted to heat which is transferred by convection into the drying chamber to heat the crop located within the opaque chamber. This mode of drying is usually good for some vegetable or herbs or other food species which are colour sensitive or reduces in quality when exposed to direct sunlight especially food containing beta-carotene such as spinach, coriander etc. This is an advantage the indirect mode has over the direct mode dryer.

Although the drying rates and final crop quality are very dependent on the crop temperature in the direct mode, the setup is rather quite simple and relatively low cost making this type attractive for both small and large scale producers. Figure 2- 3 illustrates the various categories of solar dryers.

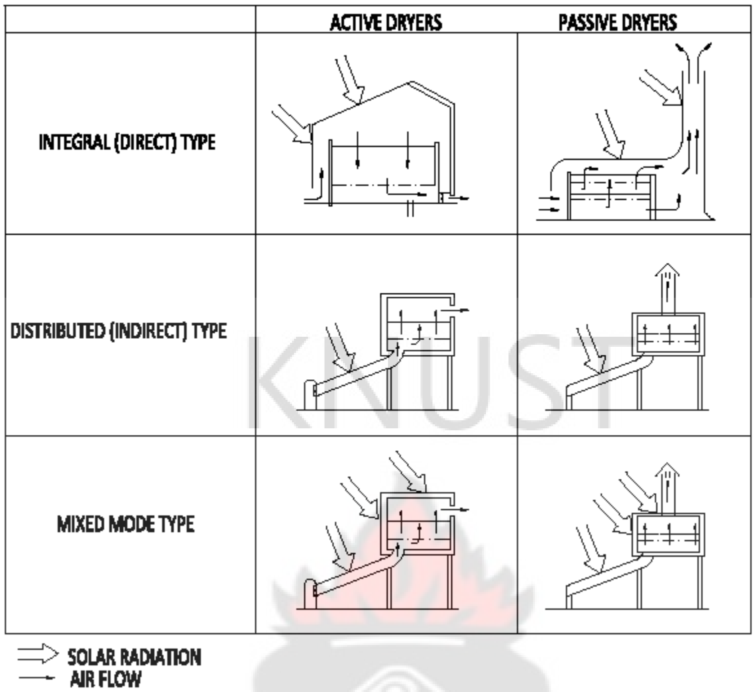

Figure 2- 3: Different Types of Solar Dryers
(Ekechukwu and Norton 1998)

2.1.3.2.2 Passive and Active Solar Dryers

Passive and active solar dryers can also be classified into the direct, indirect or mixed mode type but the main difference between them is the mode of air circulation. For the passive solar dryers, air circulation is by natural convection whilst the active type dryers are suited for large scale application where blowers provide forced circulation of heated air. Active dryers are usually used for drying high moisture produce (Seveda et al 2011).

2.1.3.3 Typical Examples of Passive Solar Dryers

This section focuses on examples of passive solar dryers which is the main area of interest in this thesis. There have been several designs of passive solar dryers, some more complex than others but one characteristic that stands out for the passive solar dryer is the low cost, the simplicity and low maintenance associated with it. Because they do not require mechanical parts such as fans or blowers, the extra cost of sourcing for an alternative source of energy to power the mechanical parts are not required. However, most of them are used on a domestic scale as they have limited loading rate. As mentioned previously, the passive solar dryer like the active dryers can be classified further into direct, indirect or mixed mode type based on the mode of exposure to the sun.

Folaranm (2008) worked on a simple solar maize dryer, which he described as a distributed passive solar dryer. It was an indirect type solar dryer which consisted mainly of a collector and a drying chamber (Figure 2- 4). The collector was made up of a wooden box covered with glazing which allows radiation through. The radiation is subsequently absorbed by the absorber plate which was basically a black painted metal plate. Warm air collected in the collector travels to the opaque drying chamber by convection and heats up the maize which are lined up on drying trays in the chamber. Temperatures above 45°C were typically recorded against the ambient temperature around 27°C when the dryer was tested in August in Nigeria. The dryer was able to dry the sample maize effectively to a moisture content of about 12.5% which is a satisfactory moisture level for effective storage throughout the year (Folaranm 2008).

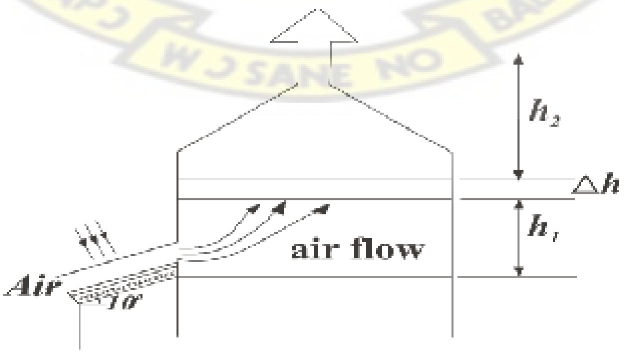

Figure 2- 4: Solar Maize Dryer
(Folaranm 2008)

A solar mango dryer was also introduced in Uganda, which was designed as a box with a wooden frame with shelf inside to support the drying products. The dryer was completely covered by glazing which allows solar radiations through. The mango slices are laid on trays made up of chicken nets which allow free flow of air around the drying produce. It has been said that the dryer was relatively affordable (Weiss and Buchinger n.d.).

Another one, reported on by Ogheneruona and Yusuf (2011) was the direct natural convection solar dryer. The dryer is a cabinet shaped mobile dryer sloped at 5^o to match the latitude of the testing location (Warri, Nigeria). Irradiation is incident on the dryer through a transparent cover which acts as glazing. Air vents are located at the front and back of the dryer to facilitate air flow in the dryer. The major design considerations during the initial design of the dryer were, "harvesting period during which the drying is needed, daily sunshine hours for the selection of the total drying time, quantity of air needed for drying, daily solar radiation to determine energy received by the dryer per day and wind speed for the calculation of air vent dimensions" (Ogheneruona and Yusuf 2011).

2.2 Parabolic Collector System

The general working principles behind solar dryers has been looked at; this section will highlight the vital areas of interest concerning principle behind parabolas and parabolic troughs. The key characteristic of the parabolic shape is the ability to refocus any incident radiation that is parallel to its axis to a focal point. This is what makes it the ideal shape to be used in most concentrating collectors where large quantities of concentrated heat generated at the focus is converted into useful energy, like Concentrated Solar Power (CSP) plants do.

2.2.1 The Geometry of the Parabola

A parabola can be defined as the locus of a point that moves so that its distances from a fixed line called the *directrix* and a point F called the focus are equal (Figure 2- 5). From the above definition, it can then be safely concluded from Figure 2- 5 that the length of the line FC is equal to the line CS. The axis of the parabola is also the line that passes through the focus and is perpendicular to the directrix. The intersection of the parabola and its axis at a point *V* is called the *vertex,* which is exactly midway between the focus and the directrix.

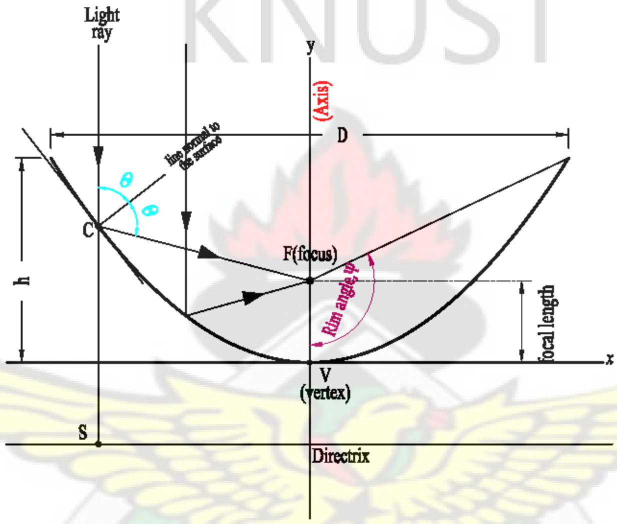

Figure 2- 5: Geometry of a Parabola

For a typical parabola the depth of the curve, ***h***, is the distance from the top of the curve to the bottom of the curve, V, as shown in Figure 2- 5 above. ***h*** is sometimes also called the height of the parabola. The aperture width or the diameter, **D**, of the parabola is also the distance from one side of the top of the curve to the other side. The distance from the focus F, to the vertex, V, is called the focal length and is calculated by the equation:

$$f = \frac{D^2}{16h}$$ *Equation 2- 6*

And the arc length of the parabolic curve, s, is also given by

$$s = \left[\frac{D}{2}\sqrt{\left(\frac{4h}{D}\right)^2 + 1}\right] + 2f\ln\left[\frac{4h}{D} + \sqrt{\left(\frac{4h}{D}\right)^2 + 1}\right]$$ *Equation 2- 7*

2.2.2 Parabolic Cylinder

The result of the movement of the parabola along the axis normal to its plane is called the parabolic cylinder which is sometimes referred to as the parabolic trough or the line focus trough when used in solar concentrators. The parabolic trough has been widely used in harnessing solar energy because of the peculiar ability of the concentrator to focus high amount of energy to a relatively small area (the absorber surface). This is possible when the sun rays are parallel to the axis of the parabola. In the case of the parabolic troughs, it forms a line perpendicular to the plane of the axis called the focal line. In view of this unique characteristic of the parabolic trough, the collector must be constantly aligned with the sun because of the constant relative movement between the sun and the earth. Stationary parabolas are therefore found to be less efficient than that of the tracking ones.

For any parabolic cylinder with the dimensions indicated in Figure 2- 5, the collector aperture area A_a, which gives an indication of the available area for radiation to be incident on the collector surface and the reflective area A_s are given by the equations:

$$A_a = l.D \qquad (m^2)$$ *Equation 2- 8*

$A_s = l.s \qquad (m^2)$ *Equation 2- 9*

Where ***l*** is the collector length and ***s*** is given in Equation 2- 7

Another parameter of interest with the parabola is the rim angle, Ψ which is the sole determiner of the shape of a parabola. It is the angle subtended between the axis of the parabola and a line drawn from the top of the curve to the focal point as shown in Figure 2- 6. It has been stated that the rim angle can have some influence on the concentration ratio (ratio of the aperture width to absorber diameter) and the total irradiance per meter of the absorber. It is calculated by the equation:

$$\tan \varphi = \frac{\left(\frac{D}{f}\right)}{2 \times \frac{1}{8} \times \left(\frac{D}{f}\right)^2}$$ *Equation 2- 10*

2.2.3 Factors affecting the performance of a parabolic collector

For any system which utilises the parabolic collector, the performance usually increases with increase in collector efficiency. The factors identified to affect the collector efficiency have been categorised into groups namely (Bendt, et al. 1979):

- Operating conditions such as the tracking mode, amount of Insolation etc.
- Material properties such as the degree of reflectance of the collector, the absorptance of the absorber etc.
- Geometric design of the receiver (absorber) such as the shape, the opening in the absorber, the absorber's surface etc.
- Concentrator geometry such as the rim angle and the concentration ratio

CHAPTER 3: DESIGN OF THE DRYER

3.1 Philosophy of Design

The basic concept behind the Parabolic Solar dryer is to explore the possibility of using the parabolic trough collector systems such as those used in the line focus CSP Plants (Figure 3-1) and combining it with the simple glazing collector system to increase the efficiency of the solar dryer.

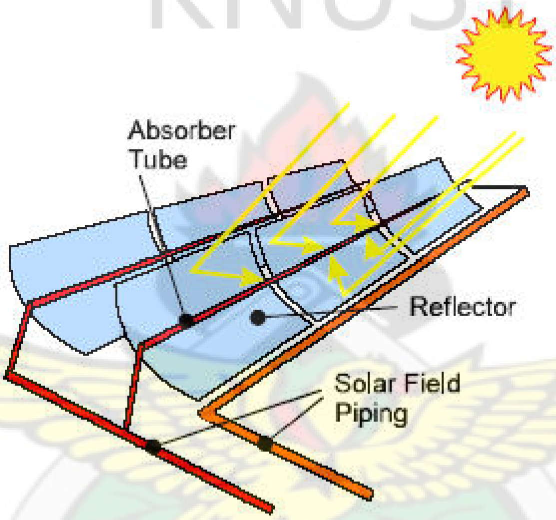

Figure 3- 1: CSP Plant
(solarPACES n.d.)

3.2 Working Principle of the dryer

The dryer is essentially designed as a mixed mode passive solar dryer with the parabolic trough deflecting indirect heat into the chamber whilst the glazing also allows direct heat into chamber.

Incident direct radiation parallel to the axis of the trough (Figure 3- 2 and Figure 3- 3) will be reflected to the trough's line focus. However, the absorber which is located above the parabolic trough is positioned right in the path of the focal line and is therefore in the position to absorb the incoming reflected radiation. With the aid of convection, concentrated heat in the absorber is subsequently dispersed to the drying chamber consisting of a wooden box. The drying chamber houses the drying crop supported on wire mesh placed some few centimetres above the absorber. At the same time, the glazing located at the top of the drying chamber, allows both diffused and direct radiations into the chamber which is directly absorbed by the drying products.

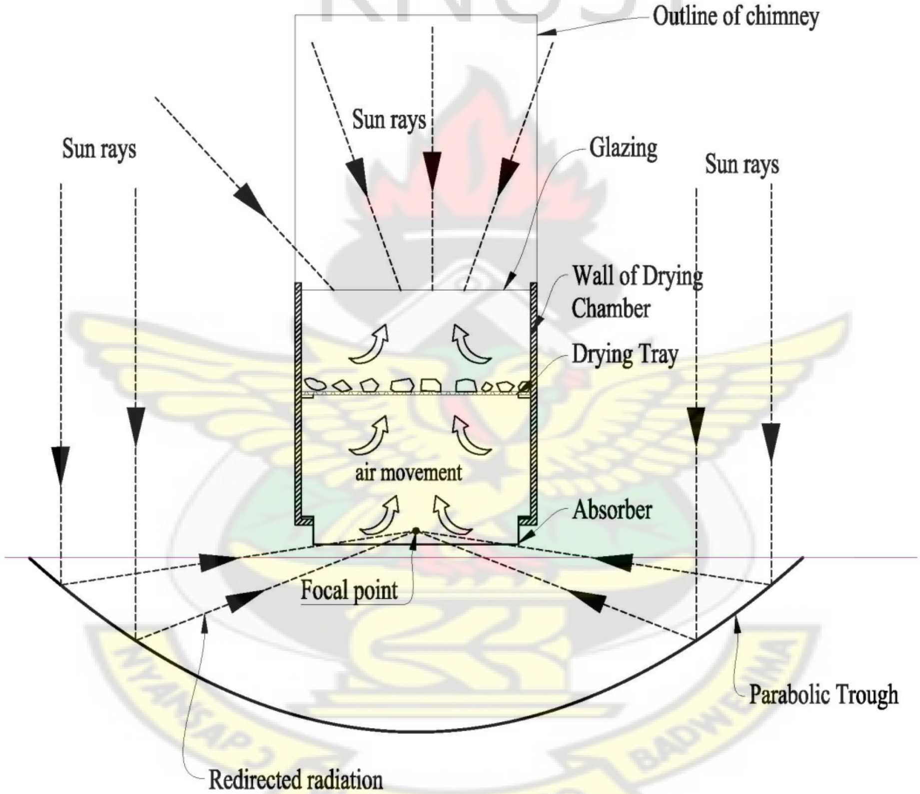

Figure 3- 2: Schematic Diagram of the Parabolic Solar Dryer (Crossectional view)

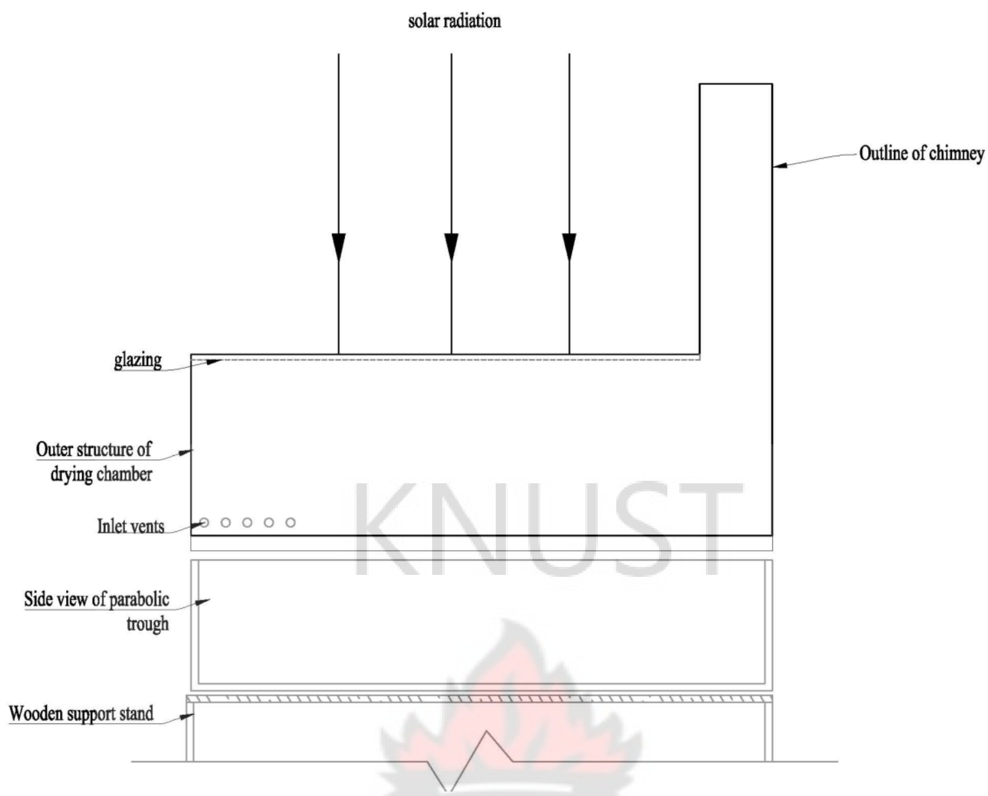

Figure 3- 3 Schematic Diagram of the Parabolic Solar Dryer (Side View)

Air flow in the chamber is facilitated by air vents which are located at the front and sides of the chamber. Cool fresh air enters the bottom vents and is heated up in the chamber and after the absorption of moisture from the drying products, it then exits the chamber through the top vents located in the chimney.

The addition of both sources of heat is expected to increase the drying rate of the food and therefore the overall efficiency of the solar dryer.

3.3 Design Considerations

The combined parabolic and glazed flat plate collector solar dryer is a fairly new concept and as such detailed comprehensive design procedures for this type of dryer is lacking in literature. The parabolic trough was the pivot point in the design of the solar dryer since the glazed flat plate collector system in a solar dryer has already been developed by several researchers as mentioned in Chapter Two. Consequently in this thesis, the idea was to find a balance between the most economic size for building the prototype and also set some basic values for some parameters of the dryer which will be the basis for investigating the performance of the dryer in future researches.

These parameters were:

- The diameter of the parabolic trough
- Diameter to depth ratio
- Geometric Concentration Ratio

3.3.1 Diameter and diameter to depth ratio

The diameter considered in building the prototype dryer was arbitrarily chosen to be 800mm in length which was basically to get a small sized parabolic trough which was to allow easy mobility of the dryer in and out of the construction workshop and also during the test phase. Based on this value, an appropriate diameter to depth ratio was selected which will give a focal point located above the parabolic trough. This was to facilitate the movement of air into the dryer to facilitate the drying process.

3.3.2 Geometric Concentration Ratio (CRg)

The geometric concentration ratio is defined by Stine and Geyer (2001) as the ratio of the collector aperture area to the receiver surface area. For a parabolic collector system, an increase in the concentration ratio will result in the subsequent reduction in the heat loss per aperture and also a part of the solar radiation that is intercepted by the receiver (Bendt et al. 1979). In the case of the dryer this will be the drying chamber. This will eventually result in an increase in the total output energy of the collector.

For the parabolic solar dryer, the receiver surface area will be replaced by the surface of the drying chamber during the calculation of the CRg (Figure 3- 3). During the design, the CRg was made to be defined by the size of the drying chamber. After an appropriate size of the drying chamber was chosen, the CRg was calculated.

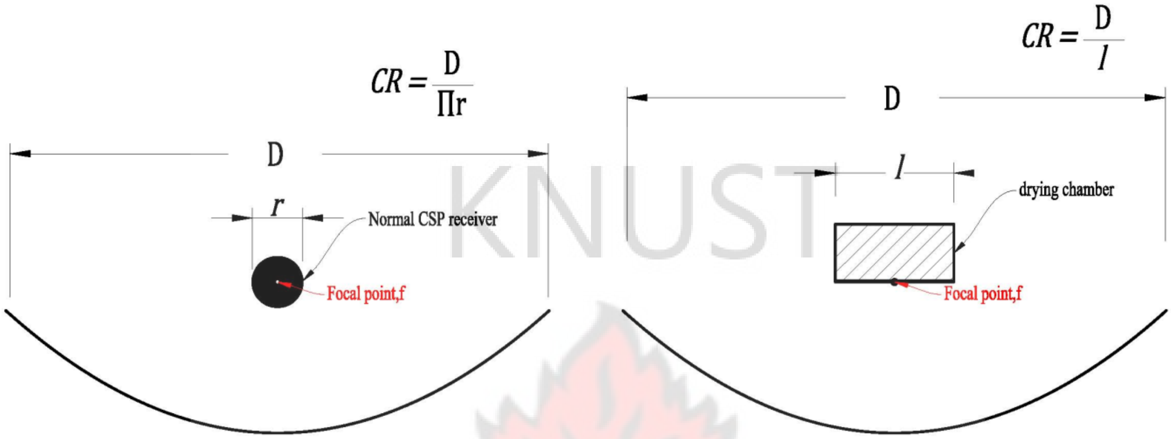

Figure 3- 4: CRg for the normal trough collector and the Parabolic solar dryer

3.4 Design Calculations

3.4.1 The geometry of the parabolic solar dryer

From Equation 2- 6, the focal length was calculated using the already selected aperture width of 800mm and the depth of the parabolic trough of 180mm (aperture width to depth ratio of 4.44). This gives a focal length of about 222mm, which places the focal line of the parabolic trough above the collector.

The CRg was then calculated using the aperture width of 800mm and the drying chamber width of 250 mm which gives a CRg of 3.2.

3.4.2 Air flow requirement

For a produce to be able to dry effectively, the surrounding air should be able to move away after absorbing moisture from the product and replaced with a less humid one for the drying process to continue. In naturally ventilated dryers this is a factor that has to be incorporated at the design stage or else the drying efficiency of the dryer might be affected since higher mass flow rates results in an increase in the drying efficiency and a lower mass rate decreases the drying efficiency. Hence, inlet and outlet vent holes were provided to facilitate air circulation within the solar dryer. The areas of the vents were calculated from the Equation 3-1 given by Weiss and Buchinger for naturally ventilated solar dryers

An initial air flow rate of 0.25 m/s was chosen based on a recommendations by Forson et al.(2007) which gives an estimate between 0.20 to 0.40 m/s for naturally ventillated dryers. Using preliminary initial tests result of the dryer which gave an average internal temperature of about 42°C and measured average ambient temperature of about 36°C, the area of the outlet vent was calculated to be about 6281.6 mm^2 using an inlet area of 1357 mm^2. During the experiment this area was reduced to 3326.4 mm^2 on the third day to evaluate the effect of the change in the area of the outlet opening.

$$C_2 = \sqrt{\frac{\frac{gH\,(T_{in} - T_{amb})}{T_{in}}}{1+\frac{{A_2}^2}{{A_1}^2}}} \qquad \textit{Equation 3- 1}$$

3.5 Additional Design Options Considered:

Other design options considered during the design and construction of the prototype dryer were:

- A movable cover which can be replaced with a glazed or opaque cover to change the dryer from direct to indirect dryer or vice versa depending on the product being dried.
- Foldable legs which will facilitate portability of the dryer set up.
- Movable parabolic trough to increase portability and also to facilitate the tracking of the sun if the option is to be considered.

CHAPTER 4: MATERIALS AND METHODS

4.1 Construction of the Prototype Parabolic Solar Dryer

After the initial design of the dryer, the parameters arrived at were used in constructing a prototype dryer, which was essentially made of these major components:

- Concentrating collector
- Glazing
- Drying chamber
- Absorber
- Opaque cover

The dryer also had foldable legs and a movable parabolic trough (Figure 4- 1).

4.1.1 Parabolic Trough Collector

The concentrating collector is made up of aluminium sheet which has been moulded into the shape of a parabola to have an aperture width of 800mm and a depth of 180mm. The curve is held in place by wooden ribbed buttons which also takes the shape of the parabolic trough. The trough had a rim angle of 83.97° and a collector length of 1m. To allow maximum incident radiation for the collector, an azimuth angle of 0^{o} was chosen.

Aluminium was chosen as the concentrator material because it was most readily available and has an appreciably modest reflectivity for radiant energy. It is estimated that the reflectivity of aluminium roofing sheets was in the range of 75 to 80% when new, and 60% after several years of exposure to the weather (Hindalco Industries Limited n.d.). However, the aluminium used may have relatively low solar reflectance like bare aluminium which is said to have a solar reflectance in the region of about 60 % (Lawrence Berkeley National Laboratory 2000).

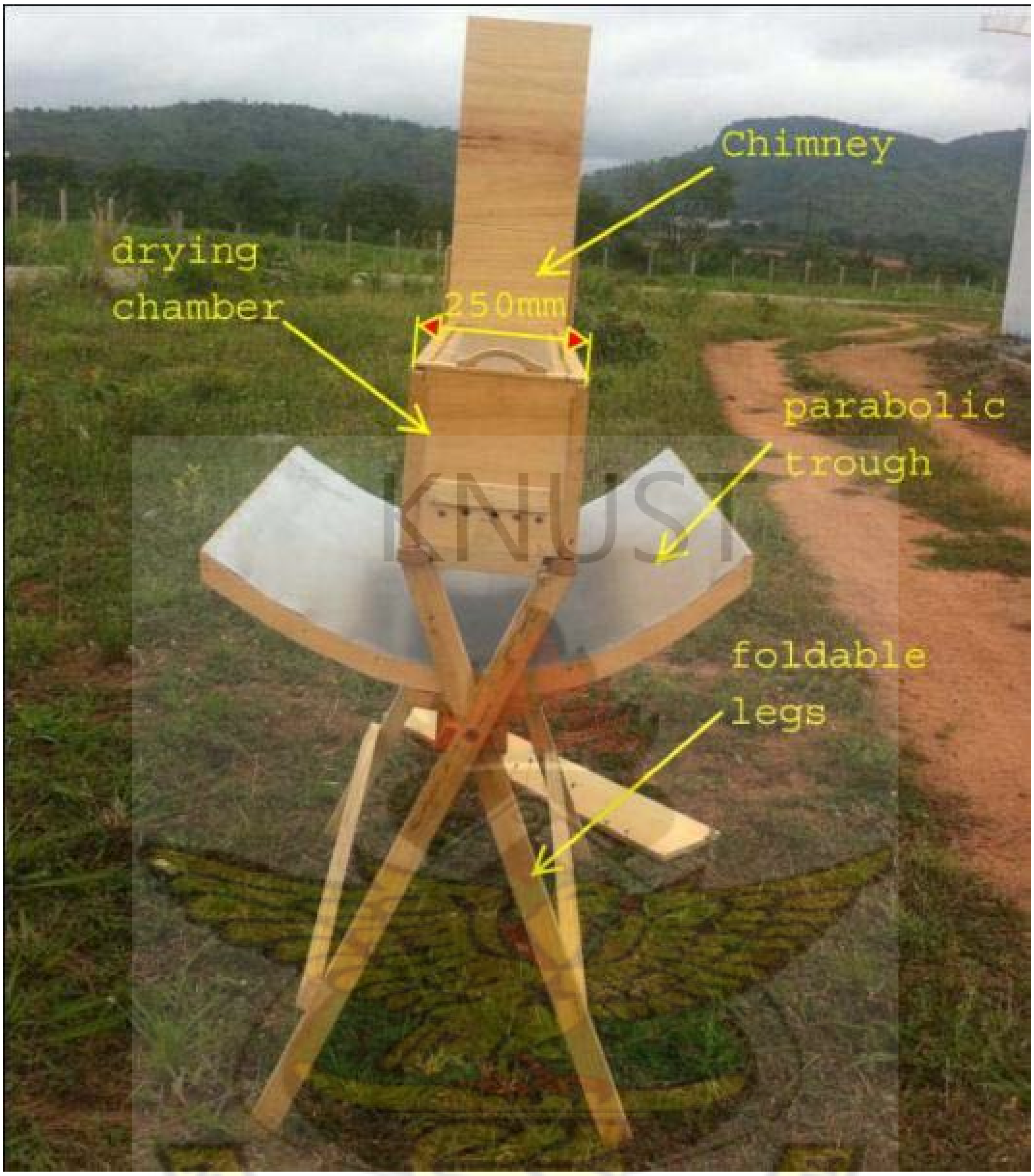

Figure 4- 1: A picture of the prototype parabolic solar dryer

Figure 4- 2: Picture showing the outlet vent of the dryer

4.1.2 Glazing

The top of the drying chamber (cover plate) is made of transparent thin plastic film cover which serves as the glazing and turns the drying chamber into a flat plate collection system. It allows solar radiation into the drying chamber which is trapped in there to heat up the drying product and the surrounding air. It also has the additional function of protecting the food produce from the weather and also prevents dust and other substances in the atmosphere from directly contaminating the drying products. It has a total area of $0.1456m^2$.

4.1.3 Drying Chamber:

The drying chamber is made up of wood with the glazing as cover. It has an overall dimension of about 0.25 m x 0.25 m x 1.0 m with a chimney height of 0.85 m. The chimney houses the outlet vent which has an area of 6281.6 mm^2 (Figure 4- 2).The drying chamber was made of wood primarily because wood is a poor conductor of heat and will reduce radiation losses. It has also been found to be relatively cheaper and more readily available than other construction materials such as steel.

Inside the drying chamber is a wire mesh on which the produce being dried is supported on. It has adequate perforations to allow easy circulation of air around the produce.

The bottom of the drying chamber is closed off by a black painted aluminium sheet which acts as the absorber. The absorber is heated by focused radiation reflected from the parabolic trough directly underneath it which in turn transfers the heat to the cooler air in the drying chamber coming from the bottom inlet vents.

Aluminium was chosen because it is more readily available and has a high thermal conductivity of 235 W·m−1·K−1 at 250 K (efunda Inc 2013).

The inner sides of the box is painted black for absorption of solar radiation and also serves as a way of preserving the wood and also reduces the absorption of moisture by the wood.

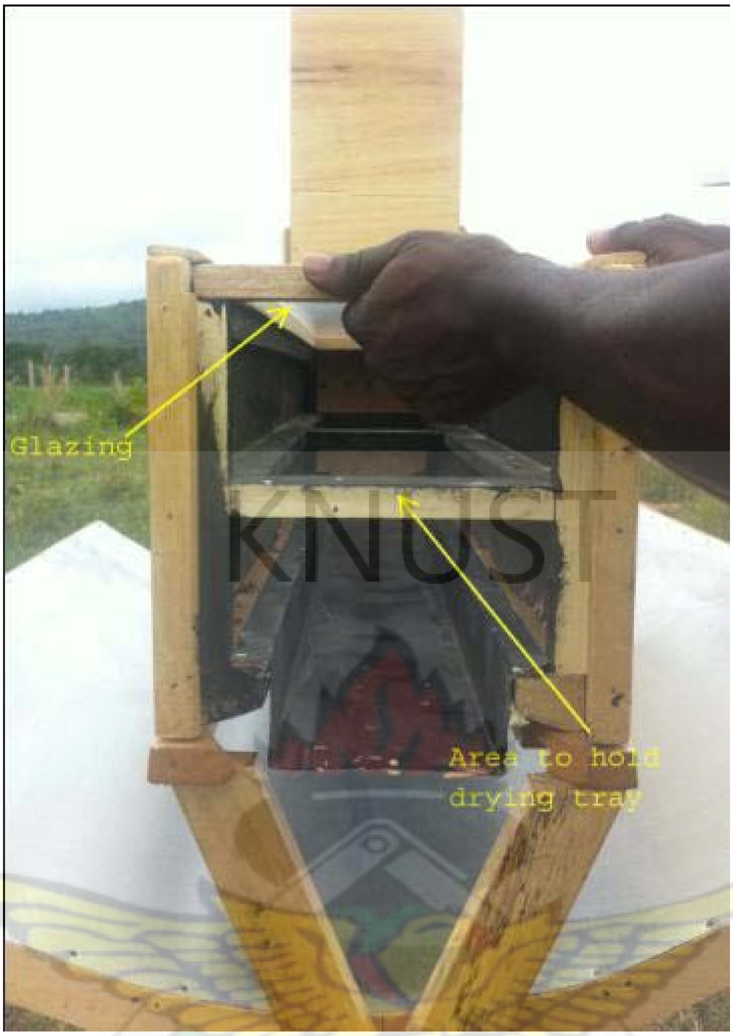

Figure 4- 3: Inside View of the Drying Chamber

4.2 Experimental Procedure

An experiment was conducted on the prototype parabolic solar dryer to study the performance of the dryer based on the initial parameters set during the design phase. Okra was selected to be used as the drying produce because it is one of the most readily available food produce in the test location.

4.2.1 Test Location

The dryer was tested in the Bui Project Resettlement Township which had geographical coordinates of about 8.24°N,-2.25°E. The weather condition in the locality was not exceptionally favourable for the test, since data from the nearest Meteorological station at Wenchi (about 90km away) indicated the month of July to be the second month with the worst monthly solar radiation in the locality. It measured daily solar radiation on a horizontal surface for July to be about 3.51kWh/m²/d (RETScreen Climate Database 2011).

4.2.2 Sample Preparation

The samples of Okra used for the test was bought from the Techiman market and kept in the refrigerator until the testing time.

Before the test, the okra was washed and the head was removed. The okra was then split into halves to facilitate the drying process.

4.2.3 Detailed Test Procedure

a) Three samples of okra were taken for the moisture content test. Samples were weighed (Figure 4- 4) before putting in the oven and dried at a temperature of 110°C until the mass during oven drying stabilised. The moisture content (wet basis) was then calculated using Equation 2-4.

b) The drying trays in the dryer were weighed empty before the test.

c) The okra was then arranged on top of the drying tray and the mass checked and recorded.

d) The drying trays with the produce were then fed into the solar dryer which had been already set up at the test location.

e) The mass of the trays with the produce were again checked at the end of each drying day during the test period.

f) The dryer was tested continuously for two days before reducing the area of the outlet vent on the third day to measure any effect of the change in the vent area.

g) The parabolic trough remained in the fixed position throughout the testing period and could only receive optimum direct irradiance during the solar noon.

h) At the same time the solar dryer was being tested, a control test using open sun drying on a tarred road was conducted. Both the dryer and the control were exposed to the same weather conditions with the exception of the times the control samples had to be covered to prevent wetting from the light rain which fell on the second and third day of drying

Figure 4- 4: Okra and tray being weighed before drying

4.3 Instrumentation and Measurement

4.3.1 Relative Humidity and Temperature

During the drying process, two combined thermometer and humidity data loggers were used to monitor some performance parameters of the dryer. One was located inside the drying chamber and the other, outside the drying chamber. Each data logger took both the temperature and the humidity at 5 minute interval.

The Lascar EL-USB-2 Humidity, Temperature and Dew Point USB Data Logger had a measuring range of -35°C to 80°C for temperature measurement and 0 to 100% RH measurement. It also had a measuring accuracy of 0.5°C for temperature and 3.0% for relative humidity.

4.3.2 Solar Radiation

A handheld pyranometer, Ambient Weather TM-206 was used in measuring the solar irradiance incident on the collector surface. It has a measuring accuracy of about 10W/m² or 5%, whichever is greater in sunlight and an additional temperature induced error of 0.38W/m²/deg.

4.3.3 Moisture Content Measurement

The mass of the drying crop was measured using a digital balance with a measuring range of 0.1g whilst the samples were dried in an oven with a temperature range of about 110°C.

CHAPTER 5: RESULTS AND DISCUSSIONS

5.1 Assessment of Measured Parameters

Testing of the solar dryer spanned between July 6 and July 8 with a total drying period of about 26 hours. Temperature and relative humidity variation inside and outside the drying chamber was measured with automatic data loggers which were logged at five minutes intervals. This allowed for a more accurate assessment of the dryer performance. Hourly instantaneous solar irradiance data was also recorded during the drying period.

5.1.1 Temperature Variation

Data obtained from the temperature log are presented graphically in Figure 5- 1. It indicates that during the initial hours of drying, the internal dryer temperatures recorded were usually greater than the ambient temperatures with the maximum difference of 11°C recorded after about an hour of drying on the first day. This was also the maximum recorded for the whole drying period. Generally, the average daily internal temperatures of the dryer recorded were higher than the ambient temperatures for the drying period (Table 5- 1).

Table 5- 1: Average Daily Temperature recorded during drying

Date	Ambient temp (°C)	Internal temp(°C)
06/07/2013	33.8	38.3
07/07/2013	31.4	35.0
08/07/2013	32.6	36.7

To investigate the effect of a reduction in outlet area on the performance of the dryer, the area of the outlet vent was decreased from 6281.6mm^2 to 3326.4mm^2 on the third day. Recorded internal and ambient temperatures for the third day shown in Figure 5- 1, indicate a general decrease in dryer internal temperature with very little difference between that and the ambient temperatures. This is in agreement with with Equation 3-1 when the internal temperature is made the subject of the equation as shown in Equation 5-1 below. It confirms that the internal temperature is directly proportional to the outlet temperature.

$$T_{in} = \frac{T_{amb}}{\left[1 - \left(\frac{C_2^{\,2}\left(1+\frac{A_2^{\,2}}{A_1^{\,2}}\right)}{gH}\right)\right]} \qquad \textit{Equation 5- 1}$$

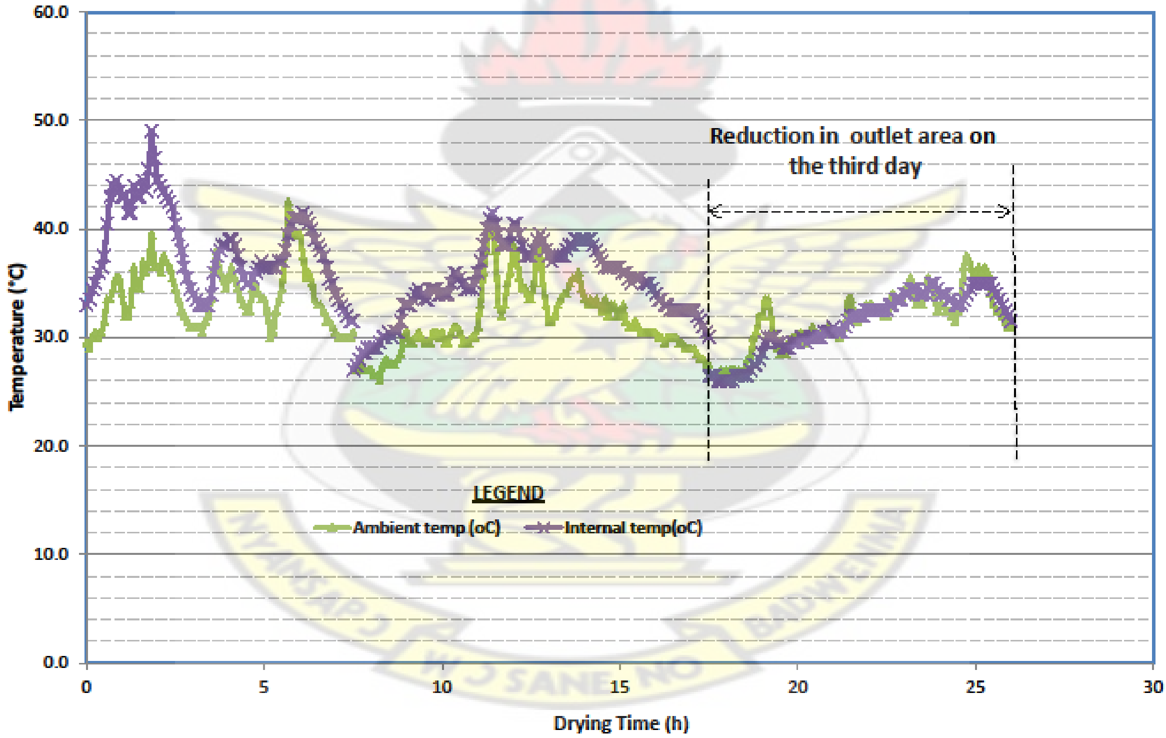

Figure 5- 1: Variation of internal and ambient temperaturesof dryer during the test period

5.1.2 Total Irradiance

Hourly instantaneous solar irradiance data obtained for the drying period have been indicated in Table 5- 2, 5-3 and 5-4.

Table 5- 2: Hourly Irradiance Recorded for the 6th of July 2013

Time	**Measured Irradiation (W/m^2)**
06/07/2013 09:00	284
06/07/2013 10:00	264
06/07/2013 11:00	431
06/07/2013 12:00	120
06/07/2013 13:00	249
06/07/2013 14:00	258
06/07/2013 15:00	292
06/07/2013 16:00	107
Average	250.6
Maximum	431
Minimum	107

Table 5- 3: Hourly Irradiance Recorded for the 7th of July 2013

Time	**Measured Irradiation (W/m^2)**
07/07/2013 08:15	144
07/07/2013 09:00	204
07/07/2013 10:00	223
07/07/2013 11:00	212
07/07/2013 12:00	201
07/07/2013 13:00	496
07/07/2013 14:00	292
07/07/2013 15:00	334
07/07/2013 16:00	214
07/07/2013 17:00	191
07/07/2013 18:00	26
Average	230.6
Maximum	496
Minimum	26

Table 5- 4: Hourly Irradiance Recorded for the 8th of July 2013

Date/Time	**Measured Irradiation (W/m^2)**
08/07/2013 08:00	126
08/07/2013 09:00	275
08/07/2013 10:00	341
08/07/2013 11:00	441
08/07/2013 12:00	375
08/07/2013 13:00	427
08/07/2013 14:00	118
08/07/2013 15:00	308
Average	301.4
Maximum	441
Minimum	118

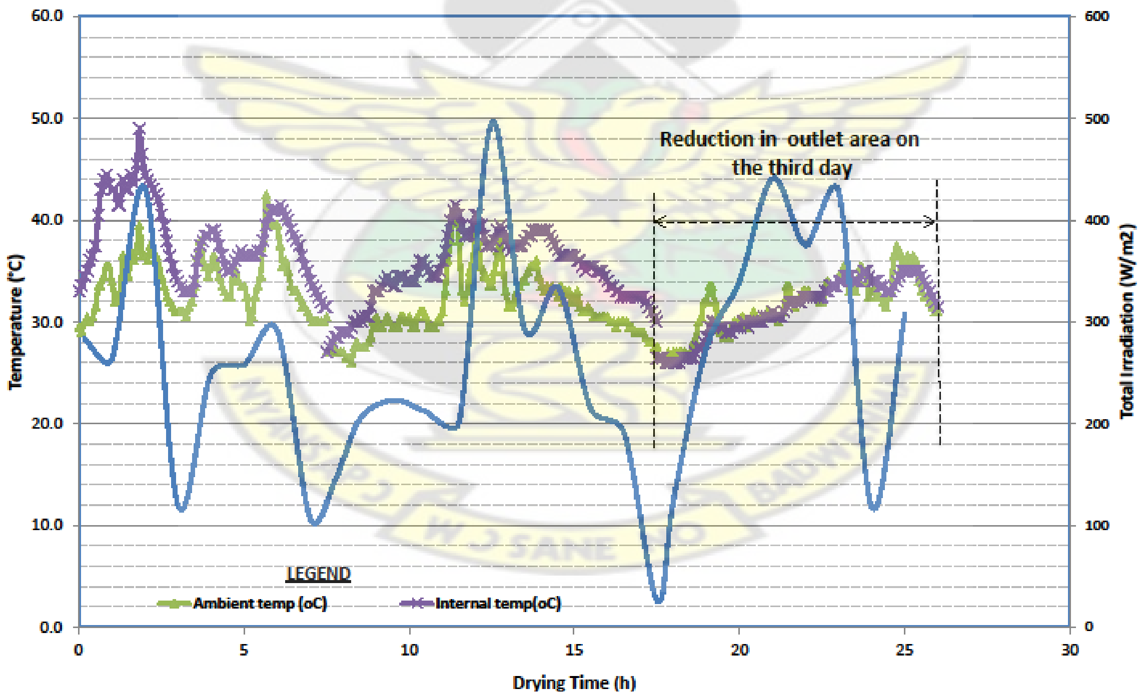

Figure 5- 2: Irradiation and Temperature variation

Irradiance was seen to greatly affect the ambient and internal dryer temperatures. As shown in Figure 5- 2, increases in both ambient and internal temperatures were realised with increase in irradiance. This shows that in days when there are high irradiance, higher internal dryer temperatures can be recorded which will facilate the drying process.

5.1.3 Relative Humidity Variation

From Figure 5-3 it can see seen that during the initial hours of drying, the internal relative humidity (RH) of the dryer was lower than the ambient RH; however subsequent values recorded were higher than the ambient RH. It was especially high during the third day when the area of the outlet opening was reduced (Figure 5-3). The increase in the RH might have been caused by a reduction in the air mass flow rate which resulted in an increase in the internal RH. The internal RH measurements recorded were taken above the crop in the dryer.

The average RH recorded for each day of the period has been presented in Table 5- 5. It shows the average internal RH measured during the last two days of drying to be generally higher than the ambient RH.

Table 5- 5: Average Daily Relative Humidity recorded during drying

Date	Ambient RH(%)	Internal RH(%)
06/07/2013	56.0	55.9
07/07/2013	61.1	64.6
08/07/2013	60.7	68.2

Generally, the dryer performance in terms of the data recorded for the relative humidity was not satisfactory since there was not much difference between the RH in the dryer and the ambient RH. A much lower internal RH would have increased the drying rate of the dryer and hence increased the efficiency of the dryer.

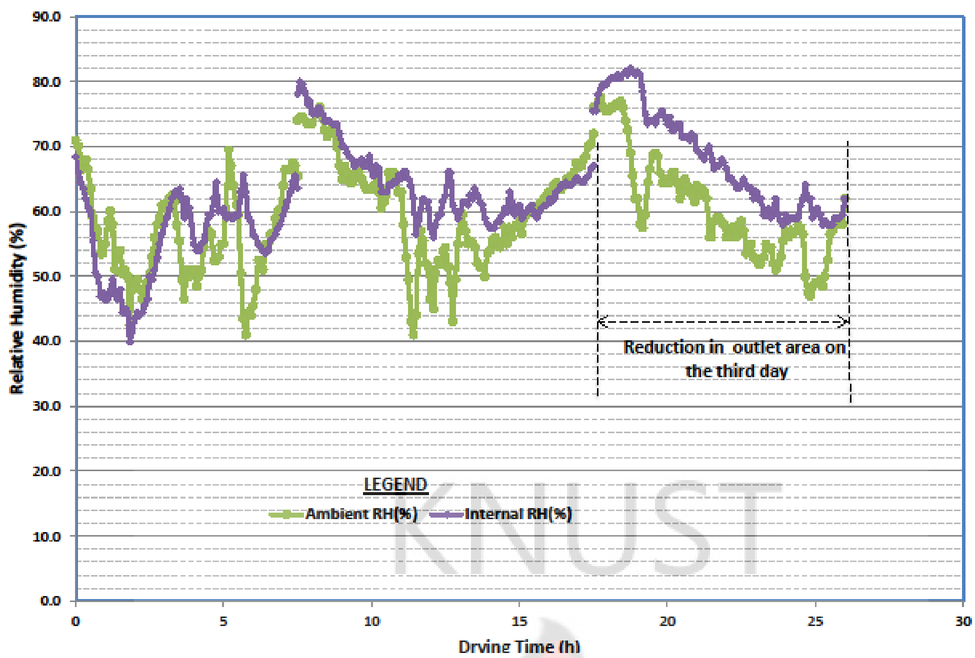

Figure 5- 3: Variation of internal and ambient RH of dryer during the test period

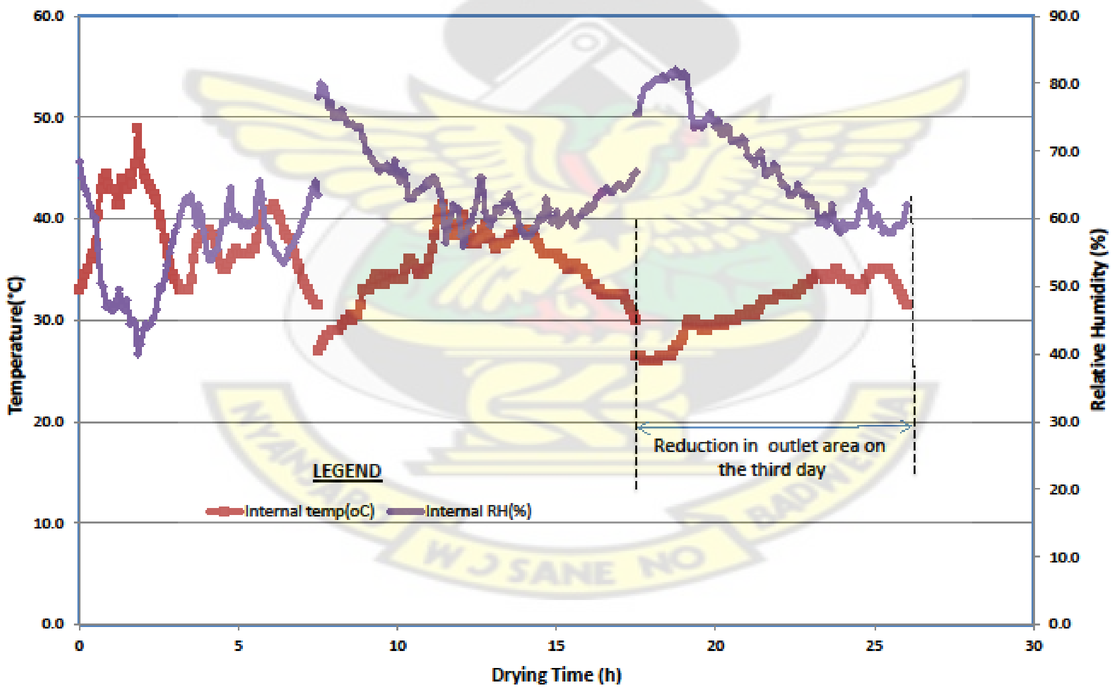

Figure 5- 4: Internal Temperature and RH variation

Figure 5- 4 shows the effect the internal relative humidity and temperature have on each other. An increase in temperature resulted in a decrease in RH and vice-versa.

5.2 Dryer Performance against Open Sun Drying

During the testing of the solar dryer, a control test was also conducted by drying another set of okra using the open sun drying method under the same conditions and at the same time to properly assess the dryer performance. The okra used for both the solar and open sun drying was taken from the same batch and therefore should have the same initial moisture content.

The initial moisture content of the okra used for the experiment was determined to be about 90.7% on wet basis (w.b.) with the final moisture content for the open sun and the solar drying being 47.1% w.b. and 56.8% w.b. respectively. On the average, the set of okra dried by the open sun drying method was about 9.7% lower than the solar dried okra. This shows that the open sun drying performed better than the solar drying for the duration of the experiment. However during the testing period, the open sun drying was intermittently interrupted by rains and the samples had to be covered to prevent them from wetting. If the produce which was open sun dried had been allowed to be exposed to the weather, the moisture content would have dramatically increased and resulted in higher final moisture content.

Table 5- 6 summarises the drying data recorded for both the solar and open sun drying. The drying rate for the different types of drying method was calculated using Equation 2-2.

Table 5- 6: Drying data for the solar dryer and open sun drying

Date/Time	Cumulative Drying Duration (hrs)	Moisture Content (%)		Drying Rate (g/hr)	
		Solar Dryer	Open Sun drying	Solar Dryer	Open Sun drying
06/07/2013 09:00	0.00	90.7%	90.7%	11.1	13.4
06/07/2013 16:30	7.50	87.4%	84.6%	11.1	13.4
07/07/2013 18:00	17.50	78.7%	68.5%	10.2	10.2
08/07/2013 16:00	26.00	56.8%	47.1%	9.5	8.1

It was realised that the average drying rate during the open sun drying was slightly higher than that of the solar dryer. Figure 5- 5 shows a steep curve for the open sun drying and a gentler one for the solar dryer which indicates that the moisture was lost relatively faster during the open sun drying than in the solar drying. The curves intersect at a time where the drying rate of both types of drying methods is equal i.e. after about 18hours of drying.

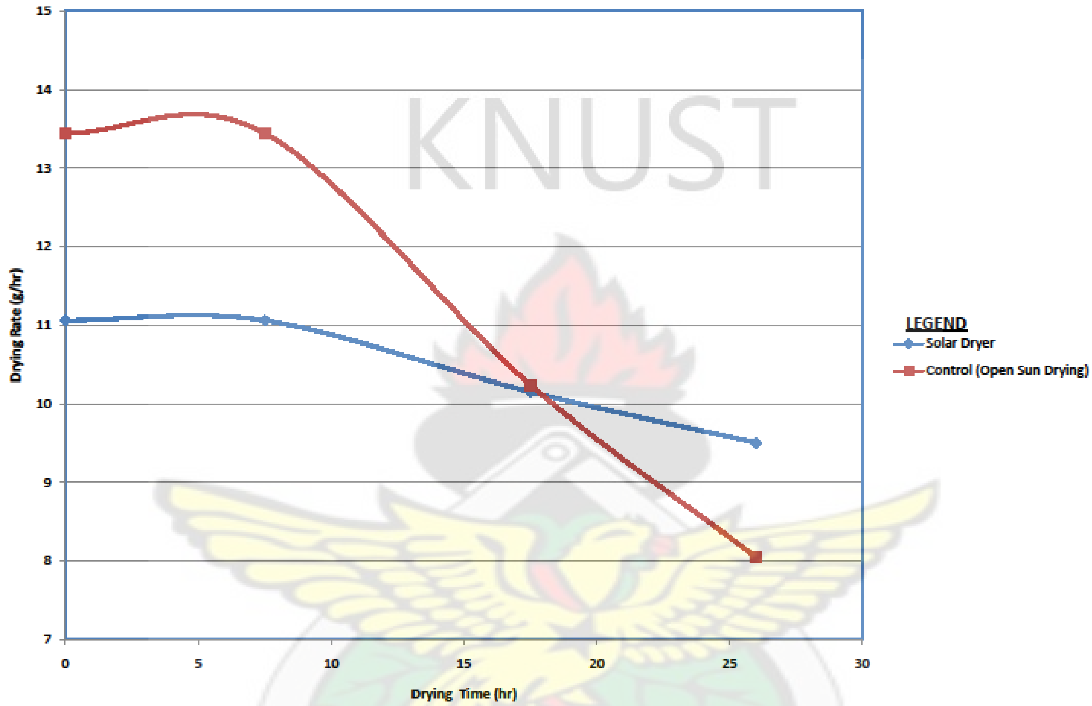

Figure 5- 5: Variation of Drying Rate with drying time

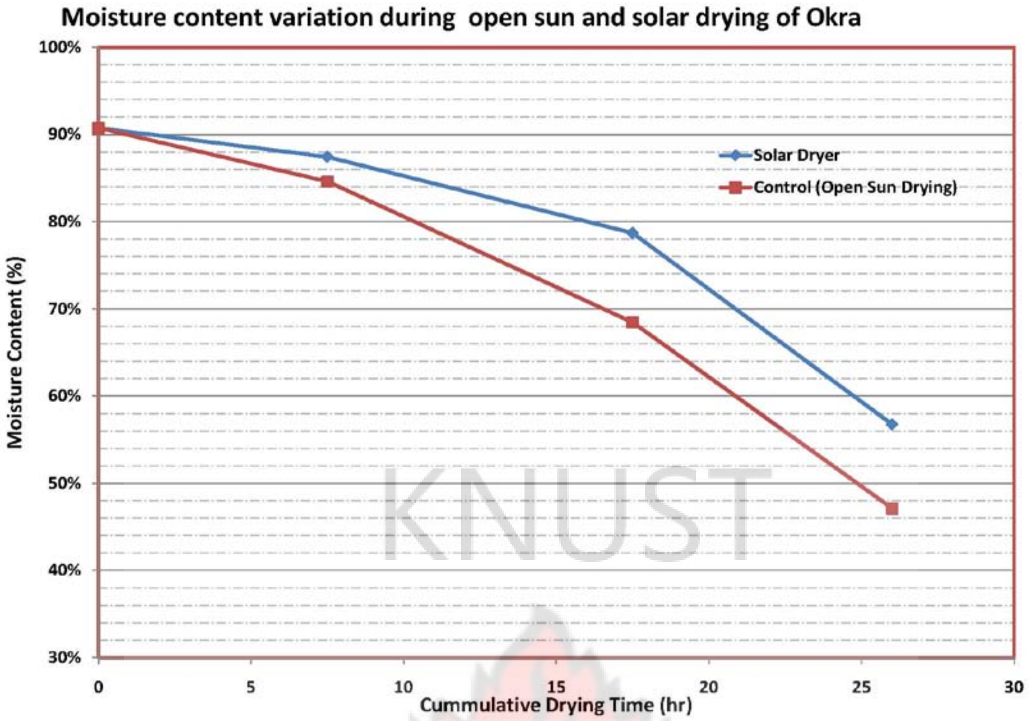

Figure 5- 6: The drying curve of moisture content versus drying time for open sun and solar drying of Okra

Figure 5- 6 shows the drying curve obtained for okra during both the open sun and solar drying. It was attained by plotting the moisture content versus drying time for the whole duration of drying for both kinds of drying method. The moisture content for both methods dropped steeply from the initial moisture content of 90.7% w.b.

5.3 Overall Dryer Performance

5.3.1 Estimation of Available Solar Resource

The horizontal flat plate collector component of the dryer has the ability to utilise both the direct and diffuse irradiance which makes up the total available irradiance measured by the pyranometer. It can be expressed by the following equation (Stine and Geyer 2001):

$I_{t,a} = I_{b,n}\cos\theta + I_d$ *(W/m2)* *Equation 5- 2*

However, concentrating collectors like the parabolic trough can only utilise the beam irradiance component of the total irradiance which is the $I_{b,n}\cos\theta$ (W/m^2) component of the total irradiance called the direct aperture irradiance, where:

$I_{b,n}$ is the beam normal irradiance and θ is the angle of incidence

5.3.1.1 Sample calculation procedure

The estimation of the diffuse and direct component of the measured total irradiance was done for a typical drying day (July 7) and results are summarised in Table 5-7. A sample of the calculation procedure followed to arrive at the results summarised in Table 5-7 has been detailed in the following steps for 8:00AM GMT standard time.

Solar Time;

The solar time was calculated from the standard time which was used in taking the hourly global irradiation with the pyranometer.

At the testing location where the geographical coordinates are 8.24°N,-2.25°E

$$\text{Solar time} = \text{standard time} + 4(0 - 2.25) + E$$

Where E is the equation of time estimated to be -4.6 for N=188 (July 7) which gives a correction of -13.6 minutes.

Thus 8:00AM GMT standard time is 7:46AM Solar time

Hour Angle

For calculating the hour angle of 7:46AM solar time, the difference between the solar time and the solar noon is -4.2333 therefore the hour angle is calculated as;

$$\text{Hour angle} = 15 \times (-4.233) \cong 63.5°$$

Extraterrestrial Irradiance

The hourly extraterrestrial irradiance, $I_{o,}$ in W/m^2 at anytime between sunrise and sunset is given by (Duffie and Beckman 1990);

$$I_O = G_{sc} \times (1 + 0.033\cos\frac{360n}{365})[\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta] \qquad \textit{Equation 5- 3}$$

For the solar times 7:46AM with a corresponding hour angle of -63.5°, the hourly extraterrestrial irradiance on a horizontal surface was calculated to be;

$$\mathbf{I_O = 611.8W/m^2;}$$

Using a G_{sc} of $1367W/m^2$, a declination of 22.6° for N=188 (July 7)

Hourly Clearness Index

For the hourly clearness index, $K_{T;}$

$\mathbf{K_T = \frac{I}{I_0}}$ *Equation 5- 4*

Where I is the hourly measured irradiance on a horizontal surface and the I_o is the calculated hourly extraterrestrial irradiance.

Therefore for the solar time of 7:46AM, and *I* from Table 5-3, the clearness index was calculated as;

$$\mathbf{k_T = \frac{144}{611.82} = 0.235}$$

<u>*Diffuse Irradiance and Direct Irradiance*</u>

The estimation of the diffuse component of the total radiation was then calculated based on the empirical relation (Equation 5-5) suggested by Erbs et al (1982) as cited by Batlles et al. (2000):

$$\frac{\mathbf{I_d}}{\mathbf{I}} = \begin{cases} \mathbf{1.0 - 0.09k_T} & \mathbf{for\ k_T \leq 0.22} \\ \mathbf{0.9511 - 0.1604k_T + 4.388{k_T}^2 - 16.638{k_T}^3 + 12.336{k_T}^4} & \mathbf{for\ 0.22 < k_T \leq 0.80} \\ \mathbf{0.165} & \mathbf{for\ k_T > 0.80} \end{cases} \quad \textit{Equation 5- 5}$$

Therefore for the k_T of 0.235 (calculated above) which is greater than 0.22 but less than 0.8, then the second line of Equation 5-5 will be used to estimate the daily diffuse fraction as;

$$\mathbf{\frac{I_d}{I} = 0.977}$$

The diffuse component of the total radiation at 7:46AM solar time on July 7 is then estimated as;

Diffuse component $\mathbf{I_d = 0.977 \times 144 = 140.7}\boldsymbol{W/m^2}$

The beam irradiance was then estimated to be:

$$I_b = \text{Total irradiance} - \text{Diffuse irradiance} \qquad \textit{Equation 5- 6}$$

And thus for the diffuse irradiance calculated above, the beam irradiance was estimated to be **3.3W/m^2**.

This procedure was used in estimating both the diffused and the direct irradiance for all the hours the total irradiation measurements were taken and have been summarised in Table 5-7.

Table 5- 7: Estimated Available Solar Resource on July 7,2013

Standard Time (hh:mm)	Solar Time (hh:mm)	Hr Angle	Hourly Extraterrestrial Irradiance (W/m2)	Hourly Total radiation (W/m2)	Clearness Index, K_T	I_d/I	Diffuse Irradiance (W/m2)	Direct Irradiance (W/m2)
08:00	7:46 AM	-63.50	611.8	144	0.235	0.977	140.7	3.3
09:00	8:46 AM	-48.50	873.3	204	0.234	0.978	199.5	4.5
10:00	9:46 AM	-33.50	1080.2	223	0.206	0.981	218.9	4.1
11:00	10:46 AM	-18.50	1218.4	212	0.174	0.984	208.7	3.3
12:00	11:46 AM	-3.50	1278.6	201	0.157	0.986	198.2	2.8
13:00	12:46 PM	11.50	1256.6	496	0.395	0.848	420.5	75.5
14:00	1:46 PM	30.00	1119.0	292	0.261	0.970	283.1	8.9
15:00	2:46 PM	45.00	927.0	334	0.360	0.893	298.1	35.9
16:00	3:46 PM	60.00	676.8	214	0.316	0.936	200.4	13.6
17:00	4:46 PM	75.00	385.5	191	0.496	0.668	127.7	63.3
18:00	5:46 PM	90.00	72.8	26	0.357	0.896	23.3	2.7

A comparison of the measured hourly total irradiance and the estimated direct irradiance indicates very minimal contribution of the direct component (Figure 5- 7) to the available solar resource needed for effective drying. This is largely due to the intense cloudy conditions during the drying period especially on July 7. The highest was recorded at about 75.5W/m^2 which was some few minutes from the solar noon.

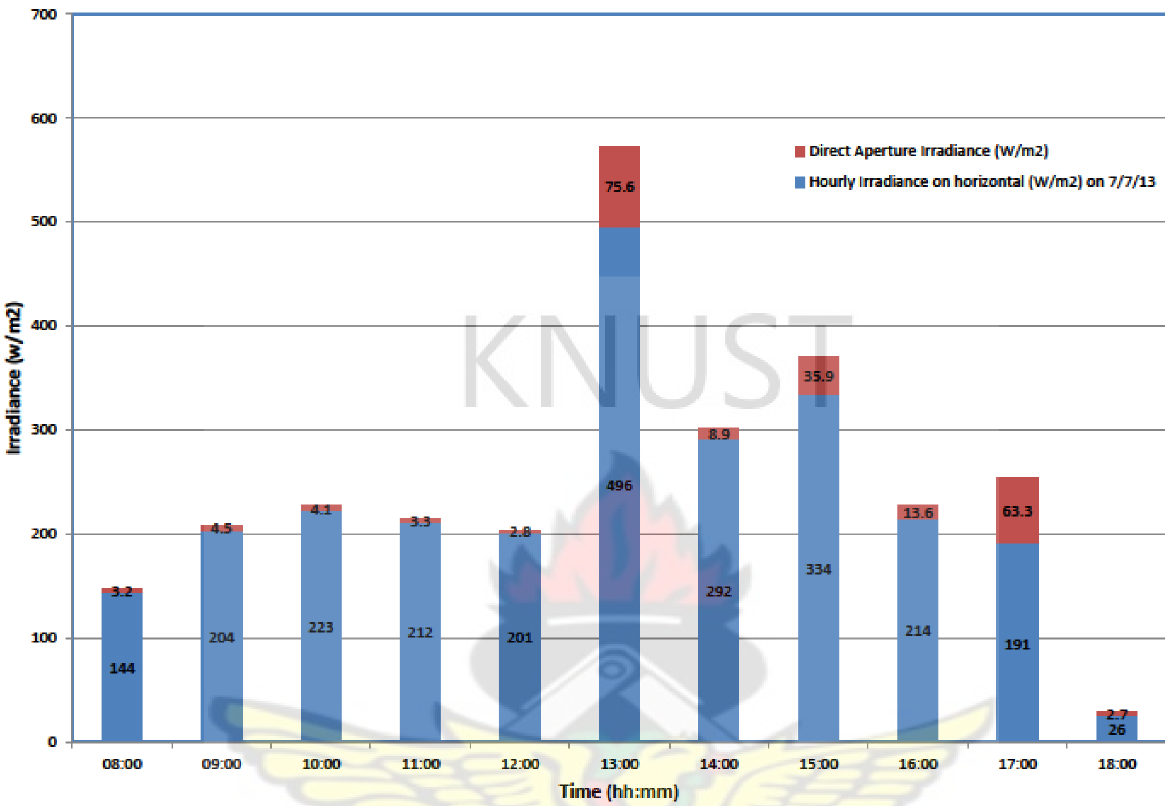

Figure 5- 7: Measured Irradiance and the Calculated Direct Apperture Irradiance for July 7

5.3.2 Drying Efficiency

The drying efficiency is one of the means of assessing and evaluating the overall performance of solar dryers. It is a ratio of the heat utilised for moisture removal to the heat available for moisture removal. From the estimated data in Table 5- 4, the average drying efficiency was calculated for July 7.

For this type of parabolic solar dryer the available energy for utilisation of drying will be the sum of the solar resource from both the flat plate collector and the parabolic trough. The drying efficiency, d_e, can then be determined from the equation:

$$d_e = \frac{\dot{m} C_p (T_{out} - T_{in})}{A_a \times I_{b,n} \cos\theta + A_c \times I_{t,a}} \times 100$$ *Equation 5- 7*

Where:

A_a (m^2) is the parabolic collector aperture area(calculated by Equation 2- 6)

A_c (m^2) is the area of the glazing

C_p (J/kgK) is the specific heat capacity of air

$\dot{m}$ (kg/s) is the mass flow rate

The mass flow rate was calculated using the equation given by Sodha *et al.* (1987) which was quoted by Akoy, et al (Akoy, et al. n.d.).

$$\dot{m} = \frac{m_{dr}}{h_f - h_i}$$ *Equation 5- 8*

where:

m_{dr} (kg/s) is the average drying rate on July 7 (calculated using Equation 2- 2)

h_f (kg/kg of dry air) is the final humidity ratio

h_i (kg/kg of dry air) is the initial humidity ratio

For July 7, the estimated drying rate from data given in Table 5- 6 is about 2.63×10^{-6}kg/s. The final and initial humidity ratios were estimated using the psychometric chart which gave about 0.023kg/kg and 0.0177kg/kg respectively for the day's average ambient temperature and RH of 31.4°C and 61.1% and the day's average internal temperature and RH of 35°C and 64.6%. The air mass flow rate was then estimated to be about 4.96×10^{-4}kg/s.

The area of the flat plate collector, A_c was measured to be 0.91x0.16m and the trough aperture dimensions were 0.8x1m.

This brings the average drying efficiency for July 7, to about 8.1% using the average of the measured total hourly irradiance and the calculated hourly direct aperture irradiance for that particular day with an assumed Specific Heat Capacity of air of 1003.5J/kgK.

This efficiency of 8.1% was found to be quite low compared to that of other natural convection solar dryers with recorded performances between 12.3% and 23.0% by Forson, et al. (2007) and Abdullahi et al. (2013) respectively.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

A comparative analysis of the drying rate of the solar dryer and open sun drying concludes that the solar dryer performed poorly. This was confirmed by the very low average drying efficiency calculated for July 7 which was about 8.1%.

The dryer did not also record huge difference between the ambient and the internal temperature. The maximum difference recorded was about 11°C.

Poor performance of the dryer can be attributed to the following:

a) Low geometric concentration ratio: The ratio estimated for the dryer was about 3.2. A low geometric concentration ratio of this range implied that the available aperture area which can receive the incoming direct solar irradiance has been reduced by the area of the receiver, in this case the drying chamber. The smaller the geometric concentration ratio the lower the energy transferred to the absorber and hence to the chamber for drying. A low geometric ratio also indicates that larger portion of the parabolic trough is being shaded by drying chamber which can in turn affect the efficiency of the parabolic trough.

b) Poor air mass flow rates might also have affected the performance of the dryer which might have been caused by the inadequate sizing of the air vents since actual drying chamber conditions during drying was not used in the initial design phase. An increase in air mass flow rates would increase the ventilation which will in turn enhance the drying process.

c) The estimated reflectance of the aluminium sheet used as the parabolic collector material is about 0.6 which is almost the same as that of bare aluminium sheet. This low reflectance has the effect of reducing the amount of radiation which will be reflected onto the absorber. In comparison, polished surfaces such has silver glass mirrors used in CSP plants have high reflectance of about 0.94.

d) The possibly low transmittance of the transparent plastic sheet might also have contributed to the relatively poor performance of the dryer, although the actual transmittance value was not known.

e) The non-tracking parabolic collector which remained fixed in one position during the drying period also contributed to the low efficiency recorded.

6.2 Recommendation

- It is recommended that in order to improve the overall dryer efficiency, the trough should be redesigned to track the sun since fixed troughs will only receive maximum radiation from the sun at midday and loose the rest of the irradiation for most parts of the day.
- In redesigning of the dryer, the geometric concentration ratio should be made to define the size of the drying chamber and higher concentration ratios should be considered since it has the possibility of increasing the overall performance of the dryer.
- A concentrator with high reflectance should be selected.
- Glazing material selected should also have high transmittance value.

6.3 Future Work

- Future work on this dryer should look at redesigning the dryer using established design procedures for flat plate collectors and incorporating the parabolic collector afterwards. However the design of the parabolic collector should always consider geometric concentration ratios greater than 3.2, possibly in the region of 10 and above.
- Future works should also look at testing the dryer on days with very good direct normal irradiance to also assess the dryer during these times.
- Future work could also look at extending the drying time until produce being dried attain an acceptable moisture content for storage.

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