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DESIGN AND EVALUATION OF SOLAR MAIZE GRAIN DRYER WITH A BACK-UP HEATER

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A thesis submitted to Department of Environmental and Biosystems Engineering, School of Engineering, University of Nairobi in partial fulfilment of the requirements for the award of the degree of Master of Science in Environmental and Biosystems Engineering.

2014

DECLARATION

I hereby declare that this thesis is my original work. To the best of my knowledge, the work proposed here has not been submitted for a degree programme in any university.

………………………………………… …………………

Tonui K. Stephen **Date**

This thesis has been submitted for examination with our approval as university supervisors for the award of the Degree of Master of Science in the Department of Environmental and Biosystems Engineering, School of Engineering of the University of Nairobi.

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DESIGN AND EVALUATION OF SOLAR MAIZE GRAIN DRYER WITH A BACK-UP HEATER

ABSTRACT

A solar dryer integrated with a simple biomass burner was designed and constructed with locally available materials to dry maize. The dryer was composed of solar collector, drying chamber, back-up heater and airflow system all integrated together. The back-up heater provided alternative heating during cloudy weather conditions or at night when solar radiations were low. The dryer was designed based on climatic conditions of Mau summit located in Nakuru County, Kenya. The average ambient conditions were 26ºC air temperature and 72% relative humidity with daily global solar radiation incident on horizontal surface of about 21.60MJ/m^2/day. This study describes the design considerations and results of calculations of design parameters. A minimum of 3.77m^2 solar collector area was required to dry a batch of 100kg maize grain in 6 hours under natural convection from the initial moisture content of 21% to final moisture content of 13% wet basis. Using similarity laws a dryer with collector area of 0.6m^2 was fabricated and used in experimental drying tests under varied heat source conditions namely; solar, biomass and a combination of solar and biomass. Solar assisted dryer system efficiency was estimated at 57.7% with average drying rate of 0.077kg/hr with back-up heating operation increasing solar dryer efficiency by 17.8%.

Keywords; Design, Solar collector, Biomass heater, Solar drying, Maize, Evaluation

DEDICATION

I dedicate this project in a special way to my late father Mr. Solomon Busienei for the encouragement and his financial support he gave me throughout my pursue of academics to this extend.

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

To my wife, Joyce Chelangat, who has been the source of my hard work and for her supportive sacrifices she has made.

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LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
CFC	Chlorofluorocarbon
GDP	Gross Domestic Product
GPS	Geo-positioning System
GSI	Grain System International
GTZ	GesellschaftfürTechnischeZusammenarbeit
IFPRI	International Food Policy Research Institute;
Kg	Kilogram
KWh	Kilowatts-hour
MJ	Mega joules
NASA	National Aeronautics and Space Administration
NCPB	National Cereals and Produce Board
PGCP	Philippine German Coconut Project
PUF	Polyurethane foam
UV	Ultra Violet

CHAPTER ONE
1.0 INTRODUCTION

1.1 Background

In many parts of the world there is a growing awareness that renewable energy has an important role to play in extending technology to the farmers in developing countries to increase their productivity (Waewsak *et al*., 2006). Solar thermal technology is rapidly gaining acceptance as an energy saving measure in agricultural applications. It is preferred to other alternative sources of energy such as wind and shale, because it is abundant, inexhaustible and non-polluting. (Akinola *et al*., 2006).

Drying is the oldest and widespread method of preserving food stuffs that utilizes this abundant source of energy and plays great economic importance all over the world. There are two types of water present in food items; the chemically bound water and the physically held water, in drying it is only the physically held water that is removed. The most important reasons for the popularity of dried products are longer shelf-life, product diversity as well as substantial volume reduction. This could be expanded further with improvements in product quality and process applications.

Maize being the most important staple food in sub-Saharan Africa has over time been preserved through this method. In 2005, the top exporters of maize in sub-Saharan Africa were South Africa, Tanzania, Uganda, Zambia and Swaziland, with the top importers of maize Zimbabwe (a maize exporter until the late 1990s), Angola, Ghana, Kenya and Mozambique (Meridian institute, 2009). According to Kenya Maize Development Programme (KMDP) maize is the primary staple food crop in the Kenyan diet with an annual per capita consumption rate of 98 kilograms -contributing about 35% -of the daily dietary energy consumption. Indeed, 90% of the rural households grow maize and production is dominated by small scale farmers who produce 75% of the overall production. The other 25% is grown by large scale farmers (Erastus, 2011).

Facing a growing population, several studies (World Bank, 2003) note that it is critical for Kenya and other African countries to increase maize production in order to feed their people. The national maize production ranges between 24 and 33 million bags per annum which does not keep pace with the domestic consumption levels (estimated over 36 million bags in 2008) due to high rate of population growth estimated to be 2.9% per annum. (Kangethe, 2011). .

In Kenya, the major food safety hazard associated with maize is mycotoxins contamination that are produced by many species of fungi which contaminate maize during pre and post harvest periods. This indeed has contributed to loss of part of the maize harvests due to fungal and microbial attacks causing high post-harvest losses. These wastage and damage could easily be prevented by proper drying through the utilization of the plentiful renewable solar energy given that Kenya lies within the equator and is blessed with abundant solar energy all the year round with an annual average insolation levels of 5.62kWh/m^2/day (NASA) . Drying process of the maize involves progressive loss of moisture content in the grains, it involve moisture removal due to simultaneous heat and mass transfer. Maize is often not fully dried at the farm; it is therefore harvested, threshed and dried to moisture content of about (11.8%-13%) for safe storage or sales.

Therefore, the application of solar dryers in Kenya can easily reduce post harvest losses and significantly contribute to the availability of food in the country. Further, it can help reduce Case-fatality rate (CFR) caused by aflatoxin poisoning witnessed in some parts of the country for quite some time due to poor drying of the grains (Refer; Appendix A5.2), Aflatoxin poisioning has killed a number of people and livestock all over the country, for instance in Eastern province where as of 20th July 2004 alone during its outbreak 317 cases and 125 deaths had occurred (Korir *et al.,* 2012).

Estimations of post harvest losses are generally cited to be of the order of 40% but they can, under very adverse conditions, be nearly as high as 80%. A significant percentage of these losses are related to improper and/or untimely drying of foodstuffs such as cereal grains, pulses, tubers, meat and fish among others (Togrul *et al*., 2004). Mechanized dryers though faster and give a better quality product, are expensive and requires substantial quantities of fuel or electricity to operate, leading to high cost of drying (Ajay, 2009). Therefore solar energy can easily be harnessed by a proper design of solar dryers for drying crops and achieve controlled grain drying at lower costs.

In Kenya, drying of agricultural produce is accomplished majorly through open-air drying/Sun-drying and mechanized dryers, with limited application of solar dryers. Open-air drying is the oldest, most inexpensive and extensively used option since early times and is practiced in many parts of the world including Kenya's rural areas. This method though entirely depends on weather conditions,is labour intensive, unhygienic, unreliable, time consuming, result in non-uniform drying, and requires a large area for spreading the produce to dry and in some places have failed to produce expected results.

Mechanized drying, majorly employed in industrialized regions and sectors, utilize dryers with boilers to heat incoming air, and fans to force air through at a high rate. Mechanized drying is faster than open-air drying, uses much less land and usually gives a better quality product. But the equipment is expensive and requires substantial quantities of fuel or electricity to operate, hence high cost of drying (Ajay, 2009). Therefore, the intermediate drying technology that take care of sun-drying disadvantages, ecofriendly and economically feasible to small scale is the application of solar dryers. Currently, in Mau summit, farmers use sun drying where maize grains are spread on the ground using polythene sheets and canny bags, this method is inadequate to solve the problems hence need to design a better drying system. This prompted the study towards the design and evaluation of solar dyer for maize grains in Mau-summit region in Kenya.

1.2 Problem Statement

Maize crop is usually harvested with moisture content of between 19% and 25% which is a favourable environment for the growth of moulds (fungi) that causes grain spoilage and mycotoxin contamination resulting to losses. Further, short-rains and less sun hours experienced in Mau-summit during harvesting season makes sun drying process very unreliable and is often associated with problems such as poor quality grains due to exposure of grains to rain and dust, untimely drying and contamination resulting from poor handling facilities.

According to research by IFPRI, (2010) grains dried in direct contact with bare ground are more susceptible to contamination by fungi that produce aflatoxins which is popular to many households using this traditional method. Poor drying due to overreliance on heat from the sun has been cited as a major cause of aflatoxin contamination in the country, which is estimated to claim up to 30 per cent of harvests every season (Appendix A5.5).

The scarce mechanized dryers though appropriate for use to address the above problems; are inaccessible to small scale farmers. On the other hand, farmers lack financial capacity to procure and operate mechanized dryer which requires substantial quantities of conventional fuel or electricity to operate.

These scenario leaves farmers without proper dried grains which is a threat to human health, propagate post harvest losses and render production of maize uneconomical.

1.3 Justification

Currently there is growing demand for modern technology by farmers as they race to tame heavy losses occasioned by grain contamination. Government and donor partners are nowdays advocating adoption of modern drying techniques to replace roadside sun drying and mitigate against rising cases of grain contamination. This has seen the set up of budget allocation towards buying of fixed and mobile maize mechanical driers respectively to reduce post-harvest losses (Appendix A5.5) which again might not offer immediate solution due to cost, availability locally amd proximity to farmers as the project is at pilot stage.

The proposed solar maize grain dryer will provide a solution to problems facing farmers since it enables drying of grains in an enclosed unit; this keeps the grains safe from damage by adverse weather conditions and animals. The grains are also dried using solar thermal energy indirectly in a cleaner and safe way, incorporating back up heater in the design enables night or all weather drying hence ultimately shortening the drying time. Besides, it enables farmers to store the grains at right moisture content to fetch better market price, an adequate consideration for their cost of production and profit margin since better and efficient dried grains is achieved.

Furthermore, the dryer is not expensive to construct and operate as it uses locally available material and skills to run compared to other alternative drying methods. Besides, in Mau-Summit rural areas conventional sources of energy like petrol and electricity are at times inaccessible or expensive to consider operating mechanized dryers often associated with higher rate of performance. Thus, this dryer will counteract the above underlying problems.

1.4 Hypothesis

The solar dryer with a back-up heater will enable all-weather and faster drying process reducing the grain drying time, grain loss and improve quality of dried grains.

1.5 Objective

The overall objective of the study was to design, construct and characterize a solar maize grain dryer with biomass back up heater to reduce grain drying time and improve drying efficiency.

Specific Objectives

1. To design and fabricate a collector to harness solar thermal energy.
2. To design fabricate and assemble solar dryer pertinent parts which include drying chamber, back-up heater, and airflow system.
3. To test and evaluate the thermal performance characteristics of the fabricated solar dryer.

1.6 Scope of study

The study focused on the design and fabrication of a solar maize grain dryer, appropriate for small scale farmers in Mau-summit location with the following components: solar collector made of a glass cover plate and heat absorber made of corrugated iron sheet, drying chamber trays made of mild steel sheet, air flow system and a biomass operated back-up heater. The study entailed testing and evaluating thermal performance of the dryer in terms of system efficiency and drying rate.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Maize drying

Drying Involves implies moisture removal, which is an adiabatic process. After growth ceases and maize crop has reached maturity, a considerable amount of moisture must still be removed from the grain before it can be safely stored. The lower the moisture content and temperature, the longer the maize can be stored safely. High moisture grain will deteriorate rapidly at high storage temperatures. In addition, wet grain will undergo chemical changes. There are more severe problems encountered in storing high moisture grain, as these are usually associated with the growth of various storage fungi and resulting mycotoxin production.

Quality for commercial maize is defined by government National Cereals and Produce Board grading standards. Depending on the type of grain, quality may include such factors as germination levels, stress crack occurrence, breakage susceptibility, heat damage, and milling or processing indices. These factors can be affected by the dryer design, operational procedures, initial and final grain moisture contents, drying air temperatures, airflow rates and grain cooling procedures after drying.

2.1.2 Maize Storage

With the evolution of a more planned agricultural system in the Middle Ages, maize was stored on loam threshing floors or in grain lofts. Storage on the floor was used for the last 150 years or so. The grain lofts were semi-automated in the 19th century with the introduction of drop tube systems, or were further improved as self-emptying silos (Boumans, 1985). The old building system of the grain cells, laid out in natural or man-made bricks, can be regarded as the predecessor of modern silo building. Only the application of reinforced concrete at the beginning of the 20th century made it possible to erect larger units by G. Boumans, (1985).

2.2 Traditional methods of Drying

Traditional drying of agricultural produce can be achieved through the following methods:

- Open-air drying
- Sun-drying
- Fossil drying e.t.c

2.2.1 Open-Air Drying and sun-drying.

These are the oldest, most inexpensive and extensively used option since early times; it practiced in many parts r regions of the world including Kenya's rural areas. The major disadvantage of this method is contamination of the products by dust, birds, animals and insects, spoiled products due to rain, wind and moisture, and the method totally depends on prevailing weather conditions. Further, the process is labour intensive, unhygienic, unreliable, time consuming, non-uniform drying, and requires a large area for spreading the produce to dry. Besides, this method also prolongs drying and may result in the deterioration of the quality of the crops or grains.

2.3 Mechanized dryers

In industrialized regions and sectors, open air-drying has now been largely replaced by mechanized dryers.Mechanized dryers has boilers to heat incoming air, and fans to force it through the maize at a high rate. Mechanized drying is faster than open-air drying, uses much less area and usually gives a better quality product. But the equipment is expensive and requires substantial quantities of fuel or electricity to operate, hence high cost of drying (Ajay, 2009). Highly mechanized dryers can be of the following type: either high temperature batch dryer; high temperature continuous-flow dryer or high temperature re-circulating Type Dryer, (El Fidal, 2004)

2.4 Solar dryers

Solar dryer transforms solar energy into heat that helps remove the moisture of grains and crops. Most of the solar dryers have three major drier components:

- A drying/ food chamber in which food is dried,
- A solar collector that heats the air, and
- Some type of airflow system (Forced or natural)

Air is circulated by fans, which uses 20-40W of power from a photovoltaic panel, a generator, or a central utility. Air is forced into the solar collector by the fans where it is heated by the solar energy, and then flows on to the food drying section. An advantage of the PV powered system is that, depending on the solar radiation, the air throughput is automatically adjusted by the speed of the fans (Mathew *et al*., 2001).

Solar drying may be classified into direct, indirect, mixed-modes and hybrid. In direct solar dryers, the air heater contains the grains and solar energy passes through a transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed. In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed, while in the mixed-mode type of dryer, the heated air from a separate solar collector is passed through a grain bed and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or roof. A hybrid system is one where additional heat is provided through the burning of fuel or biomass. This enable night drying since the dryer does not only depend on solar energy, hence drying is accelerated ultimately reducing drying time. Table 2.1 highlights advantages and disadvantages of the above classes of solar dryers.

Table 2.1 Advantages and disadvantages of the four types of solar food driers

Classification	Advantages	Disadvantages
Direct	• least expensive • simple	• UV radiation can damage food
Indirect	• products protected from UV • less damage from temperature extremes	• more complex and expensive than direct sun
Mixed-mode	• less damage from temperature extremes	• UV radiation can damage food • more complex and expensive than direct sun
Hybrid	• ability to operate without sun reduces • chance of food loss is minimised • allows better control of drying • fuel mode may be up to 40x faster than solar	• expensive • may cause fuel dependence

2.4.1 Source of solar energy

Solar energy is energy comes from the sun. Every day the sun radiates an enormous amount of energy. The sun radiates more energy in one second than people have used since the beginning of time. All this energy comes from within the sun itself. Like other stars, the sun is a big gas ball made up mostly of hydrogen and helium. The sun generates energy in its core in a process called *nuclear fusion.*

During nuclear fusion, the sun's extremely high pressure and high temperature cause hydrogen atoms to break apart and their nuclei to fuse or combine. Some matter is lost during nuclear fusion. The lost matter is emitted into space as radiant energy.

It takes millions of years for the energy in the sun's core to make its way to the solar surface, and then approximately eight minutes to travel the 93 million miles to earth. The solar energy travels to the earth at a speed of 186,000 miles per second, equivalent to the speed of light. Only a small portion of the energy radiated by the sun into space strikes the earth i.e. one part in two billion. This energy has been utilized by man in various diverse ways since time in memorial. This uses as regards Mau-summit area includes electrical energy stored in batteries to power electrical appliances, solar heaters to heat water systems e.t.c. Attempts have been made to collect and use this energy adequately and efficiently since it is less free, inexhaustible, and renewable. (Meridian institute, 2009)

2.5. Existing designs for different types of solar dryers

When drying foods, the key is to remove moisture as quickly as possible at a temperature that does not seriously affect the quality i.e. flavor, texture and color of the food. If the temperature is too low in the beginning, micro organisms may grow before the food is adequately dried, if the temperature is too high and the humidity too low, the food may harden on the surface. This makes it more difficult for moisture to escape and the food does not dry properly (Adu *et al.*, 2012)

Successful drying depends on:

- Enough heat to draw out moisture, without cooking the food
- Dry air to absorb the released moisture; and
- Adequate air circulation to carry off the moisture.

Examples of already developed dryers in various part of the world are briefly discussed below:

2.5.1. PGCP Solar Coconut Drier

A small, portable, and inexpensive coconut drier was developed and tested as part of the GTZ Philippine German Coconut Project (PGCP). The drier is an improvement of traditional open-air sun drying by reducing drying time and increasing the quality of the dried coconut, as demonstrated in tests from 1994-95.

The PGCP drier required 4-5 days of drying time, whereas open-air drying required 5-7 days. With the PGCP solar drier, approximately 50% of the coconuts maintained their white color, but with open air drying less than 20% stayed white. As shown in Figure 2.1, the drier consists of a frame of bamboo (or rattan) supporting a clear plastic sheet in a dome shape. The coconut halves are spread on the ground and then the drier is placed over them.

The first day of drying should be sunny to produce a quality dried product. This drier is most suitable for farms of one hectare or less, and requires an elevated site where rain water will run off. It is possible the drier may be adapted to products other than coconuts, provided the required temperature is less than 60℃.

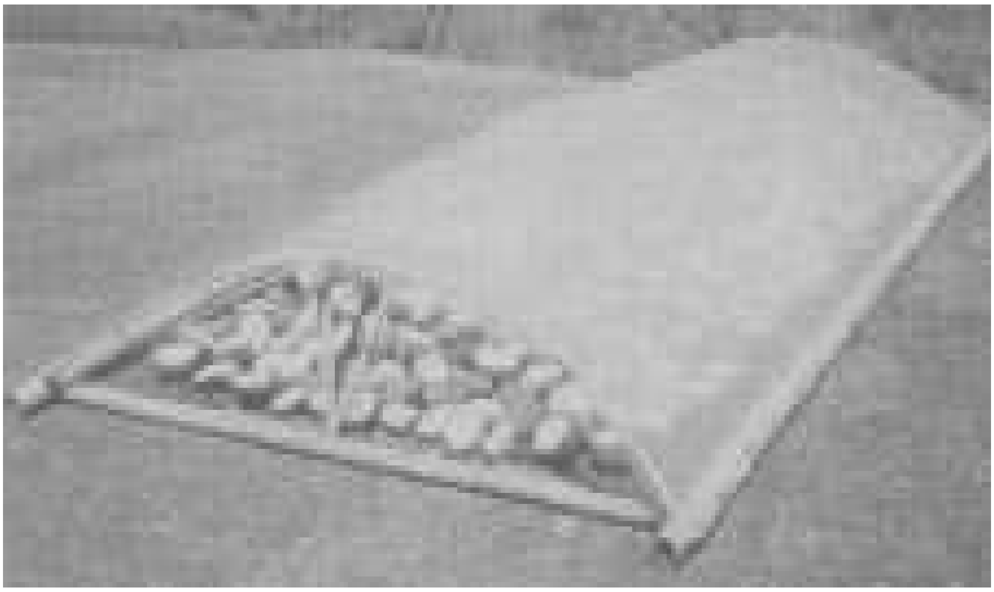


Figure 2.1: PGCP Coconut Drier. (Villaruel, 1996)

The cost of one drier is estimated as 15 US$, and replacement plastic will cost approximately 3US$ every two to three years. The frame can be constructed with local skills and materials. This PGCP solar drier was not actually adopted by farmers; they favored the indirect type coconut husk-fired natural draught PGCP copra dryer with a processing capacity of 2000 nuts per two days of operation.

2.5.2 Kenya Black Box Solar Drier

More than 90 “black box” solar driers were tested in Kenya from 1996-97 as part of a GTZ project. Although various factors hindered the success of the project, the driers were pronounced technically reliable and economically viable. Without any special promotion, individuals in other areas who knew of the black box drier project began their own drying activities. In addition to over 1 ton of mangoes; smaller amounts of guavas, papaws, bananas, vegetables, greens, and tomatoes were also successfully dried.

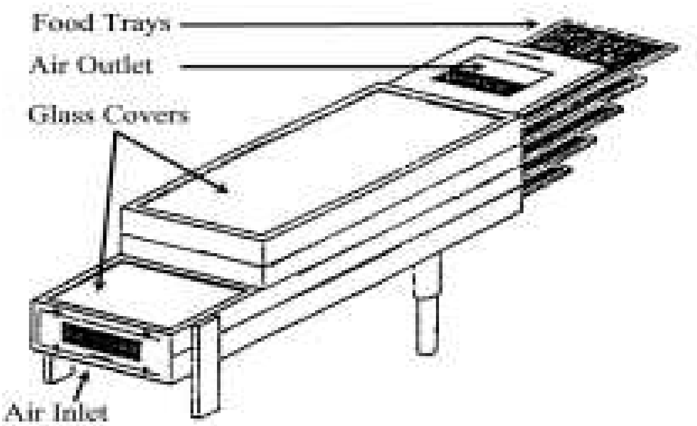


Figure 2.2: Kenya black box solar drier (Eckert, 1998)

The black box solar drier consisted of a heating chamber and a drying chamber, each with a glass cover to allow sunlight to enter. The glass traps the solar heat inside so that the drier temperature reaches up to 40℃ above ambi ent. The two glass tops together measure approximately 2m x 0.8m, for an effective collector area of 1.7m^2. Fresh air enters the heating chamber through a vent near the bottom of the drier. The heated air rises into the drier chamber and flows around the trays, absorbing moisture from the produce. Air exits near the top of the drying chamber through a wire-gauze covered vent.

The drying chamber holds food trays with wire gauze bottoms, each 1m^2. This is enough area to dry 15-20kg of fresh mangos per day in the Kenyan climate, resulting in approximately 0.5kg/day of dried product. Kenyan carpenters manufactured these driers in 1996 for 340 US$ each.

In the 1996-97 projects, mangos were sliced 1mm thick so that drying could be completed in one day. Drying was started early in the morning and trays were rotated every two hours for even drying. The slices were dry in late afternoon, and immediately stored in airtight containers.

Successful drying requires the drier to be exposed to bright sunlight and re-oriented throughout the day to keep the glass facing the sun. The black box solar drier can be appropriate for small-scale drying in areas with a climate conducive to solar drying with convection what (Mathew *et al*., 2001).

2.5.3. An intermittent solar dryer for cocoa beans

The experimental dryer was made mainly of wood and consisted of the following major components: the solar collector; the drying chamber and the heat storage chamber. An air duct connects the upper end of the solar collector to one end of the drying chamber; while, the other three sides were partitioned internally, 125mm wide, to form the heat storage chambers. The surfaces of the collector, the drying chamber and heat storage chambers were covered separately with glass doors. A five- speed axial flow fan is located inside the air duct to blow hot air during the period of insolation, drawing hot air from the solar collector and discharging onto the beans in the drying chamber. Consequently, the beans are dried by a combination of convective heating of the hot air and the direct radiation through the glass cover. The dryer was mounted on a wheeled frame made of 50×50×3 mm angle iron. The prototype was designed to hold a batch of 50kg of wet cocoa beans. The set up of the design is as in figure 2.3 below (Fagunwa *et al*., 2009).

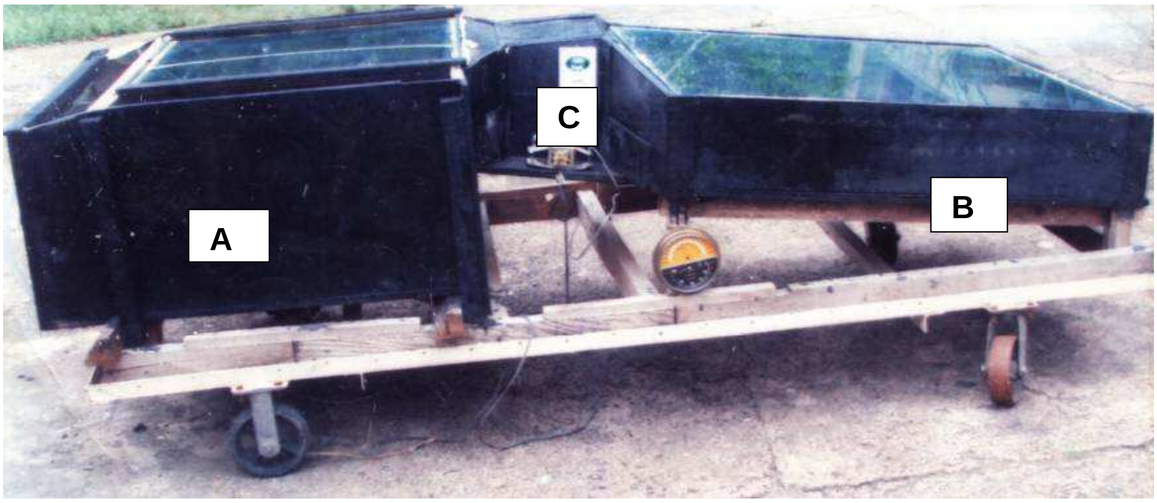


Figure 2.3: Picture of the design solar dryer: A, drying chamber; B, solar collector; C, fan housing (Fagunwa *et al*., 2009).

2.5.4 Simple Solar Maize Dryer

This typical Distributed Passive Solar Energy Dryer is made up of the following basic units:

- A drying chamber
- An air-heating solar energy collector, which consists of cover plate, absorber plate and insulator

It is designed in such a way that solar radiation is not incident directly on the maize, but preheated air warmed during its flow through a low pressure thermos phonic solar energy air heater or collector made up of an insulating material (polystyrene), absorber plate (aluminium) sheet painted black and a cover glass (5mm thickness) measuring 100mm x 50mm all arranged in this order contributed to the heating. The test results gave temperature above 45^{O}C in the drying chamber, and the moisture content of 50kg of maize reduced from 20% to about 12.5% moisture content wet basis in three days of 9 hours each day of drying (27hours drying time)

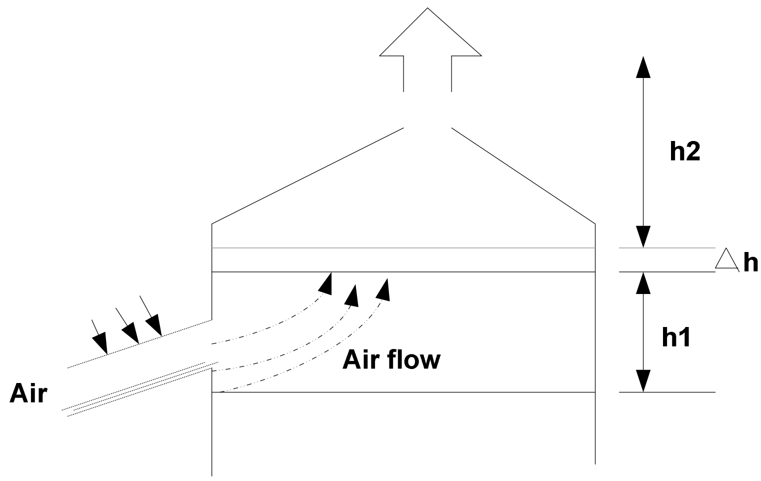


Figure 2.4: Representation of the Solar Maize Dryer (Joshua, 2008).

2.5.5 Performance evaluation of a v-groove solar air collector for drying maize

(Zea mays) in Iraq (Abdullah and Gatea, 2011)

A solar drying system was constructed, consisting of three parts (solar collector, drying chamber, and air blower). Solar collector having V-corrugated absorption plate of two air passes, a single glass cover was used. The total area of the collectors measeured 2.04

m². The dimension of the drying chamber were 1.06m, 0.66m and 0.56 m for width, depth, and height, respectively. 38 kg of corn were dried. The moisture content was reduced from 21% to 13% within four hours of drying. The drying air temperatures at the inlet of the dryer were found in the range of 30 to 45ºC when the range of ambient air temperature was from 8.5 to 20ºC and total solar radiation intensity was from 270 to 560 W/m^2. Increasing volumetric air flow rate from 0.025 to 0.030 m^3/s raises the daily solar collector efficiency by 3.25%, while increasing volumetric air flow rate from 0.030 to 0.035 m^3/s raises the solar daily collector efficiency by 11.11%. The drying rate is reduced with the decrease of moisture content. Efficiency of the collector is very much dependent on air flow rate.

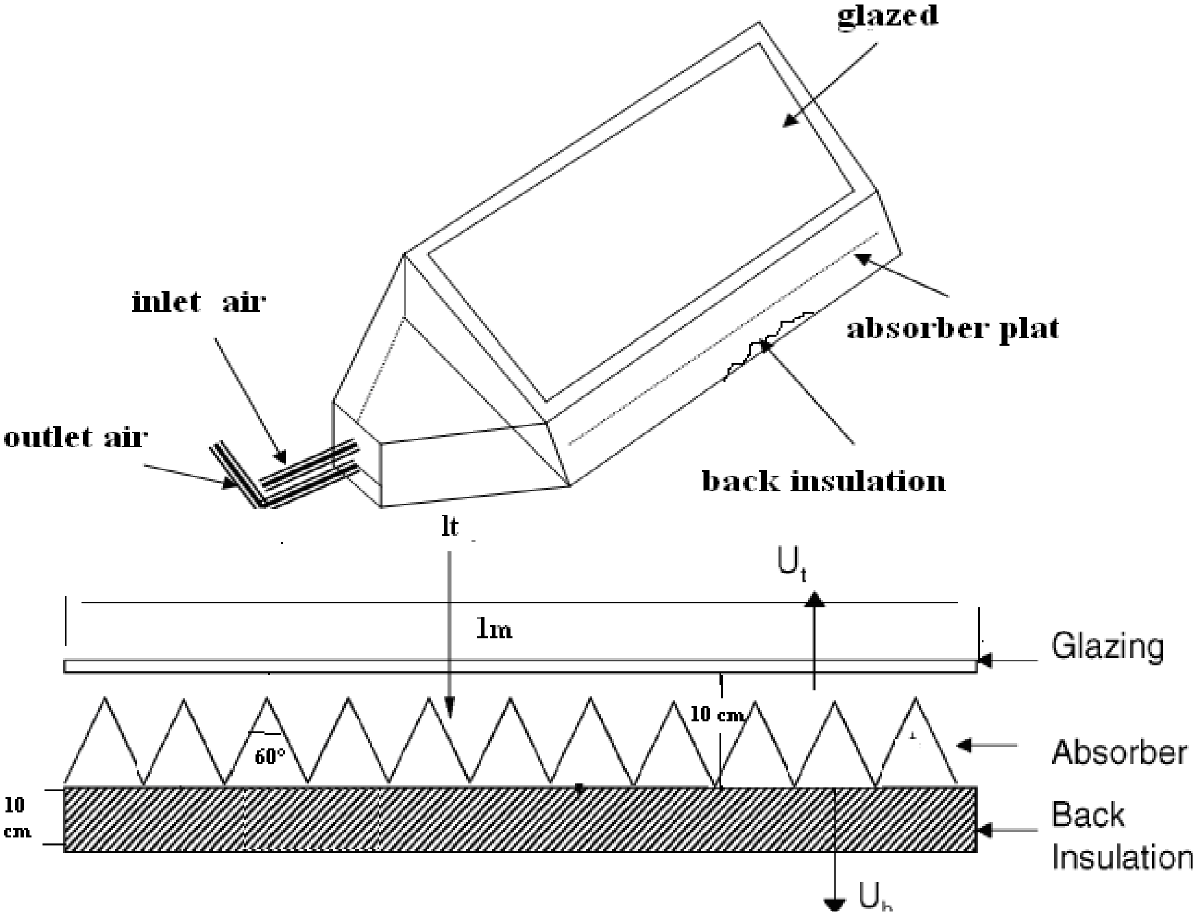


Figure 2.5: Isometric view and V-groove of the air solar collector
(Abdullah and Gatea, 2011).

2.6. Components of most common solar grain dryer

2.6.1. Solar collector.

Energy from the sun can be converted into solar power for thermal applications, such as to provide direct heat to air or liquid. Solar energy can be trapped more efficiently depending on the type of solar collectors used. Each type of solar collector is designed to absorb the shorter wavelengths of light which are received from the sun (0.3-2mm in length) but prevent heat wavelengths (2-10mm in length) from escaping by utilizing the greenhouse effect then delivers radiant energy either directly or indirectly to a working fluid. There are various types of solar thermal collectors that are normally used depending upon performance requirements: these include; Flat plate, evacuated tubes, and heat pipe tube.

Flat plate collectors have been extensively used than others. They are either corrugated, bond duct or tube-in-plate type with different clamping arrangements. The performance of the flat plate collector depends upon various design parameters, such as the number of covers, type and thickness of glazing, anti-reflecting coating on cover glass, heat mirror coating on the inner glass, the type of coating on the collector plate, spacing between the collector and the inner glass, an evacuated space between the collector and the inner glass, the arresting of convective movement between the collector plate and the inner glass by using transparent insulation material, and the type of insulation used. All these are responsible for the performance of a flat plate collector. There are several other operational parameters, such as the mass flow rate of fluid, solar radiation, inlet temperature, ambient temperature, wind speed, sky conditions, and dust deposition on glass cover which also affect the collector performance (Alghoul *et al*., 2005).

The most simple flat plate solar collector(or absorber) commonly used is often a dark colored box with a transparent cover. It raises the air temperature between 10 and 30℃ above ambient. This may be separate from the drier chamber, or combined (as with direct driers). Often the bottom surface of the absorber is dark top remote solar absorption. Glass is recommended for the absorber cover, although it is expensive and difficult to use. Plastic is acceptable if it is firm or supported by a rib such that it does not sag and collect water (Mathew *et al*., 2001).

Desirable features of solar thermal collector materials

- **Transparent cover**

This is used to cover the absorber. It protects the absorber together with the structure frame from adverse weather conditions like dust and rain from coming in contact with the absorber. It also retards the heat from escaping by acting as a heat trap for infrared (thermal) radiation (i.e. forming a confinement for heated air). Therefore, it reduces radiation losses and convection to the atmosphere.

The most common materials used for cover plates are glass, flexi glass, fibreglass, reinforced polyester, thin plastic films and plastics (Joshua, 2008). The cover properties includes ability to transmit incoming shortwave solar irradiation while transmitting none of the longwave radiation emitted by the absorber

- **Absorber**

This can be made of metallic or other materials but painted black to absorb the incident solar radiation transmitted by the cover thereby heating the air between it and the cover. In most cases the corrugated or v-grooved absorbers are used to improve the heat transfer coefficient between the absorber plate and the air as well as increasing the absorption of solar radiation.

- **Insulation**

This prevent the loss of thermal energy at the bottom and on the sides of the collector hence minimize overall heat loss from the system. It is placed under the absorber plate. The insulator must be able to withstand stagnation temperature, fire resistant and not subject to out-going gassing and should not be damaged by moisture or insect.

Insulating materials are usually fibreglass, mineral wool, Styrofoam and urethanes, but selective grade of CFC free polyurethane foam (PUF) as insulation material ensures superior performance with minimum heat loss (Joshua, 2008).

2.6.2 Drying chamber/ Compartment

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

2.6.3 Air flow system

There are two types of airflow that take place in most of the solar dryers that utilizes the aspect of solar collector, namely: Natural and forced convention.

a) Natural convection

This utilizes the natural principle that hot air rises. The effects of natural convection may be enhanced by the addition of a chimney in which exiting air is heated even more. Natural convection driers require careful use; stacking the product too high or lack of sun can cause air to stagnate in the drier and halt the drying process

b) Forced convection

In forced convection air is forced through the drying chamber with artificial means like fans or turbo-ventilator. The use of forced convection can reduce drying time by three times and decrease the required collector area by 50%. Consequently, a drier using fan may achieve the same throughput as a natural convection drier with a collector six times as large (Matthew *et al*., 2001).

It is necessary to have a fan in the drying system in order to maximize the drying quality and to minimize drying time. The airflow should be variable, so that an optimal drying temperature may be reached. This fan should be of low power consumption which may be driven by a solar cell panel or a small generator driven by a motor.

- **Fan system**

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

- **Turbo-ventilator**

This create a draught that enables heated air to flow upward in the solar collector, pass through the food stuffs arranged in trays taking out the moisture from the food.

Wind driven turbo ventilators are used all over the world because of their low capital and installed cost, adaptability, high capacity per vent, and overall reliability. Operation is simplicity in itself. As the vent hood is rotated by the wind, the saturated inside air is exhausted through the vanes and the natural inward flow of heated air from the collector is boosted.

2.6.4 Chimney

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

2.6.5 Biomass back up heater

In case of low solar irradiation during the day or if there is intention of reducing drying time or ensuring night drying process, the drying process can be backed up by a biomass heater.

Biomass (especially fuelwood) is a dominant source of energy, and commonly burned using inefficient technologies in most developing countries.As long as this resource is harvested sustainably; it can provide the required backup thermal energy for solar drying in developing countries (Madhlopa *et al*., 2007).

If biomass heater is used as backup fuel for cloudy days and night operations then the payback period of the dryer is reduced.

This heater is necessary to have a flue gas chimney to be discharging the flue gas behind the drying chamber to prevent filtration of smoke into the drying chamber. Consequently, the height of the flue gas chimney should be set to an appropriate height.

2.7 Recent work on maize dryers using a pre-heater

Onigbogi *et al*, (2012) presented the design and construction of a domestic passive solar dryer.The dryer is composed of solar collector (air heater) and a solar drying chamber constraining rack of three cloth (net) trays both being integrated together. The air allowed in through air inlet is heated up in the solar collector and channeled through the drying chamber where it is utilized in drying the maize. The design was based on the geographical location of Abeokuta (7.15°N and 3.35° E) and meteorological data was obtained for proper design specification.

The dimensions of the dryer so designed are 94cm x 45cm x 101cm (length x width x height). Locally available material were used for the construction, chiefly comprising of wood (gmelina), glass, aluminum metal sheet, copper and net cloth for the trays. The optimum temperature of the dryer was 50.50°C with a corresponding ambient temperature of 34.50° C. The moisture content removal of 43.2% and 40.6% in maize and plantain respectively using the solar dryer was achieved against 28.2% and 27.89% in maize and plantain respectively. using the sun drying method and indication 15.0% and 12.71% difference respectively, The rapid rate of drying in the dryer reveals its ability to dry food items reasonable rapidly to a safe moisture.

2.8 Proposed maize solar dryer design distinguishing features

Previous research efforts has been focused on designing and constructing simple natural and convection solar dryer to serve the remote areas of most African countries not connected to the national electric grid and with no capacity to access alternative sources of energy which are far much too expensive. The use of solar technology has often been preferred for the drying to reduce energy costs and economically speed up drying which would be beneficial to final quality of product. In Africa, Nigeria and Ghana have shown a lot of activity in the field of solar dryers compared to Kenya.

The recent solar dryer design by Onigbogi *et al*, (2012) is a mixed mode type which entirely depends on the solar energy unlike the proposed design which is integrated to a biomass heater to allow for night and all weather drying. This makes the current design more efficient and a reliable drying method.

Our designed maize dryer used used the same principles of design followed by the recent solar dryer designs done world over. The design is aimed at addressing food crop drying challenges within Kenya and its environs with similar meteorological conditions as Mau summit region.

2.9 Overview of Solar Dryer designs

The following points are considered generally in design of direct natural / forced convection solar dryer system:

a) The amount of moisture to be removed from a given quantity of maize grain.
b) Harvesting period during which the drying is needed.
c) The daily sunshine hours for the selection of the total drying time.
d) The quantity of air needed for drying.
e) Daily solar radiation to determine energy received by the dryer per day.
f) Wind speed for the calculation of air vent dimensions.

2.10 Similtude Criteria

The characteristics of an enclosed air-jet have been studied by using prototype system, scale-models, and numerical simulation. However, a precise mathematical model is impossible for the extremely complex microstructure of room airflow. Model tests will always be required if the prototype is not available and no precise mathematical–physical prediction model is established. Model studies are practical for simulating the behavior of a prototype and can be used to validate a numerical simulation. Similitude, or the relation between a model and prototype, is an important issue when using model studies. The similitude criterion between a model and prototype is important to guarantee that the experimental results of the model can be used to predict the behavior of the prototype. (Yu *et al,* 1999, 2006).

Complete similitude of the Isothermal airflow field between the model and prototype must satisfy the geometric similitude, kinematic similitude, dynamic similitude, and all boundary conditions.

Only partial similarity between the model and prototype could be satisfied because most of the dimensionless parameters affecting airflow performance have equal importance in most of the realistic problems.

The traditional method for investigating similitude requirements uses dimensional analysis and the Buckingham Pi theorem. Only knowledge of variables related to the problem of interest are required. The risk with this method, however, is that if one or more important variable is neglected, serious mistakes of model design could result (Yu and Hoff, 1999).

A more sophisticated method of similitude analysis is derived from governing differential equations and the associated initial and boundary conditions. This method gives necessary Pi terms directly and is a more rigorous statement of similitude.

Reynolds number (Re), has been widely used as the similitude criterion for an isothermal airflow in an enclosure, but experimental results do not always show that the Reynolds number is the appropriate similitude criterion. Jet momentum ratio (Rm), which is defined as the ratio of inertia force and total drag due to viscous shear at the walls of the enclosure has been validated as an appropriate similitude criterion through recent experiments, but Rm in m^2/s^2 is a dimensional parameter and is not a valid criterion since a similitude parameter must be dimensionless (YU *et al,* 2006).

2.10.1 Similitude parameters

The dimensionless similitude parameters derived from the governing differential equation approach for isothermal conditions follow:

Froude number:

$$F_r = \frac{V}{\sqrt{g \,.L}} \tag{2.1}$$

Where, Fr, is the ratio of inertial to gravitational forces.

V, is the characteristic velocity of flow

g is gravitational acceleration

L is characteristic length of flow

Similarity requires:

$$\frac{V_m}{\sqrt{g_m l_m}} = \frac{V}{\sqrt{gl}} \tag{2.2}$$

$g_m = g$ results in a relation between diffuser air speed as:-

$$\left(\frac{Vm}{V}\right) = \left(\frac{\sqrt{Lm}}{\sqrt{L}}\right) = \lambda^{-1} \tag{2.3}$$

Where, λ is the geometric scaling between the model and prototype.

- **Euler number:**

$$\mathrm{Eu} = \frac{\mathrm{Po}-\mathrm{Pd}}{\frac{1}{2}\rho V^2} \tag{2.4}$$

Euler number represents the ratio of pressure to momentum forces, similarity requires that:-

$$\left(\frac{\mathrm{Po}-\mathrm{Pd}}{\frac{1}{2}\rho V^2}\right)_m = \left(\frac{\mathrm{Po}-\mathrm{Pd}}{\frac{1}{2}\rho V^2}\right) \tag{2.5}$$

If the same working fluid between the model and prototype is used, then $\rho m = \rho$ and the relations simplifies to:

$$\left(\frac{\mathrm{Po}-\mathrm{Pd}}{V^2}\right)_m = \left(\frac{\mathrm{Po}-\mathrm{Pd}}{V^2}\right) \tag{2.6}$$

Where, ρ is the density of the fluid.

Po is the upstream pressure.

Pd is the downstream pressure.

V is a characteristic velocity of the flow.

If pressure difference between inlet and outlet are the same between model and prototype, the relation further simplifies to:

$$Vm = V \tag{2.7}$$

- **Reynolds number:**

$$\mathrm{Re} = \frac{\rho V L}{\mu} \tag{2.8}$$

Re represents the ratio of inertia to viscous forces, Similarity between model and prototype requires:

$$\left(\frac{\rho VL}{\mu}\right) m = \left(\frac{\rho VL}{\mu}\right) \quad (2.9)$$

Where,

V is the mean velocity of the fluid

μ is the dynamic viscodity of the fluid.

ρ is the density of the fluid

L, is characteristic length

If the same working fluid between model and prototype is used, then $\rho m = \rho$ and $\mu m = \mu$, resulting in the following requirements between diffuser air speeds:

$$\left(\frac{Vm}{V}\right) = \left(\frac{L}{Lm}\right) = \lambda \quad (2.10)$$

Where, λ is the geometric scale between prototype and model.

- **Jet Momentum Ratio, *Rm*:**

Using Rm as the similitude criterion results in the design condition of scaling law between the model and prototype (denoted by subscripts *m* and *p*) as

$$\left(\frac{hu^2{}_d}{L+H}\right)m = \left(\frac{hu^2{}_d}{L+H}\right)p \quad (2.11)$$

Where *H* is the enclosure height in m

L is the enclosure length in m

u_d is the air jet velocity at the diffuser in m/s

As $$\left(\frac{h}{H+L}\right) m = \left(\frac{h}{H+L}\right) p \quad (2.12)$$

then:

$$(u^2{}_d)\, m = (u^2{}_d)\, p \quad (2.13)$$

or

$$(u_d)\, m = (u_d)\, p \tag{2.14}$$

Using *Eu* as the similitude criterion will result in the same design condition

2.10.2 Scaling Model

Similarity analysis indicates that similarity parameters for isothermal airflow were *geometry, Froude number, Euler number, jet momentum ratio* and *Reynolds number* between model and prototype. Froude is important for compressible flow and for motions with free liquid-vapor surfaces in the flow. The isothermal airflow in a slot-ventilated enclosure is considered as a homogeneous fluid without free liquid-vapour surfaces, thus the froude number was not considered.

The remaining similarity parameters require higher inlet airspeed in the model based on Reynolds number but the same inlet airspeed between the model and prototype based on both Euler number and jet momentum ratio. (YU e*t al,* 2006).

Therefore, the Euler number and jet momentum ratio were used to relate the prototype and the model in order to achieve kinematic and dynamic similarities. Geometric similarity were obtained by scaling the linear dimensions by a constant ratio between the model and prototype

CHAPTER THREE

3.0 THEORETICAL FRAMEWORK

3.1 Total solar radiation and useful heat gained by dry air leaving the collector

Due to the elliptical orbiting of the earth around the sun, the distance between the earth and the sun fluctuates annually and this makes the amount of energy received on the earth's surface (**I'_{sc}**) to vary in a manner given by Equation. 3.1

$$I'_{sc} = I_{sc} * \{1 + 0.033\cos\left(\frac{360n}{365}\right) \qquad (3.1)$$

Where I_{sc} is the solar constant which is valued at 1367 W/m^2 and n is the day of the year which varies from n = 1 to n = 365.

The direct solar radiation, I_b, reaching a unit area of a horizontal surface in the absence of atmosphere can be expressed as in Equation. 3.2.

$$I_b = I'_{sc}\{\sin(\varphi - \beta)\sin\delta + \cos\delta\cos\omega\cos(\varphi - \beta)\} \qquad (3.2)$$

where φ is latitude (degrees), β is angle of inclination of surface from horizontal (degrees), *δ* is angle of declination (degrees) and *ω* is hour angle (degrees).

The angle δ; (angle between the sun's direction and the equatorial plane) is evaluated from the Equation (3. 3).

$$\delta = 23.45\sin\left\{360\left(\frac{284+n}{365}\right)\right\} \qquad (3.3)$$

On the other hand, ω is computed by Equation (3.4a),

$$\omega = 15\ (12 - H_r) \qquad (3.4a)$$

where H_r is the hour of the day in 24 hour time.

- **Length of the day, N**:

The length of the day, N (hours) is given by:

$$N = ({}^2/_{15})\cos^{-1}(-\tan\varphi\tan\delta) \qquad (3.4b)$$

Where; φ is latitude (degrees) and δ is angle of declination (degrees)

- **The diffuse radiation, I_d.**

This is that portion of solar radiation that is scattered downwards by the molecules in the atmosphere. During clear days, the magnitude of I_d is about 10 to 14% of the solar radiation received at the earth's surface. I_d can be estimated as direct radiation incident at 60^o on the collector surface by Equation (3.5),

$$I_d = CI_b \cos 60^o = 0.5CI_b \quad (3.5)$$

where C is the diffuse radiation factor.

- **The total solar radiation, I_T,**

I_T incident on the horizontal surface is therefore given by adding the direct and diffused components of solar radiation as shown in Equation (3.6). The total solar radiation is of great importance for solar dryers since it captures the required components of solar energy that is harnessed in the dryer ((Ezekoye *et al*., 2006).

$$I_T = I_b(1 + 0.5C). \quad (3.6)$$

3.1.1 The energy balance on the solar collector

The energy balance on the absorber is obtained by equating the total heat gained to the total heat lost by the heat of the solar collector. Therefore, absorber

$$I_T A_c = Q_u + Q_{cond} + Q_{conv} + Q_R + Q_\rho \quad (3.7)$$

Where:

I_T= rate of total radiation incident on the absorber's surface (Wm^{-2});
A_c = collector area (m^2);
Q_u= rate of useful energy collected by the air (W);
Q_{cond}= rate of conduction losses from the absorber (W);
Q_{conv}= rate of convective losses from the absorber (W);
Q_R = rate of long wave re-radiation from the absorber (W);
Q_ρ= rate of reflection losses from the absorber (W).

The three heat loss terms Q_{cond}, Q_{conv} and Q_R are usually combined into one-term (Q_L), i.e.,

$$Q_L = Q_{cond} + Q_{conv} + Q_R \tag{3.8}$$

If **τ** is the transmittance of the top glazing and I_T is the total solar radiation incident on the top surface, therefore,

$$IA_c = \tau\, I_T A_c \tag{3.9}$$

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

$$Q_\rho = \rho \tau I_T A_c \tag{3.10}$$

Where; ρ is the reflection coefficient of the absorber. Substituting Equations (3.8), (3.9) and (3.10) into Equation (3.7) yields:

$$\tau I_T A_c = Q_u + Q_L + \rho \tau I_T A_c, \qquad \text{or}$$

$$Q_u = \tau\, I_T A_c\, (1 - \rho) - Q_L.$$

For an absorber $(1 - \rho) = \alpha$ and hence,

$$Q_u = (\alpha\tau) I_T A_c - Q_L \tag{3.11}$$

Where

α is solar absorptance.

Q_L composed of different convection and radiation parts. It is presented in the following form (Bansal *et al*., 1990):

$$Q_L = U_L A_c\, (T_c - T_a) \tag{3.12}$$

Where:

U_L = overall heat transfer coefficient of the absorber ($Wm^{-2}K^{-1}$);

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

T_a = ambient air temperature (K).

From Equations (3.11) and (3.12) the useful energy gained by the collector is expressed as:

$$Q_u = (\alpha\tau) I_T A_c - U_L A_c (T_c - T_a) \tag{3.13}$$

Therefore, the energy per unit area (q_u) of the collector is

$$q_u = (\alpha\tau)I_T - U_L(T_c - T_a) \quad .(3.14)$$

If the heated air leaving the collector is at collector temperature experimentally, the heat gained by the air, Q_g is:

$$Q_g = \dot{m}_a C_{pa} (T_c - T_a), \quad (3.15)$$

Where:

$\dot{m}_a$ = mass of air leaving the dryer per unit time (kgs^{-1});

C_{pa}= specific heat capacity of air ($kJkg^{-1}K^{-1}$).

The collector heat removal factor, F_R, is the quantity that relates the actual useful energy gained of a collector, Q_u Equation. (3.13), to the useful gained by the air, Q_g Equation (3.15). Therefore,

$$.FR = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{(\alpha\tau)I_T A_c - U_L A_c(T_c - T_a)} \quad (3.16)$$

Therefore, $Q_g = A_c F_R[(\alpha\tau)I_T - U_L A_c(T_c - T_a)]$. (3.17)

The steady state thermal efficiency of the solar air collector,η_c is given by Hottel–Whillier–Bliss equation 3.18 (Forson *et al*, 2007) defined as the ratio of useful energy gained by the air in the collector to solar radiation incoming to the collector (Itodo *et al*., 2002):

$$\eta_c = \frac{Q_g}{I_T A_c} \quad (3.18)$$

Where; Q_g= heat gained by air in the collector.

A_c = Area of the collector (m^2);

I_T = Average solar insolations (KJ/s),

3.1.2 Energy Balance Equation for the Drying Process

The total energy required for drying a given quantity of grains can be estimated using the basic energy balance equation for the evaporation of water;

$$m_w L_v = m_a C_p(T_1 - T_2) \quad (3.19)$$

Where:

m_w= mass of water evaporated from the food item (kg);

m_a= mass of drying air (kg);

T_1 and T_2 = initial and final temperatures of the drying air respectively (K);

C_p= Specific heat capacity of air at constant pressure ($kJkg^{-1}K^{-1}$).

L_v= Latent heat of Vaporization of Water ($kJkg^{-1}K^{-1}$).

- **Moisture Content (M.C.):**

The moisture content is given as:

$$MC\ (\%) = \left(\frac{M_i - M_f}{M_i}\right) \times 100\% \text{ ; wet basis} \qquad (3.20)$$

Where;

M_i= mass of sample before drying and

M_f= mass of sample after drying.

- **The mass of water evaporated or moisture loss**

This can be obtained using Equation. 3.21 or 3.22:

$$m_w = \frac{m_i(M_i - M_e)}{100 - M_e} \qquad (3.21)$$

Where:

m_i= initial mass of the food item (kg);

M_e = equilibrium moisture content (% dry basis);

M_i= initial moisture content (% dry basis).

Also this can still be obtained by using equation 3.22

$$m_w = (m_i - m_f) \qquad (3.22)$$

Where;

m_i is the mass of the sample before drying and

m_f is the mass of the sample after.

During drying, water at the surface of the substance evaporates and water in the inner part migrates to the surface to get evaporated. The ease of this migration depends on the porosity of the substance and the surface area available. Other factors that may enhance quick drying of food items are: high temperature, high wind speed and low relative humidity.

- **Average drying rate**

Average drying rate, M_{dr}, is determined from the mass of moisture to be removed by solar heat and drying time by the following equation (3.23):

$$M_{dr} = \frac{m_w}{t_d}. \tag{3.23}$$

Where:

m_{dr} = average drying rate, kg/hour; m_w = mass of water evaporated and t_d = overall drying time

- **The mass of air needed for drying** is calculated using equation given as follows:

$$\dot{m}_a = \frac{M_{dr}}{[W_f - W_i]} \tag{3.24}$$

3.1.3 Drying process mechanisms

Producing safe, high quality dried produce requires careful procedures throughout the entire preservation process. incorrect drying can dramatically degrade food and brings the risk of food poisoning. Therefore all adjustments must be constantly controlled to achieve appropriate drying.

The whole drying process is illustrated as shown on the psychometric chart and a flow diagram.

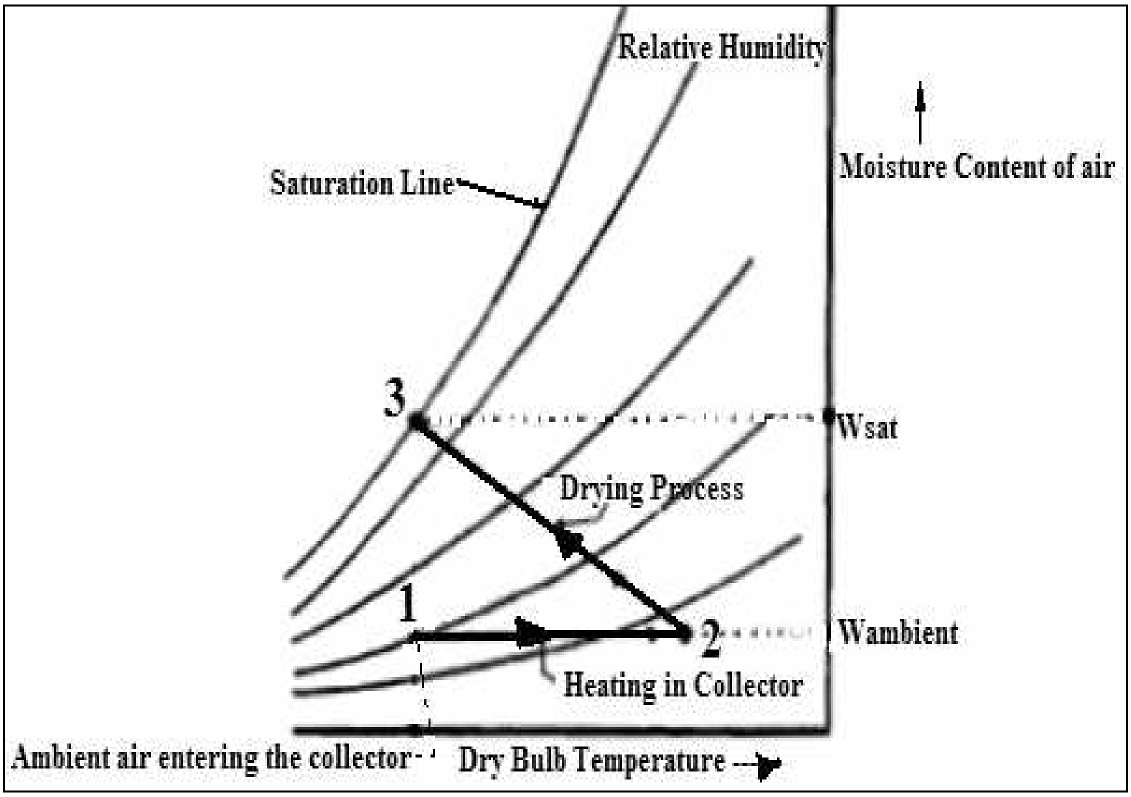


Figure 3.1: Drying Process on Psychometric Chart (Kudal *et al.,* 2009).

3.1.4 Dryer or drying process efficiency therefore is given as;

$$\eta_{syst} = \frac{(M_W \times L_v) + (M_g \times Cp_g \times \Delta T)}{Q_a} \tag{3.25}$$

Where;

$Q_a = M_a Cp_a (T_{\text{into drying chamber}} - T_{\text{ambient temperature}})$,

M_w = mass of evaporated water,

L_V= latent heat of vaporization,

M_g = mass of the grains dried,

Cp_g = specific heat capacity of the grains and

ΔT = change in temperature of the chamber.

(Ezekoye *et al*., 2006),

3.1.5 Biomass heater efficiency

The overall thermal efficiency of the heater can be defined as the ratio of useful heat transferred to the drying air to the energy potential of fuel (Bena& Fuller, 2002). This efficiency is a product of the combustion efficiency and the efficiency of heat transfer to the air. In this project an overall efficiency of the heater, was calculated as:

$$\eta_{over} = \frac{heat\ transfered\ to\ air\ entering\ the\ drying\ chamber}{calorific\ value\ of\ biomass\ used} \qquad 3.26$$

3.2 Solar dryer pertinent parts design

a) Solar collector area

From the total useful heat energy required to evaporate moisture and the net radiation received by the collector, the solar drying system collector area A_c, in m^2 can be calculated from the following equation:

$$A_c I_T \eta = E = m_a(h_f - h_i)t_d \qquad (3.27)$$

Therefore, area of the solar collector is:

$$A_c = E/I_T\eta \qquad .(3.28)$$

Where

E is the total useful energy received by the drying air, kJ;

I_T is the total global radiation on the horizontal surface during the drying period, in kJ/m^2

η_c is the collector efficiency, which is assumed to be in the range of 30 to 50% (Sodha *et al.*, 1987).

b) Collector Air duct depth:-

The determination of the air duct depth is to some extent an iterative procedure.The overall depth of the collector air duct channel "*s*" is calculated and if this proves suitable for the desired mass flow rate and the average value of the velocity of air inside the collector, the value is acceptable. Otherwise, some or all the estimated / assumed values are altered and/or the space configurations of the solar collector are altered to achieve the desired value of "*s*" subject to all the constraints imposed on the design.

Following from the continuity equation, for one-dimensional steady flow the weighted average velocity at the exit of the solar collector is related to the channel overall cross-section by the relation

$$V_c = \frac{V_a}{sW}. \qquad (3.29)$$

Where;

V_c is the maximum collector outlet velocity under natural air circulation conditions, in m/s

Va is the volumetric flow in m^3/s

W is the width of the collector in m

c) Absorber Surface Area

The surface area of the absorber A_{ab} is approximately equal to the area of the collector surface area, A_c; this is related to the length, L_c and width, W of the solar collector as follows:

$$A_{ab} = A_c = L_c \times W. \tag{3.30}$$

d) The amount of moisture to be removed from the product, m_w [kg] is calculated using the following equation:

$$m_w = m_p \frac{(M_i - M_f)}{(100 - M_f)} \tag{3.31}$$

Where;

m_p[kg] is the initial mass of product to be dried;

M_i [%] and M_f [%] wet basis are the initial moisture content and the final moisture content, respectively.

e) Final relative humidity or equilibrium relative humidity, ERH [%] of moist air at the exit of drying process can be calculated using sorption isotherms equation given as follows

$$a_w = 1 - exp[-exp(0.914 + 0.5639 lnM)] \tag{3.32a}$$

$$M = \frac{M_f}{(100 - M_f)} \tag{3.32b}$$

$$ERH = 100 a_w \tag{3.32c}$$

Where a_w is the water activity; M [kg_w/kg_S] dry basis.

f) The mass of air needed for drying is calculated using equation given as follows:

$$\dot{m}_a = \frac{m_w}{t_d[W_f - W_i]} \tag{3.33}$$

Where:

m_w = amount of moisture to be removed, kg

w_f and w_i = final and initial humidity ratio, respectively, kg H_2O/kg dry air

t_d = total drying time, hrs

g) The quantity of heat required to evaporate the water would be:

$$E = m_a (h_f - h_i)\, t_d \tag{3.34}$$

Where:

E = total heat energy, kJ

m_a = mass flow rate of air, kg/hr

h_f and h_i = final and initial enthalpy of drying and ambient air, respectively, kJ/kg_{da} read using psychometric charts

t_d= drying time, hrs

h) Average drying rate

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

$$m_{dr} = \frac{m_w}{t_d} \tag{3.35}$$

i) Sizing of the dryer chamber

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

$$L_{dc} = \frac{A_{dc}}{W} \tag{3.36}$$

j) Area of Drying bed

The effective drying bed area A_{db} is obtained from first principles by relating the solid density of the wet material to its mass and the corresponding volume as

$$A_{db} = \frac{W_W}{\rho_{gr} h_L \xi (1 - \varepsilon_V)} \tag{3.37}$$

Where;

W_W is the mass of the crop to be dried,

ρ_{gr} the bulk density of the crop on wet basis,

h_L the layer drying bed thickness,

ξ, the crop porosity,

ε_v the loading bed void fraction.

k) Air vent dimensions:

The air vent is calculated by dividing the volumetric airflow rate by wind speed:

$$A_v = \frac{V_a}{V_W} \tag{3.38}$$

Where;

$A_{v,}$ is the area of the air vent, m^2,

$V_{w,}$ wind speed, m/s.

The length of air vent, L_v will be equal to the length of the dryer. The width of the air vent can be given by:

$$B_v = \frac{A_v}{L_v} \tag{3.39}$$

Where;

B_v is the width of air vent, m

l) Pressure drop through the drying bed

The resistance to the flow of air through a packed bed of agricultural produce is expressed in the form.(Jindal *et al.* 1978; Forson 2007).

$$u = a\,(\Delta \frac{P_B}{hL}) \tag{3.40}$$

where;

u is the superficial air velocity,

$\boldsymbol{h_L}$ the drying bed thickness and

a is a constant whose value is determined experimentally.

For natural circulation of air through a thin layer of crop ($h_L \leq 0.20$ m), the value of the constant is $0.465 m^3 s/kg$.

The total pressure drop across the solar collector and the air vent is comparable to that across the drying bed, and hence the total pressure drop of the system is approximately twice the pressure drop of the drying bed. Hence, ($\Delta P_T = 2(\Delta P_B)$). When all pressure drops are accounted for, experience has shown that, the gross pressure drop is about six times the value of ΔP_T (Forson *et al* 2007). and given by relation:

$$\Delta P_T = 6 \times \{2\Delta P_B\} \tag{3.41}$$

m) Height of the hot air column

The height of the hot air column is the minimum height of the exit vents above the collector inlet for moist air escape to the ambient under air circulation by natural convection. In arriving at the height of the air column, it is assumed that the dryer functions under steady state conditions. It is further assumed that:

- The depth of the drying bed, h_L, is small compared to height, H, of the hot air column
- The whole structure is air tight and ambient air enters through the inlet and the moist warm air escapes through the exit vent(s).
- The steady state average values of the temperature and density of the hot air inside the dryer are T_{dryer} and ρ^*, respectively.

Applying Bernoulli's equation between the relevant sections of the dryer and simplifying
the resulting expressions leads to the relation

$$H = \frac{\Delta P_T}{g(\rho_a - \rho^*)} = \frac{\Delta P_T R}{g(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}})P_a} \tag{3.42}$$

Where;

ΔP_T is the total pressure drop in the dryer in Pa

R is the gas constant = 0.291kPa m^3/kgK

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

$T_{ambient}$ is the temperature of ambient air in Kelvin

g is the gravitational acceleration in M/s^2

P_a is the atmospheric pressure = 101.3kPa

CHAPTER FOUR

4.0 MATERIALS AND METHODS

4.1 Study Area

Mau-summit is located in Nakuru County; Kenya and situated in latitude and longitude of 0.18^{o} S and 35.62^{o}E, respectively with a mean air speed of 2.2 m/s, average annual rainfall of 74mm and cloud cover of 26% . The measured monthly mean values of minimum and maximum temperature, global radiation on horizontal surface and relative humidity of Mau-Summit in Nakuru County were collected from the archives of the Kenyan Meteorological Department (KMD) as shown in Appendix A5.4.

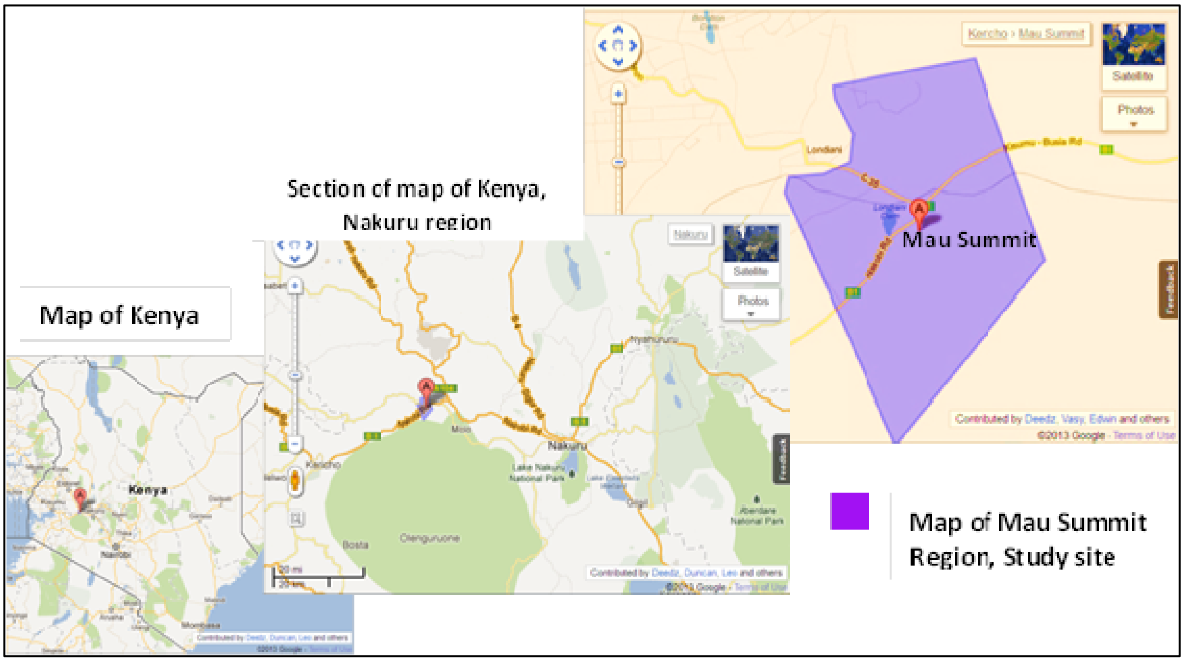


Figure 4.1: Google map of Kenya and the study site, Mau Summit region. (Google Earth)

4.2 Solar maize grain dryer fundamental design considerations

The size of the dryer was determined as a function of the drying area needed per kilogram of maize grain. The drying temperature was established as a function of the maximum limit of temperature the grain might support. From the climatic data of study area as in (appendix A5.4) the mean average day temperature for September to December is 26ºC and relative humidity is 72 %. Hence, from the psychometric chart the humidity ratio is 0.015 kg_{wv}/kg_{da}. The maximum allowable drying temperature of maize grain without compromising its quality was maintained at 50ºC and final moisture content of maize grain for safe storage at 13 % wet basis.

To carry out design calculations and size of the dryer, the design conditions applicable to mau-summit were considered. Information regarding the type of crop to be dried, loading densities acceptable, the crop characteristics and the quantity per batch were needed with data concerning the geographical location of the dryer and climatic conditions during the harvest period. The conditions, assumptions and relationships summarized in Table 4.1 were used to calculate the design parameters of the solar maize grain dryer.

Table 4.1. Design Specification and Assumption

No.	Items	Condition and assumption
1	Location	Mau-summit (latitude 0.18^{o}S and longitude 35.62^{o}E)
2	Crop	Maize Grain
3	Crop Porosity, ξ	0.42
4	Bulk Density, ρ_{gr} [kg/m^3]	721
5	Loading bed void fraction, ε_v	0.70
6	Drying period	September to December
7	Drying per Batch; Loading rate, m_g [kg/batch]	100
8	Initial moisture content, M_i [%] w.b	21
9	Final moisture content, M_f [%] w.b	13
10	Ambient air temperature, t_{am} [^{o}C]	26
11	Ambient relative humidity, RH_{am} [-],	0.72
12	Maximum allowable temperature, t_{max} [^{o}C]	50
13	Drying time (sunshine hours) t_d [hrs]	6
14	Incident solar radiation, I_T [MJ/m^2/day]	21.60
15	Wind speed, w_s [m/s]	2.2
16	Collector efficiency, η_c [%]	50
17	Average thickness of grain, th_m[mm]	9.13
18	Vertical distance between two adjacent trays, d [cm]	15
19	Collector tilt angle, [^{o}]	0°

Sources of figures: Measurements and assumptions

4.3 Solar dryer Additional design constraints

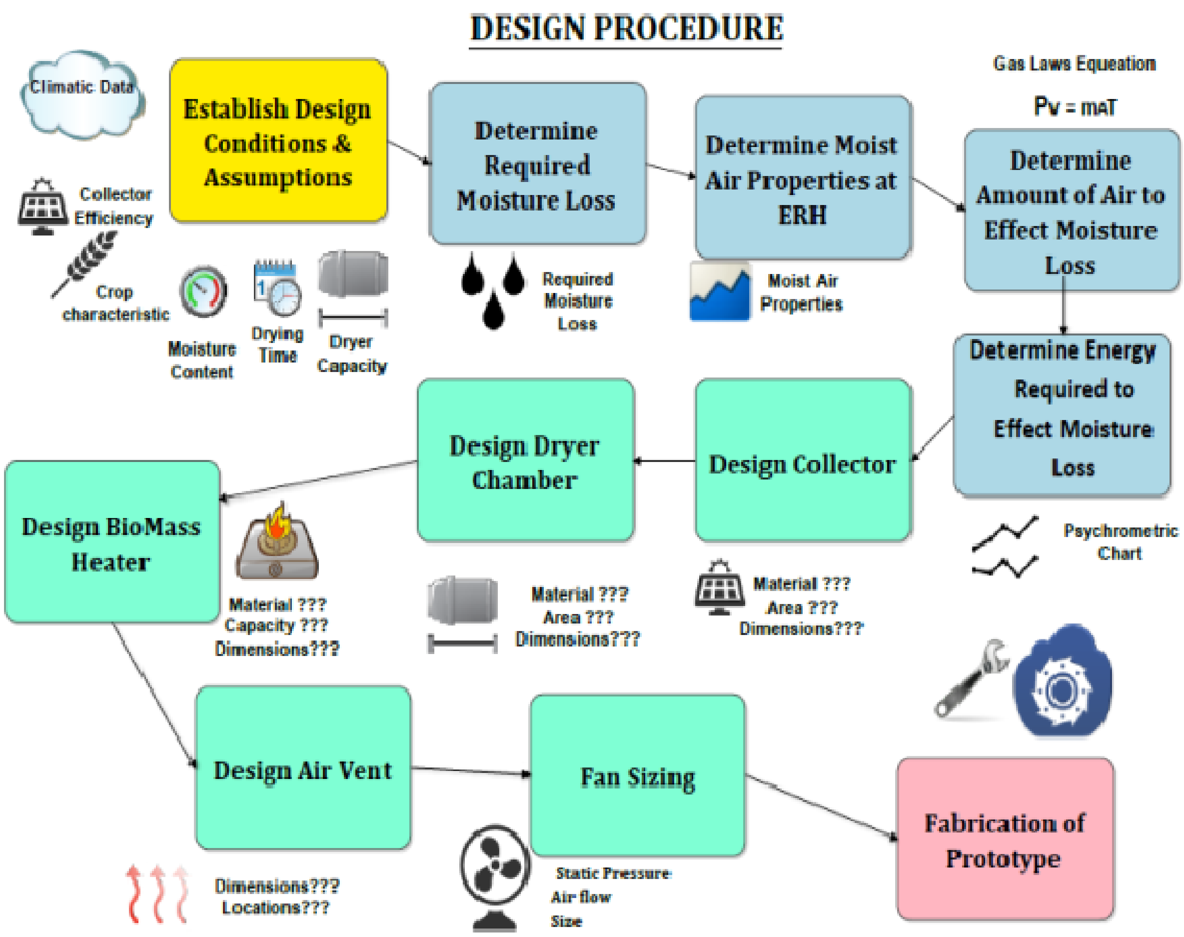
According to Forson *et al.,* (2007), the design constraints which applies to natural and forced convection dryer includes the following:

1. For airflow by natural convection, the average velocity of the drying air, v_c, at the exit(or outlet) of the collector is expected to be between 0.20 and 0.40 m/s.
2. The collector tilt (β) for maximum collection of incident solar radiation for all year round operation of a collector is to be taken as the latitude of the site where it is located in practice.
3. The aggregate drying bed thickness, h_L, is not to exceed 200 mm, the maximum value expected for thin layer drying.
4. The maximum height of the hot air column, H, is recommended to be between 2 and 6m for corresponding total pressure across the dryer between 0.8 and 2.5 Pa.
5. Simulation studies conducted in previous research showed that as the ratio of drying chamber area to the collector surface area is increased the overall drying efficiency increases. However, it was observed that for the ratio in the range of 1–2, there was no observable difference in the performance of the dryer. A value of 1.0 is therefore recommended as the ratio of the drying floor area to the collector surface area.
6. From previous research, it was noted that with an average solar irradiance in the range 300–500W/m^2, an effective drying time of 30–36 h (3–5 days depending on the sunshine duration) can be assumed for a loading density in the range 5–18 kg/m^2.
7. The length-to-width ratio of solar collector (L/W) for optimum performance is in the range 1– 2.
8. The mass flow rate, m_a , through a mixed-mode natural convection solar crop dryer has been found to lie in the range 0.02–0.9 kg/s.
9. For collectors with tilt angle up to 60°, it has been recommended that the ratio of the collector overall length-to-depth ratio (aspect ration) should be greater than 20 but less than 200 for variable flow conditions.

4.4 Design procedure

1. Establish Design conditions and Assumptions i.e. Crop characteristic, Climatic data, Dryer capacity, Initial and Final moisture content, drying time and collector efficiency.
2. Determine moisture loss required for the dryer batch.
3. Calculate the ERH and determine moist air properties at ERH.
4. From gas laws equation determine amount of air to effect moisture loss
5. From psychometric chart determine amount of energy required to effect moisture loss
6. Calculate the collector area, dimensions and select materials
7. Calculate the dryer chamber area, dimensions and select materials
8. Calculate the biomass heater capacity, dimensions and select materials
9. Calculate the air vent dimensions and vent locations
10. Design a fan with capacity to deliver the required airflow and static pressure.
11. Fabrication of the dryer for experimental drying tests.

4.5 Design Procedure Flow chart



4.6 Thermal performance evaluation for the fabricated dryer.

After the design and fabrication of the dryer, several drying experiments were performed using the fabricated dryer in view of establishing the thermal performance of the dryer and ultimately determining its economic viability. This was achieved through execution of drying experiment differently at the following conditions:

- Performances of the drying experiment when the source of energy for heating air was solar collector only.
- Performances of the experiment when the source of energy for heating air was biomass back up heater only
- Performances of the drying experiment when the solar collector and the heater were both engaged.

4.6.1 Parametric Measuring instruments

Dole grain moisture meter

This was used for moisture determination on the grains at time intervals.

Digital Point thermocouple

This was used in measuring ambient temperature, system temperatures at various points i.e. inlet to Solar Collector, Outlet to Solar Collector, Inlet / Outlet of Back up heater and Outlet temperature of the drying chamber.

Weighing Scale

This was used for determining the weight of samples and determination of moisture loss in grains

Anemometer

The ANEMOMETER VANE PROBE MODEL: AM-4201 with accuracy of +/-0.1m/s was used in determining the velocity of air flow.

Timer clock

This was used in determining the drying rate of maize grain.

Solar Meter

A Daystar DS-05A Solar Digital Meter with accuracy of +/- 0.03 within the range of (0 to 1200w/m^2) was used to measure the solar irradiance values.

Hygrometer

The Testo 625 thermo hygrometer measures humidity from 0 to 100% RH with an accuracy of ±2.5% and a resolution of 0.1%. Temperature readings from -10 to 60℃ are accurate to ±0.5℃ with a resolution of 0.1℃.

4.6.2 Experimental tests procedure

Therefore, basing on the components of this solar maize grain dryer prototype and the required parameters for its performance characteristics descriptions, the measurement system was installed in and around the dryer as illustrated in the in drying process flow diagram on figure 4.8 hence defined the tests procedure for the above three varied conditions.

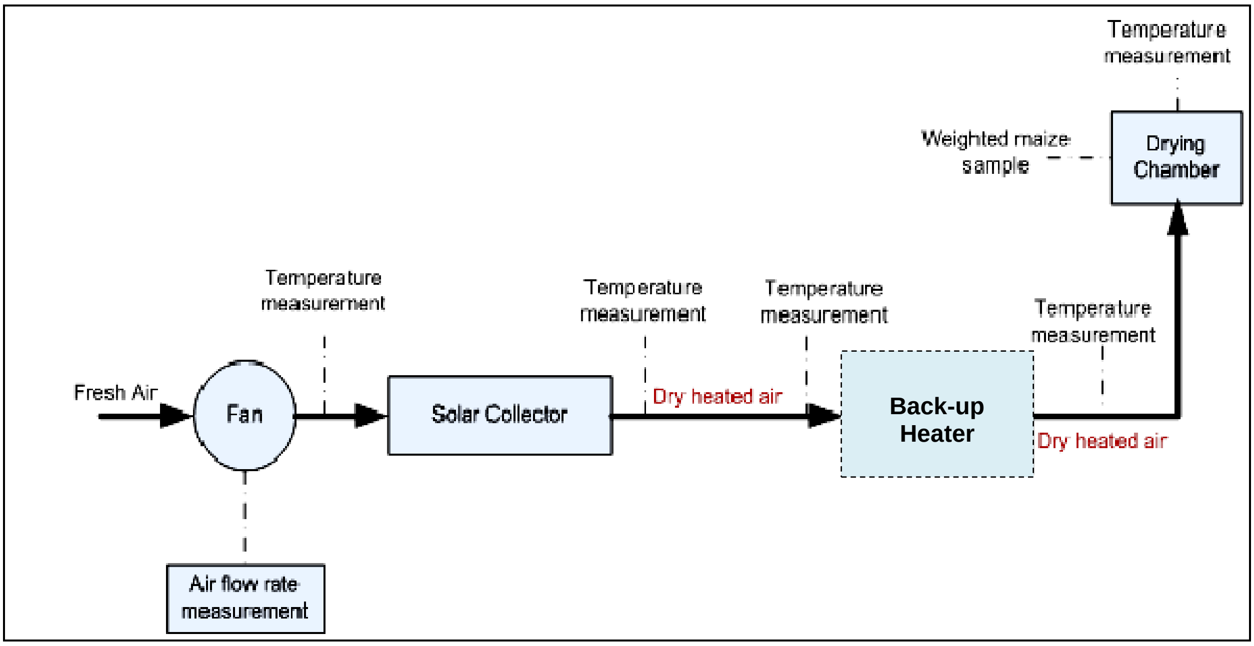


Figure 4.2: flow diagram for hybrid drying process (forced convection airflow)

From the figure 4.2, three other optional process than the hybrid system above were adopted for experimentation and validation, parametric measurements taken at appropriate positions as indicated in fig. 4.8. These processes includes:

i. Forced convection airflow and hybrid system process

Fresh air ------ Solar Collector ------ Biomass heater ----- Drying Chamber

ii. Forced convection and back up heat source system.

Fresh air ------ Biomass heater ----- Drying Chamber

iii. Forced convection and solar collector heat source system

Fresh air ------ Solar collector ----- Drying Chamber

iv. Natural convection and solar collector heat source system

Fresh air ------ Solar collector ----- Drying Chamber

The above simulated experimental test for the study were therefore undertaken generally with the following consideration:

Before drying

- Determination of moisture content (Using moisture meter)
- Weight of each maize sample
- Filling up of trays

During drying

- Registration of temperatures:- Taken at the;
  - ✓ Inlet to solar collector/ ambient air temperature
  - ✓ Outlet of solar collector
  - ✓ Inlet to biomass heater
  - ✓ Outlet of biomass heater
  - ✓ Above the drying grains/ saturated air temperature
- Emptying of trays after some time intervals
- Weighing of each maize sample to determine weight loss
- Air velocity

4.6.3 Performance evaluation for the dryer

The dryer performance was evaluated using the drying rate and system efficiency. The collector and heater efficiency was computed. Also, the drying rate which is the quantity of moisture removed from the grains in a given time was computed.

4.6.3.1 Procedure

The dryer performance was evaluated using the drying rate and system efficiency. The collector and heater efficiency was computed. Also, the drying rate (the quantity of moisture removed from the grains in a given time) was computed.

<u>Drying rate</u>

Average drying rate, M_{dr}, was determined from the mass of moisture removed by dryer and drying time as given by equation (3.23):

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

Where:

m_{dr} = average drying rate, kg/hour and t_d = overall drying time

<u>Dryer system efficiency</u>

The system efficiency was determined as detailed below.

- Solar collector: The solar collector efficiency was calculated using equation (3.18).
- Biomass heater: The heater system efficiency was calculated using equation (3.26).
- System efficiency: The system efficiency of the solar dryer and solar assisted dryer was calculated from equation (3.25).

CHAPTER FIVE

5.0 RESULTS AND DISCUSSION

5.1 Solar Dryer Pertinent Parts Design.

a) Solar collector area

The Solar Collector area was calculated from equation (3.28) which yields A_c =3.77m^2, The collector length to width ratio is taken to be, L_c/W = 1.5 which falls between recommended range for optimum performance of collector. The collector dimensions are hence Lc = 2.51m; W = 1.5m

b) Collector Air duct depth:-

The overall depth of the collector air duct channel "*s*" is calculated using equation (3.29) and yields *s* = 0.1m satisfying the constraint imposed on the value of s, since $20<L/s = 25.1<400$, satisfying the design constraint regarding the aspect ratio.

c) Absorber Surface Area

The surface area of the absorber A_{ab} was calculated from equation (3.30) and equal to the area of the collector surface area, A_c this is A_{ab} = 3.77 m^2

d) **The amount of moisture to be removed from the product,** m_w [kg] was calculated using equation (3.31) and yields m_w = 9.2kg

e) **Final relative humidity or equilibrium relative humidity, ERH [%]** of moist air at the exit of drying process was calculated from equations (3.32a) (3.32b) and (3.32c) and determined as 57%

f) The quantity of air needed for drying

Using a psychometric chart and taking input air temperature of 26℃ (dry bulb) and a relative humidity of 72%, the psychometric chart gives a humidity ratio of 0.015 kg water/kg dry air. When the solar collector heats air to optimum drying temperature of 50℃ (dry bulb), the humidity ratio remains constan t. If on passing through the grain, the air absorbs moisture until its relative humidity is equal to ERH (calculated), 57%. The psychometric chart shows the humidity ratio to be 0.021 kg water/kg dry air. The change in humidity ratio is therefore: 0.021 - 0.015 = 0.006 and the corresponding dry bulb temperature is 35.5℃.

From the gas laws equation $PV=M_ART$ (5.1)

Where;

P = is the atmospheric pressure = 101.3 KPa,

V =the volume of air in m^3.

M_A = the mass of the air in kg,

T =the absolute temperature in Kelvin, and

R = the gas constant = 0.291 kPa m^3/kg K.

For a humidity ratio increase of 0.006 kg water/ kg dry air, each kg of water will require 1/0.006 = 166.67 kg dry air. For this calculation, the absolute temperature is 35.5+ 273 = 308.5 K and the volume of air needed to remove 1 kg of water is 147.71m^3.Hence 9.2kg will require 1358.89m^3 volume of air to effect drying.

i. The volume flow rate of air V_a (m^3/hr) is calculated as shown below:

$$V_a = W_a / t_d \tag{5.2}$$

W_a = quantity of air required in m^3 = 1358.89m^3

t_d = Total drying time=6 hrs (a batch daily)

V_a= 1358.89/6 =226.48m^3/hr

For a drying time of 6 hrs operating time per day, the volumetric air flow rate is 0.06m^3/s

ii. Mass flow rate of air, m_a, kg/hr was calculated as below:

$$m_a = \rho_a \times V_a \tag{5.3}$$

ρ_a = density of drying air (Kg/m^3)=1.2kg/m^3

V_a = volumetric air flow rate

This calculation yields 271.78kg/hr. (0.08kg/s).

g) **The quantity of heat required to evaporate the water** was calculated from equation (3.34) and yields, E = 40.77MJ

h) **Average drying rate**

Average drying rate, m_{dr}, was determined from equation (3.35) and yields

m_{dr} = 1.53kg/hr

i) Drying chamber Floor Area

The ratio of Drying chamber floor area A_{dc} to Collector Area A_c is equal to 1 within recommended range of 1 – 2 in the constraints. Since two trays are considered in our design. The floor area of each drying chamber A_{dc} = 1.89m^2

j) Sizing of the dryer chamber

The breadth of the drying chamber, B, is made equal to the width (W) of the solar collector i.e. B = 1.5m; hence the length of the drying chamber is determined from equation (3.36) and is equal to L_{dc} = 1.26m.

k) Effective Drying bed Area

The effective drying bed area A_{db} was calculated from equation (3.37) and is equal to A_{db} =2.78m^2. The corresponding loading density is 18 kg/m^2 ; the value of which falls within the acceptable range of 5–18 kg/m^2 in the design constraints.

l) Air vent dimensions:

The air vent area is calculated from equation (3.38) and yields A_v = 0.03m; The length of of air vent, L_v will be equal to the length of the dryer, L_{dc} = 1.26m, while the width of the air vent is given by equation (3.39) and equal to B_v = 0.02m.

m) Pressure drop through the drying bed

The pressure drop through the drying bed is given by the equation (3.40) and equal to ΔP_B = 0.17Pa. While the total pressure drop across the solar collector and the air ducts is comparable to that across the drying bed, and hence the total pressure drop of the system is approximately twice the pressure drop of the drying bed. i.e. ΔP = 0.34Pa. When all pressure drops are accounted for, experience has shown that, the gross pressure drop is about six times the value of ΔP (Forson *et al* 2007). and given by equation (3.41) and is equal ΔP_T = 2.04Pa.

n) Height of the hot air column

The height of the hot air column is calculated from equation (3.42) and is equal to H = 2.4m. In the construction of the dryer, an allowance is made for the height of the solar collector inlet above the ground level. The height of the solar collector inlet vent above the ground level, y, should be at least 0.40m to allow air to flow naturally through it.

5.2 Computed Design parameters

Table 5.1 shows the computed results of the pertinent design parameters of the solar dryer design.

Table 5.1: Pertinent Design Parameters

No.	Parameter	Units	Data or Equation used	Value	Source
1	Initial humidity ratio, ω_i	kg_{wv}/kg_{da}	t_{am}, RH $_{am}$	0.015	Psychometric chart
2	Initial enthalpy, h_i	kJ/kg_{da}	t_{am}, RH $_{am}$	65.00	Psychometric chart
3	Equilibrium relative humidity, RH_f	%	M_f, and Isotherms Eq. (3.32c)	57.00	
4	Final enthalpy, h_f	kJ/kg_{da}	ω_i, t_f	90.00	Psychometric chart
5	Final humidity ratio, ω_f	kg_{wv}/kg_{da}	RH_f, h_f	0.021	Psychometric chart
6	mass of water to be evaporated, m_w	kg	Eq. (3.31)	9.20	
7	average drying rate, d_r	kg_{wv}/hr	Eq (3.35)	1.53	
8	air flow rate, m_a	kg/hr	Eq. (5.3)	271.78	
9	volumetric airflow rate, Va	m^3/hr	Eq. (5.2)	226.48	
10	Total useful energy, E	MJ	Eq. (3.34)	40.77	
11	Solar collector area ,A_c	m^2	Eq. (3.28)	3.77	
13	vent area, A_v	m^2	Eq.(3.38)	0.03	
14	Air Pressure Drop, P	Pa	Eq. (3.41)	2.04	Entire system
15	vent length, L_v	m	Spec.	1.26	
16	vent width, B_v	m	Eq. (3.39)	0.02	
17	Absorber Area	m^2	Eq. (3.30)	3.77	

5.3 Fan System Design and Selection

To achieve the desired drying or aeration conditions, the air flow rate is selected from the suggested air flow rates of between 13.3L/sm^3 to 26.7 3L/sm^3 for high temperature drying of up to 45 – 70℃ plenum temperatures. High air fl ow rates, batch or layers in a bin is recommended. (GSI group, 1998).

- Average grain depth for a stack considered h_L, is 0.2m, the maximum value expected for thin layer stacking of grain in a bin.
- From the STATIC PRESSURE TABLES for CORN between 0 – 600mm. (next higher value after 200mm) and 26.7 3L/sm^3 in the range of suggested air flow rates. The Static pressure for selected grain is 13.7mm water column. (Appendix A5.1).
- From earlier design calculation of the dryer, the total air flow required to effect drying is 0.06m^3/s
- From the FAN PERFORMANCE TABLE for vane axial fans at 13.7mm static pressure (25.4mm on table) and 0.06m^3/s (0.5m^3/s on the table), the appropriate fan would be a 0.56KW – 300mm Vane Axial Fan. (Appendix A5.2).

Fan selected will provide 0.5m^3/s air flow @ 25.4mm W.G static pressure

5.4 Dimensioning and Assembling of the solar maize grain dryer

5.4.1 Dimensions of the dryer

For the purpose of the experiment and because of time and resource limitations, a scale of 1 to 2.5 was used to determine the dimensions of the fabricated dryer pertinent parts. However, other dimensions were adjusted during fabrication of the dryer to address proportionality concerns. The value of scale ratio λ is made small to minimize scale effects resulting from omission of some non-dorminant forces during the design (Heller, 2012).

Key dimensions are summarized in the table 5.2 :-

Table 5.2. Dryer pertinent parts dimensions

No	Parameter	Units	Dimensions Actual Dryer	 Fabricated Dryer
1	Solar Collector			
	Length, L_c	m	2.51	1.00
	Width, W_c	m	1.5	0.60
	Collector Area, A_c	m^2	3.77	0.60
2	Solar Dryer			
	Length, L_d	m	1.26	0.50
	Width, B_d	m	1.5	0.60
3	Air Vent			
	Length, L_v	m	1.26	0.50
	Width, B_v	m	0.02	0.01
4	Back up heater			
	Length, L_b	m	1.75	0.70
	Width, W_b	m	1.5	0.60
	Depth, D_b	m	1.5	0.60
5	Height of Air Column, H	m	2.4	0.96
6	Height of Collector Inlet above ground level, y	m	0.4	0.40

5.4.2 Materials selection and fabrications of the solar collector

As discussed in literature review section the materials suitable for the collector parts were proposed. Solar collector was separated from the drying chamber but connected with a duct to allow heated air passage through to the plenum part of the drying chamber. It has a collector area of $0.6m^2$ and mounted on a horizontal square tube frame. The collector was made of block board (0.6m x 1.1m) on the sides and blockboard (1.1m x 0.7m) at the bottom, the entire structure was enclosed by a 1.5mm mild steel sheet to prevent the wooden structure from harsh weather (on the sides and the bottom) The other components included: Transparent cover plate of fibre glass material, an absorber made of Corrugated Galvanized iron sheet and an wool lining insulator inserted between the iron sheet and the wooden structure.

a) Cover Plate

This is a transparent fibre glass cover of 2.5 mm thickness placed about 0.42m above the absorber and fixed firmly to wooden frame structure. Its dimensions are 1.1m by 0.7m to prevent it from falling inside the collector.

b) Absorber Plate

This was made of galvanized corrugated iron sheet covering the entire inner lining of the solar collector coated with a black paint. The black paint contains (5%) black chromium powder to increase the iron sheet absorption capability.

c) Insulator

The insulator is mainly to minimize heat loss from the system. It was placed 25.4 mm below the absorber plate. The material used was wool of size 1m by 0.6m because of its superior performance in minimizing heat loss. Figure 5.1 show a cross section sketch of the solar collector.

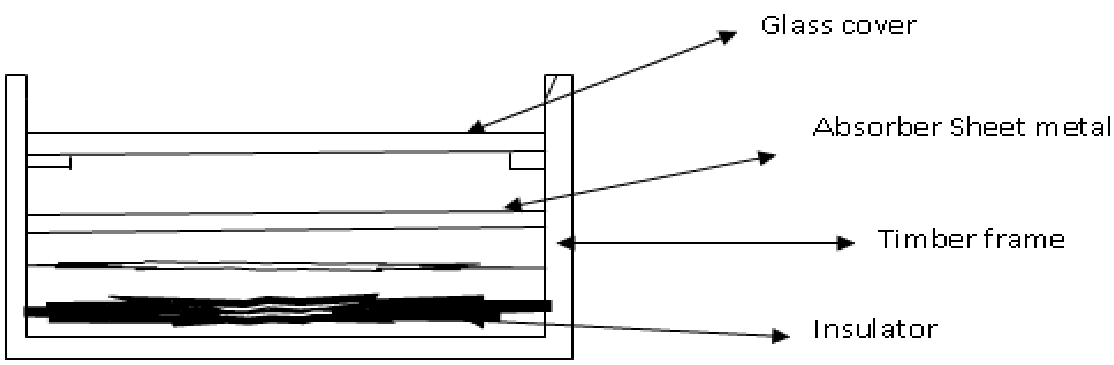


Figure 5.1 Schematic representation of solar energy collector component

5.4.3 Drying chamber

The drying chamber was made of highly polished wood held in place by wooden frame structure supported at the bottom by angle iron framework. Its bottom side of the plenum was made of mild steel sheet to allow transfer of heated air in to the dryer chambers. To further reduce heat loss by radiation and to avoid moisture absorption by the wood, the structure was painted with Aluminum paint. The dimensions of the drying chamber are 0.7mx0.6m x0.5m. Besides, the top part of the chamber is triangular cone shape with base dimensions of 0.245m by 0.245m with a height of 0.124m.

5.4.4 Drying trays

These are the triangular prism shaped trays that holds the grains during drying. There are two trays only in this chamber. Each tray is served by a dedicated ducting to convey hot air and located 0.15m apart from each other and made of 1.5mm perforated mild steel sheet with a 45° angle to increase surface ar ea of grain in contact with heated air.

Plate 5.1: Pictorial representations of the drying chamber and trays for the dryer.

5.4.5 Biomass back up heater

Based on the need to have small size burner, and having established the width of the drying chamber which was to be mounted on a common framework with the burner, the dimension of the burner was estimated as (0.7m x 0.6m x 0.6m). This biomass burner was made of a brick-wall kiln enclosed with 1.5mm thick mild steel sheet.

The heater has a flue gas chimney of diameter 0.23m and a height 1.19m cold rolled from mild steel sheet of 1.5mm thickness and located on the top side.

Plate 5.2: Pictorial view of the back-up heater structure of the dryer

5.4.6 Assembling of the fabricated dryer

The above various parts designed, dimensioned and fabricated were assembled together to form a complete prototype dryer as shown in figure 5.2 and plate 5.3

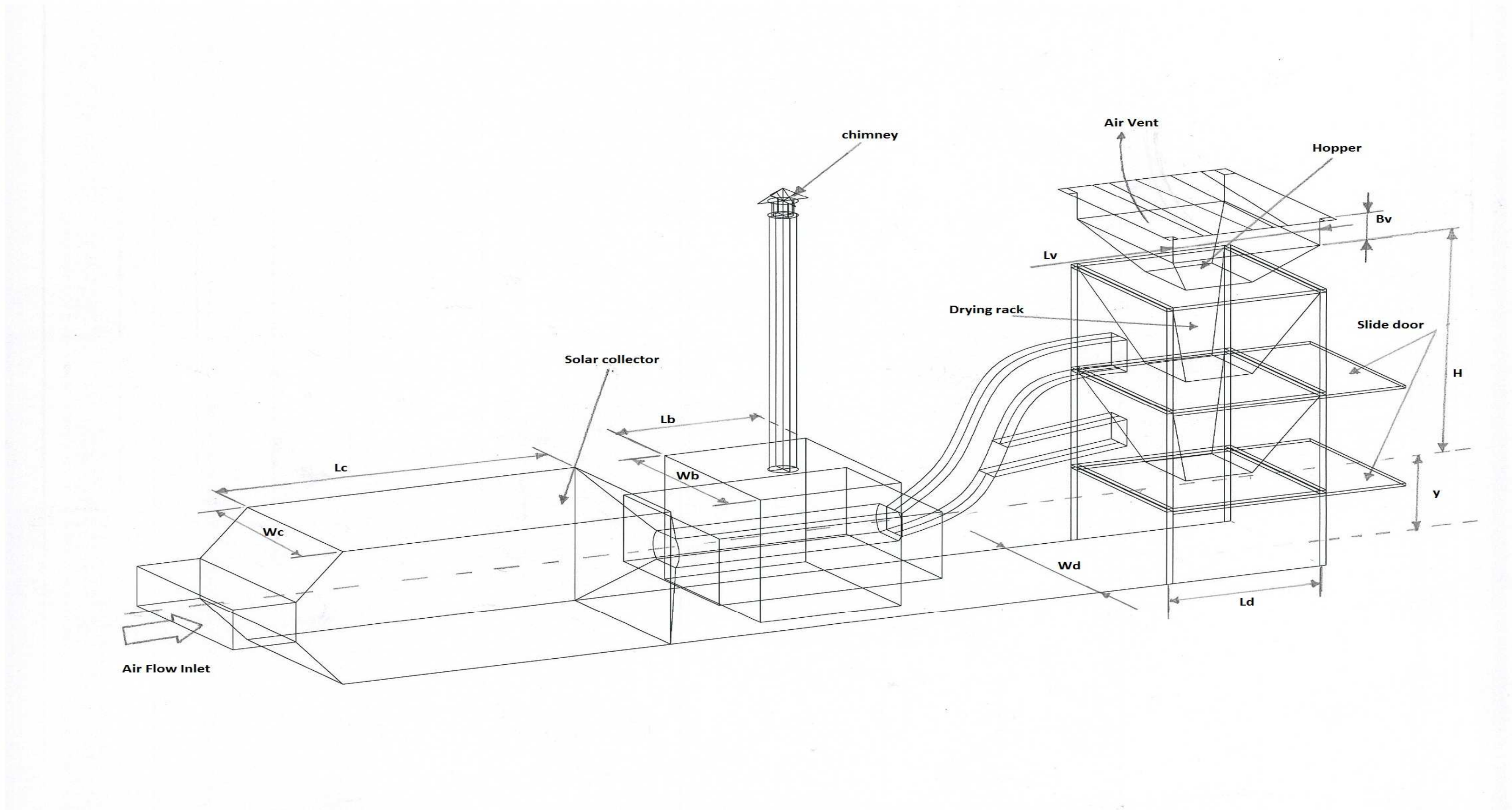


Figure 5.2: Schematic view of the Solar assisted maize dryer

Plate 5.3: Pictorial view of the assembled maize grains dryer.

5.5 Experimental Results

5.5.1 Solar Irradiance distribution

The table below shows the daily solar irradiance and ambient temperature averages measured during the months of August, September and October during which time solar dryer tests were being carried out. (Refer to appendix A1) for actual days solar irradiance and corresponding ambient temperature values.

Table 5.3: Average Values of Solar Irradiances and ambient temperatures

Time (24Hrs)	Solar Irradiance in W/m^2	Amb. Temperature ^{0}C
0800	360	19.8
0900	570	22.6
1000	820	24.5
1100	1023	27.3
1205	1030	27.4
1305	1020	27.4
1405	980	27.2
1545	820	26.8
1640	700	25.0
1740	550	24.1

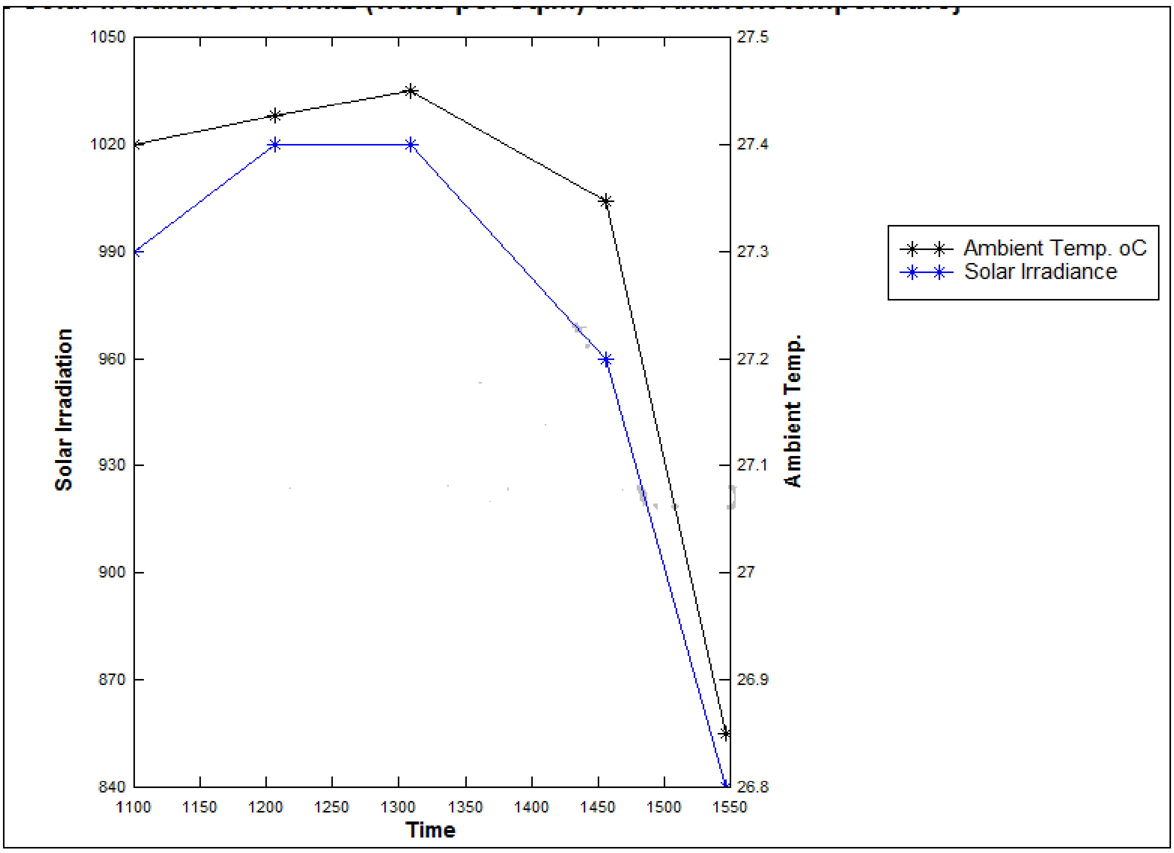


Figure 5.3: Variation of Solar irradiance (W/m^2) with time of day (Hrs)

Figure 5.3 shows the average solar irradiations and ambient temperatures during the experiment duration

The solar irradiance increases from $360W/m^2$ to a maximum value of $1030W/m^2$ at 1205hrs and remains almost constant at average values of $1000W/m^2$ between 1100hrs and 1500hrs during active solar irradiance hours. A significant drop of irradiance from $1000W/m^2$ to $550W/m^2$ is noted between1500hrs and 1740hrs.

The ambient temperatures also varied greatly with solar irradiations. The average ambient temperatures as from 11.00am to 4.00pm ranged between 26.8^oC and 28.0^oC

5.6 Open sun drying

During the performance of the dryer tests, sun drying was also performed by spreading the same amount of maize grain sample in the sun. The result of the experiments was tabulated and the performance of the method analyzed using the drying rate and drying curves. (Refer to Appendix A0) for detailed results of sampled days for each month

Table 5.4: Sun drying experiment results

Date	Time	Moisture Content, %
Day 1	11:00	19.30
	15:00	16.37
Day 2	11:00	16.62
	15:00	15.40
Day 3	11:00	15.40
	15:00	14.67
Day 4	11:00	14.91
	15:00	13.93
Day 5	11:00	13.93
	15:00	13.45
Day 6	11:00	13.69
	15:00	13.20

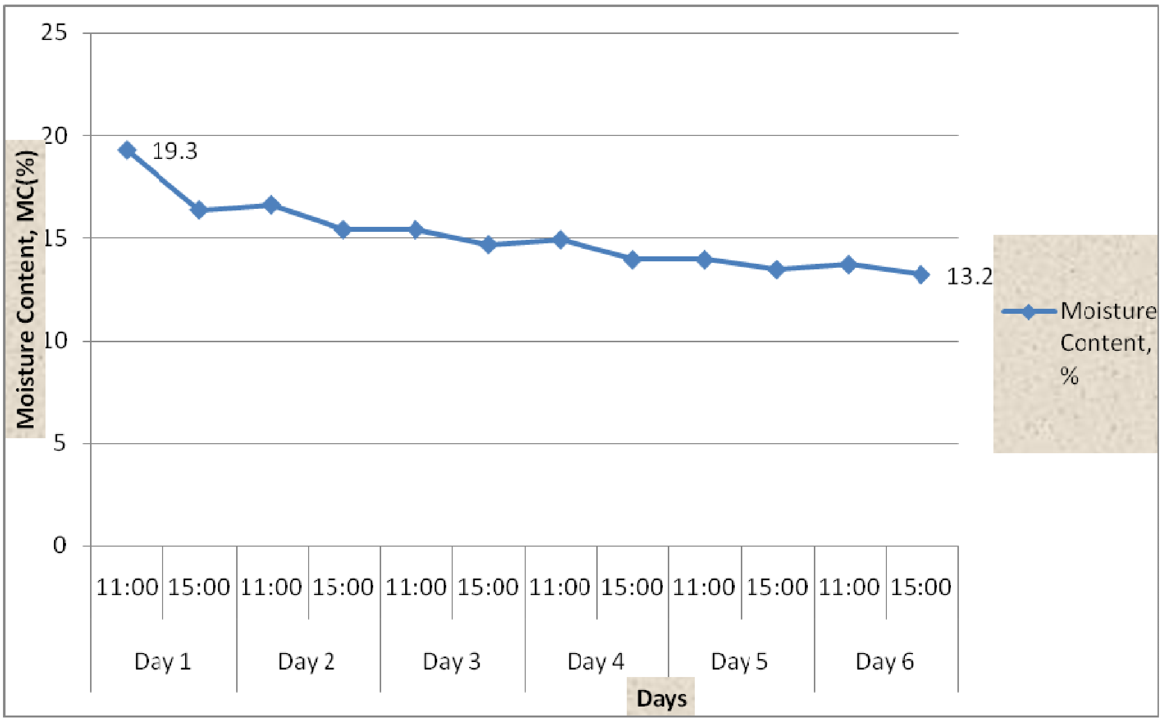


Figure 5.4: Drying Curve in the Sun drying Mode.

Maize grains sample having initial moisture content of 19.3% was dried by sun drying to a final moisture content of 13.2% in 6 days of 4 hours each during sampled days in the months of August, September and October at prevailing ambient temperatures range between 25℃ and 28℃.

Constant drying rate occurred in the first 3 days of drying of 4 hours each where up to 4.8% MC was lost. The critical moisture content occurred at 14.5% MC w.b. The falling rate occurred for next 3 days of drying of 4 hours each where only 1.2% MC was lost. This signifies tightly bound water requiring a lot of energy to remove.

Given that; Mass of moisture removed, M_w (0.25kg) over drying period of , t_d (24 hours). From equation (3.23) the average drying rate calculated is 0.0104 kg/hours

5.7 Solar dryer performance

5.7.1 No load

The temperatures of the system were measured when the solar dryer was operated with no load in it. The inlet and outlet temperatures were measured for four (4) hours before loading the dryer with maize samples on the sampled days in the month of August, September and October. The average values of T_{in} and T_{out} for each month were tabulated in table 5.5

Table 5.5: Solar Collector Inlet and Outlet Temperatures

Time, Hrs	$T_{in\ Avg.}$	August		September		October	
		T_{in}	$T_{out\ Aug}$	T_{in}	$T_{out\ Sep}$	T_{in}	$T_{out\ Oct}$
11:00	27.33	27.00	28.50	27.43	30.67	27.57	30.70
11:10	27.50	27.17	28.50	27.60	31.60	27.73	30.50
11:20	27.57	27.07	30.10	27.87	31.70	27.77	31.83
11:30	27.57	27.00	30.10	27.90	32.00	27.80	32.10
11:40	27.53	26.93	30.40	27.93	32.30	27.73	32.13
11:50	27.53	26.97	30.30	27.87	32.67	27.77	31.87
12:00	27.53	27.07	30.20	27.77	32.40	27.77	32.10
12:10	27.47	27.20	30.10	27.57	32.53	27.63	32.00
12:20	27.43	26.97	28.30	27.67	31.73	27.67	31.57
12:40	27.43	26.87	28.00	27.77	31.63	27.67	31.53
13:00	27.43	26.87	28.20	27.73	31.63	27.70	31.33
13:20	27.37	26.87	28.10	27.70	31.07	27.53	30.83
13:40	27.13	26.63	28.20	27.43	29.05	27.33	30.53
14:00	27.10	26.63	27.20	27.30	29.00	27.37	30.00
14:20	26.90	26.27	27.10	27.23	28.40	27.20	29.40
14:40	26.60	25.83	26.70	27.03	28.20	26.93	29.00
15:00	26.20	25.50	26.50	26.60	28.00	26.50	28.20

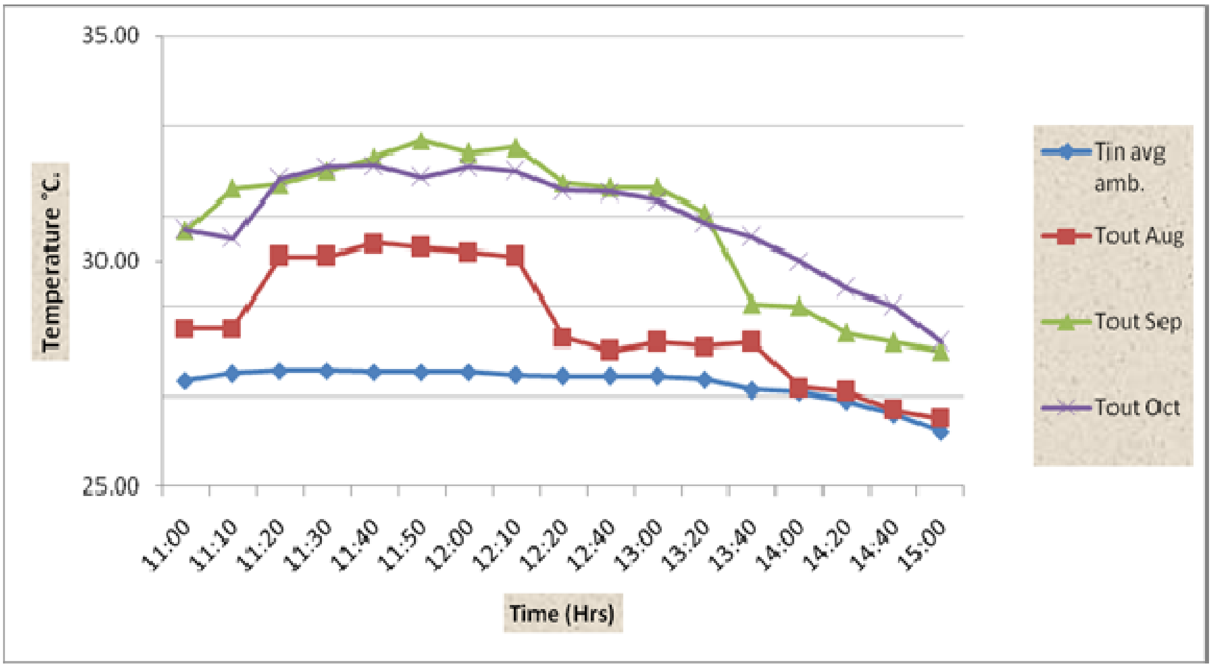


Figure 5.5: Temperatures at Inlet and Outlet of solar collector chamber

Figure 5.5 above shows the relationship between temperatures (T_{in} & T_{out}) of the system within solar collector chamber. The performance of the solar collector during this period had significant variances as highlighted below.

The average temperature increase in the month of August was 1.85 ℃., September 3.11℃ and October 3.41℃. The perfomance of the co llector is low in the month of August and almost double in the subsequent months. This can be explained by short rains experienced in August. In view of the above it is recommended that the harvesting season of maize in Mau summit be delayed to begin in September and take advantage of improved efficiency of our solar dryer.

The outlet air temperatures are higher than the inlet temparatures by an average value of 2.78℃ for the three months with a one time highest temperature increase of 4.8℃ in September. As noted, the low rise in temperature could be attributed to high altitude and high relative humidity of the study area which affects collector performance.

Therefore, the steady state efficiency of the solar air collector can be estimated using Hottel–Whillier–Bliss equation (3.18)

In determining mass flow rate, $m_a = \rho_a A V$ in kg/s

Where; A= cross sectional area of fan duct (measured) in m^2 = 0.014375m^2

V = velocity of air flow in to the system (measured) in m/s =7.1m/s

ρ_a = density of air in kg/m^3 (literature) = 1.2kg/m^3

Therefore, Q_g = mass flow rate (0.12 kg/s) × specific heat capacity of dry air (1.006 KJ/kg.K) × Average change in temperature (2.78 K);

A_c = Area of the collector (0.6 m^2);

I_T = Average solar insolations (0.958 KJ/s),

the thermal efficiency of the collector η_c was calculated as 59%.which is found to be slightly higher than that reported to by Sodha *et al* 1987. The reason is that our dryer system used forced convection which increased its efficiency than the natural convection used by the latter.

5.7.2 Loaded solar drier

The solar drier was loaded with maize grains during active solar radiations, which was from 11am until 3pm during the months of August, September and October.

The table 5.6 below shows the average weight of the sample of maize grains at the start and the end of the each days experiment. (Refer to Appendix A2) for sampled days for each month

The change in weight was attributed to loss of moisture contents.

Table 5.6: Solar drying experiment results

Date	Time	Moisture Content, %
Day 1	11:00	19.3
	15:00	14.9
Day 2	11:00	14.9
	15:00	13.7
Day 3	11:00	13.7
	15:00	13.2

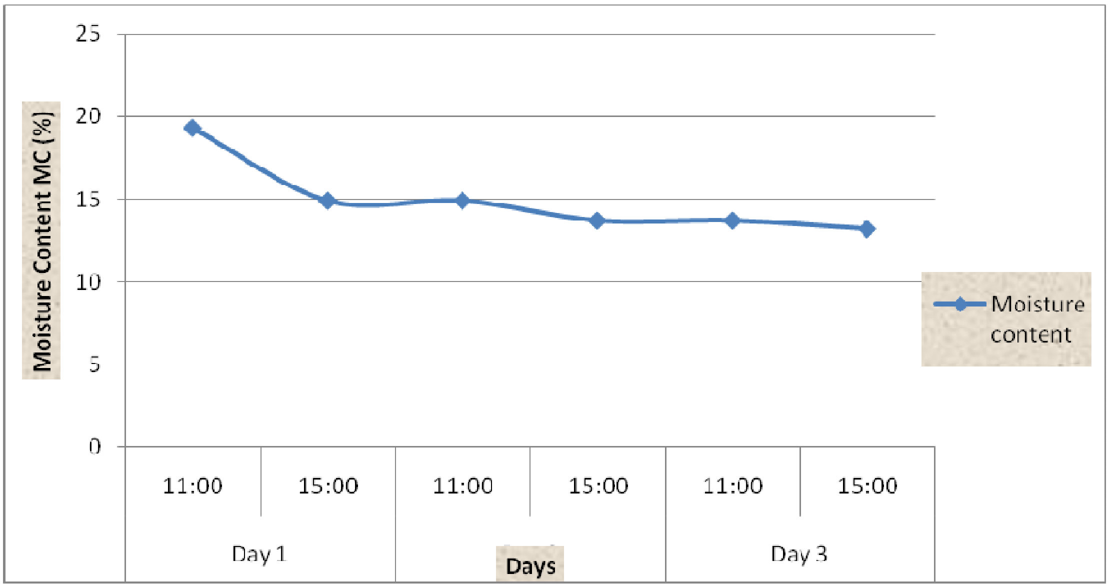


Figure 5.6: Drying Curve in the Solar drying Mode.

The Sample having initial moisture content of 19.3% was dried by solar drying to a final moisture content of 13.2% in 3 days of 4 hours each during the months of August, September and October.at prevailing drying chamber temperatures of between 27.3^{o}Cand 32.0 ^{o}C.

High moisture removal rate of MC (4.8%) was achieved in day 1 while the remaining MC of (1.3%) was achieved in 2 days again depicting the same behavior noted when using sun drying where constant drying rate phase occurred faster than the falling rate.

5.8 Biomass Heater as source of heat in the dryer

The solar drier was loaded with maize grains and the solar collector covered to allow only the biomass heater to provide required heating of air to be used for drying. The dryer test experiments was done from 11am until 3.40pm during the months of August, September and October.

The Average system temperatures, weight and moisture content of the sample for the months were tabulated in table below. (Refer to Appendix A3) for sampled days for each month)

Table 5.7: Back up heater experiment results

	Heating chamber			Drying chamber		
Time (hrs)	**T_{in} ^0C**	**T_{out} ^0C**	**ΔT ^0C**	**T_{out} ^0C**	**Wt. of Maize, kg**	**Moisture Content, %**
11:00:00	27.4	40.3	12.9	35.4	4.1	19.3%
11:10:00	27.7	43.8	16.1	36.8		
11:20:00	27.4	42.7	15.3	35.3		
11:30:00	27.4	41.5	14.1	34.3		17.6%
11:40:00	27.4	40.0	12.6	37.0		
11:50:00	27.4	40.0	12.6	37.3		
12:00:00	27.4	44.5	17.1	40.3		16.1%
12:10:00	27.2	45.7	18.5	41.0		
12:20:00	28.1	45.9	17.8	41.4		14.6%
12:40:00	27.1	42.2	15.1	40.5		
13:00:00	27.1	42.9	15.8	41.2		14.1%
13:20:00	27.0	41.8	14.8	40.6		
13:40:00	26.8	41.7	14.9	40.7		
14:00:00	26.9	41.8	14.9	40.8		13.7%
14:20:00	26.5	42.4	15.9	41.2		
14:40:00	26.5	43.0	16.7	42.7		13.6%
15:00:00	26.3	42.7	16.4	42.4		
15:20:00	26.1	42.6	16.5	42.6		
15:40:00	26.0	41.7	15.7	41.6	3.85	13.3%

The Sample having initial moisture content of 19.3% was dried by biomas heater to a final moisture content of 13.3% in 4 hours and 40 minutes during the months of August, September and October at prevailing drying chamber temperatures of between 40ºC and 45.9 ºC.

5.9 Solar drier assisted by biomass heater

The experiment was performed by combining the solar and biomass heater to dry the maize sample. The dryer test experiments was done from 11am until 3pm during the months of August, September and October.

The Average system temperatures, weight and moisture content of the sample days in the months were tabulated in table below. (Refer to Appendix A4) for sampled days for each month)

Table 5.8: Solar drier assisted by biomass heater experiment results

	Solar chamber			Heater chamber			Drying chamber		
Time (Mins)	**T_{in} ^0C**	**T_{out} ^0C**	**ΔT ^0C**	**T_{in} ^0C**	**T_{out} ^0C**	**ΔT ^0C**	**T_{out} ^0C**	**Wt. of Maize, kg**	**MC (%)**
0	27.4	31.7	4.3	31.7	43.6	11.9	36.4	4.1	19.3
10	27.7	30.7	3.0	30.7	46.8	16.1	34.8		
20	27.4	31.1	3.7	31.1	46.7	15.6	35.3		
30	27.4	31.3	3.9	31.3	46.5	15.2	36.3		16.3
40	27.4	32.7	5.3	32.7	48.0	15.3	40.0		
50	27.4	33.0	5.6	33.0	48.0	15.0	42.3		
60	27.4	31.2	3.8	31.2	48.5	17.3	45.3		14.8
70	27.2	31.4	4.2	31.4	49.7	18.3	46.0		
80	28.1	29.3	1.2	29.3	46.9	17.6	45.4		14.2
100	27.1	29.0	1.9	29.0	44.2	15.2	43.5		
120	27.1	29.2	2.1	29.2	44.9	15.7	44.2		13.9
140	27.0	28.0	1.0	28.0	44.8	16.8	44.6		13.8
160	26.8	27.8	1.0	27.8	44.7	16.9	44.7		
180	26.9	27.9	1.0	27.9	44.8	16.9	44.7	3.87	13.7

The performance of the system was analyzed using the drying rate as shown in the graph below.

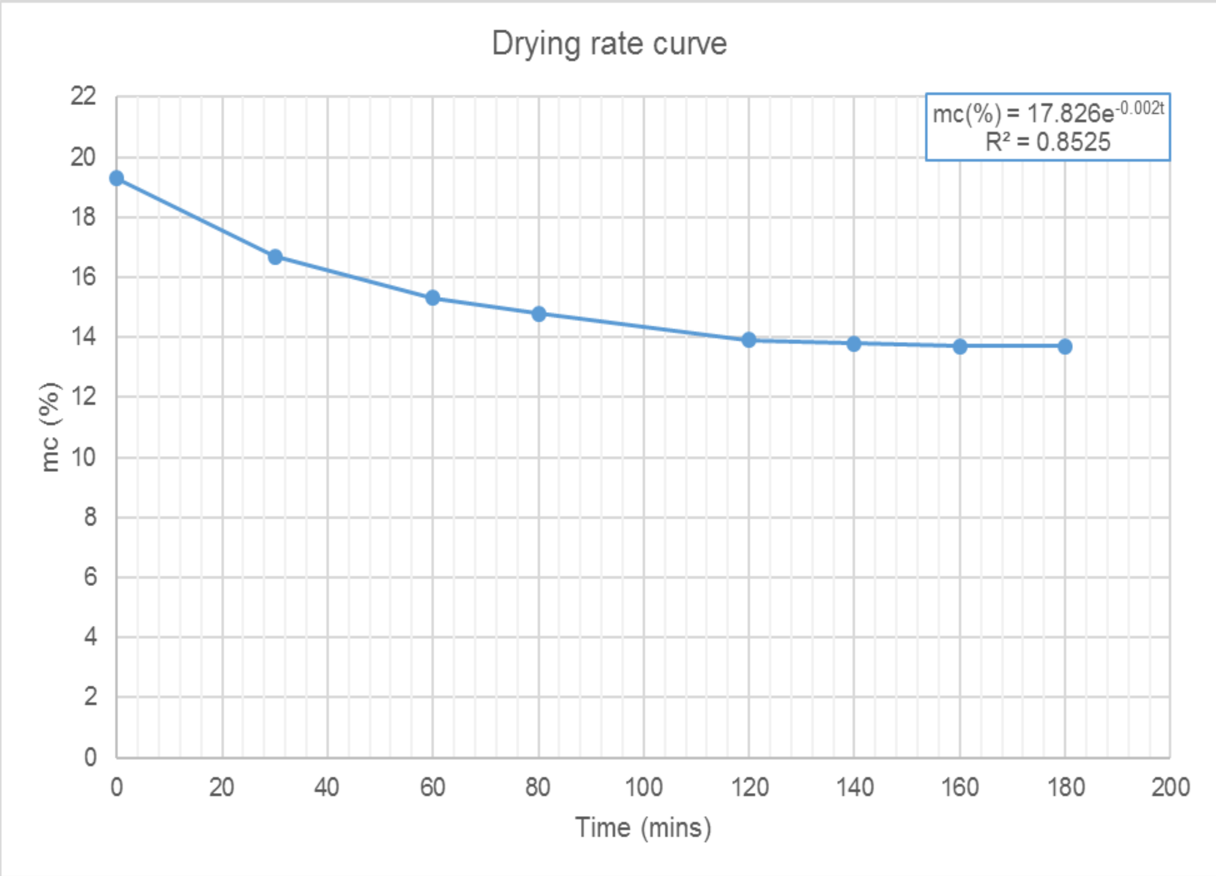


Figure 5.7: Drying curve in the assisted solar drying mode

The maize moisture content decreased exponentially with change in time from 19.3% to 13.7% within 3hrs at prevailing drying chamber temperatures between 43.6 ºC and 49.7 ºC.

As shown in figure 5.7 above, the moisture removal rate of 4.8% MC is high in the first one hour and occurs at constant drying rate up to the critical moisture content of 14.5% MC w.b. The remaining 1.2% MC was removed at falling rate phase in 2 hours. This occurred at a much lower rate due to tightly held water in the grain requiring more energy.

The drying rate equation, (Tonui *et al,* 2014) was found to be exponential with R^2 = 0.85 and conforms to other drying models by various authors.

The table below highlights existing tested models

Table 5.9. Drying models given by various authors for drying curves

Model name	Equation	Description	References
Newton	$mc(\%) = e^{-kt}$	thin-layer drying	Ayensu, (1997); Togrul & Pehlivan, (2004); Upadhyay *et al.,* 2008
Page	$mc(\%) = e^{-kt^n}$	thin-layer drying	Kaleemullah & Kailappan,(2006); Saeed *et al.*, (2006); Senadeera *et al.*, (2003)
Tonui	$mc(\%) = 17.826e^{-0.002t}$	Maize drying	Tonui *et al,* 2014
Henderson & Pabis	$mc(\%) = a.e^{-kt}$	thin-layer drying	Kashaninejad *et al.*, (2007); Saeed *et al.*, (2006); Ozdemir & Devres, (1999)

The drying rate equation obtained conforms to a drying model reported by Henderson and Pabis.

5.10 Efficiencies

5.10.1 Solar as the only source of heat

The thermal performance of the system, $\square_{syst}$ is given by equation (3.25).

Where $Q_g = m_a Cp_a$ ($T_{into\ drying\ chamber} - T_{ambient\ temperature}$), [$m_a$= 0.27 kg/s; Cp_a = 1.006 KJ/kg.k, T_{in}-T_{amb} = 3.7K; m_w = mass of evaporated water (0.27kg), L_V= latent heat of vaporization (2270 KJ/Kg), Mg = mass of the grains dried (4.1kg), CPg = specific heat capacity of the grains (1676.58 KJ/Kg.k), and ΔT = change in temperature (2.43K). Therefore the system efficiency calculated is 39.9%.

The table 5.10 shows results of comparative study of solar maize dryers by various authors

Table 5.10: Comparative study of solar dryers by various authors

Type of Dryer	Moisture Content Initial	Moisture Content Final	Drying time	Temp (℃) Amb.	Temp (℃) Ave.	Full load capacity	System efficiency (%)	Reference
Simple Maize dryer	22.5%	13%	27hrs	20	65	50kg	22%	Joshua 2008
Flat plate Absorber Collector	35%	12%	10hrs	33.5	64	450kg	21%	Bolalji BO 2005
V-groove Solar Dryer	21.1%	13%	4hrs	20	45	38kg	45%	Gatea et al 2011
Natural Convection solar dryer with fin type absorber collector	35%	12%	10hrs	33.5	64	450kg	36%	Bolalji BO 2005

The system efficiency obtained is comparable to that reported by Gatea *et al* (2011) in his solar dryer tests. The difference in drying tests location may have led to the difference in efficiency noted.

5.10.2 Biomass Heater as only source of heat

The thermal performance of the system, $\square_{syst}$ is calculated from equation (3.26).

Using temperature data recorded 4hours 40minutes of back-up heating operation, with approximately 10kg woodfuel used with calorific value as 13.1 MJ/kg, where heat transferred to the air given as m_aCp_a (T_{out} – T_{in}) where ma = 0.27kg/s, Cp_a=1.006 kJ/kgK and (T_{out} – T_{in}) =15.5K, an thermal efficiency of the back-up heater was found to be 54%.

From the active solar irradiance data obtained earlier back up heater should be engaged when the solar irradiation is low i.e. in the morning hours (0800hrs to 1000hrs) and in the evening hours (1500hrs to 1800hrs) and supplement the solar energy with back up heating system and speed up the drying process.

5.10.3 Solar and back-up heater as a combined source of heat

The thermal performance of the system, $\square_{syst}$ is calculated from equation (3.25).

Where Q_a $_=$$m_aCp_a$ ($T_{into\ drying\ chamber}$ – $T_{ambient\ temperature}$), [m_a= 0.27 kg/s; Cp_a = 1.006 KJ/kg.k, T_{in}=319.29K T_{amb} =300.31K); m_w = mass of evaporated water (0.23kg), L_V= latent heat of vaporization (2270 KJ/Kg), m_g = mass of the grains dried (4.1kg), CP_g = specific heat capacity of the grains (1676.58 KJ/Kg.k), and ΔT = change in temperature of grain (4.6K). Therefore the system efficiency in this set up when both sources of heat are engaged was calculated as 57.7%.

The back up heater improved efficiency of solar dryer by 17.8% when the dryer chamber is operated at average temperature of 45 ºC (Refer to Apendix A4 fig. 8.2) for temperature profile within the dryer chambers during drying period by solar assisted dryer. The system efficiency obtained is comparable to a mixed mode natural solar dryer with a biomass heater by Tarigan and Tekasul (2005) which yielded 63% during drying tests with ground nuts.

5.11 Average drying rate

Average drying rate, M_{dr}, is determined from the mass of moisture removed by dryer and drying time as given by equation (3.23):

5.11.1 Solar as only source of heat

Given that; Mass of moisture removed, M_w = 0.27kg

Overall drying time, t_d = 12 hours

Average drying rate = 0.023 kg/hours

5.11.2 Biomass heater as only source of heat

Given that; Mass of moisture removed, M_w = 0.28kg

Overall drying time, t_d = 4.67 hours

Average drying rate = 0.060kg/hours

5.11.3 Solar and Biomass heater as combined source of heat

Given that; Mass of moisture removed, M_w = 0.23kg

Overall drying time, t_d = 3 hours

Average drying rate = 0.077kg/hour

5.12 Summary of dryer system performance

The dryer efficiencies and drying rates of maize samples using various sources of heat is summarized in the table below.

Table 5.11. Dryer system performance

Source of heat	Drying rate (moisture removal rate) , kg/hr	Dryer efficiency (%)
Open sun drying	0.010	N/A
Solar collector	0.023	39.9
Solar collector and Biomass heater	0.077	57.7

The back-up heating system improved the efficiency of the dryer by 17.8% and improved drying rate by 0.054kg/hr

CHAPTER SIX

6.0 CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

Solar assisted dryer with collector area of $3.77m^2$ and drying capacity of 100kg was designed to dry maize grains from 21% to 13% moisture content wet bulb in 6 hours per batch under mau-summit weather conditions prevailing during the months of August to November.

A solar dryer with collector area of $0.6m^2$ was fabricated and used for experimental drying tests. A vane axial fan with capacity to deliver $0.5m^3/s$ @ 25.4mm water gauge static pressure; Power rating of 0.56KW and Size 300mm was designed and used to deliver required airflow when natural circulation was low.

Solar assisted dryer system efficiency was estimated at 57.7% with average drying rate of 0.077kg/hr with back-up heating operation increasing solar dryer efficiency by 17.8%.

In these circumstances it is evident that modern solar drying technology is faster than the open sun drying method. The solar dryer designed for the purpose has the advantages of reducing the damages caused to the product by insect, birds, rodents, mirco-organisms and the adverse climatic conditions. The drying time is also reduced considerably.

6.2 RECOMMENDATION

1) Improvements of the dryer performance can be achieved through further modifications, which include: Re-circulation of pre-heated air exiting dryer chamber to collector inlet

2) Further performance tests should be done on the dryer system at the current study area as well as in different ecological zones

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9.0 APPENDICES

Appendix A0: Sun drying experiment results for the month August, September and October, 2012

The formula for calculating moisture content on the basis weight loss measurements during the sun drying is:-

$$W=\left(1 - {}^{m2}/_{m1}\right)*100$$

W - Moisture content in %

m1 - mass of test sample before drying

m2 - mass of test sample after drying

Month of August 2012

Date	Time	Wt. of Maize, kg	$\frac{m2}{m1}$	$\left(1-\frac{m2}{m1}\right)*100$	Total Weight Loss, Kg	Moisture Content, %	Ambient Air	
							Temperature, ºc	Avg. Relative Humidity, %
18-Aug-12	11:00	4.1				19.30	27.30	68
	15:00	3.98	0.97	2.93	0.12	16.37	26.50	72
19-Aug-12	11:00	3.99	0.97	2.68	0.11	16.62	28.00	67
	15:00	3.94	0.96	3.90	0.16	15.40	27.00	67.5
20-Aug-12	11:00	3.94	0.96	3.90	0.16	15.40	27.50	68
	15:00	3.91	0.95	4.63	0.19	14.67	26.20	70
21-Aug-12	9:00	3.92	0.96	4.39	0.18	14.91	25.00	73
	15:00	3.88	0.95	5.37	0.22	13.93	26.00	72
22-Aug-12	11:00	3.88	0.95	5.37	0.22	13.93	27.10	68
	15:00	3.86	0.94	5.85	0.24	13.45	26.70	71.5
23-Aug-12	10:00	3.87	0.94	5.61	0.23	13.69	27.20	68.1
	15:00	3.85	0.94	6.10	0.25	13.20	26.80	71.5

Month of September 2012

Date	Time	Wt. of Maize, kg	$\frac{m2}{m1}$	$\left(1-\frac{m2}{m1}\right)\%$	Total Weight Loss, Kg	Moisture Content, %	Ambient Air	
							Temperature, °c	Avg. Relative Humidity, %
19-Sep-12	11:00	4.1				19.30	27.00	68.00
	15:00	3.97	0.97	3.17	0.13	16.13	26.80	72.00
20-Sep-12	11:00	3.98	0.97	2.93	0.12	16.37	27.80	67.00
	15:00	3.95	0.96	3.66	0.15	15.64	26.90	71.00
21-Sep-12	11:00	3.95	0.96	3.66	0.15	15.64	27.40	72.60
	15:00	3.91	0.95	4.63	0.19	14.67	26.10	71.00
22-Sep-12	11:00	3.91	0.95	4.63	0.19	14.67	26.50	65.00
	15:00	3.87	0.94	5.61	0.23	13.69	27.10	68.00
23-Sep-12	11:00	3.88	0.95	5.37	0.22	13.93	26.20	70.00
	15:00	3.86	0.94	5.85	0.24	13.45	26.70	71.50

Month of October 2012

Date	Time	Wt. of Maize, kg	$\frac{m2}{m1}$	$\left(1-\frac{m2}{m1}\right)\%$	Total Weight Loss, Kg	Moisture Content, %	Ambient Air	
							Temperature, ºc	Avg. Relative Humidity, %
8-Oct-12	11:00	4.1				19.30	27.10	69.00
	15:00	3.97	0.97	3.17	0.13	16.13	26.80	71.00
9-Oct-12	11:00	3.97	0.97	3.17	0.13	16.13	27.80	67.00
	15:00	3.95	0.96	3.66	0.15	15.64	26.50	72.00
10-Oct-12	11:00	3.96	0.97	3.41	0.14	15.89	27.20	68.00
	15:00	3.93	0.96	4.15	0.17	15.15	26.20	73.00
11-Oct-12	11:00	3.93	0.96	4.15	0.17	15.15	26.80	71.00
	15:00	3.91	0.95	4.63	0.19	14.67	26.00	73.00
12-Oct-12	11:00	3.91	0.95	4.63	0.19	14.67	27.10	68.50
	15:00	3.88	0.95	5.37	0.22	13.93	26.50	72.00
13-Oct-12	11:00	3.89	0.95	5.12	0.21	14.18	26.90	71.20
	15:00	3.87	0.94	5.61	0.23	13.69	26.60	71.80
14-Oct-12	11:00	3.87	0.94	5.61	0.23	13.69	27.20	70.00

4.1kg of maize grains sample having initial moisture content of 19.3% was dried by sun drying to a final moisture content of 13.4% in 6 days of 4 hours each during sampled days in the months of August, September and October.

Appendix A1: Solar irradiance and ambient temperatures

Date: 18/8/2012

Time (24Hrs)	solar Irradiance in W/M^2 (watts per sq.m)	Ambient temperature ^0C
1105	1025	27.3
1205	1035	27.6
1305	1015	27.4
1418	975	27.0
1538	718	26.5

Date: 19/9/2012

Time (24Hrs)	solar Irradiance in W/M^2(watts per sq.m)	Ambient temperature ^0C
1100	1020	27.3
1207	1028	27.4
1308	1035	27.4
1456	1004	27.2
1547	890	26.8

Date: 08/10/2012

Time (24Hrs)	solar Irradiance in W/M^2 (watts per sq.m)	Ambient temperature ^0C
1000	975	26.0
1100	1005	26.6
1200	1015	27.2
1300	1035	27.6
1400	1020	27.5

Date: 10/10/2012

Time (24Hrs)	**solar Irradiance in W/M^2(watts per sq.m)**	**Ambient temperature ^0C**
1100	1020	27.0
1205	1025	27.3
1305	1030	27.4
1405	1004	27.2
1545	855	26.5

Appendix A1.1: Average Values of Solar Irradiances and ambient temperatures

Time (24Hrs)	**solar Irradiance in W/M^2(watts per sq.m)**	**Ambient temperature ^{0}C**
1100	1023	27.3
1205	1030	27.4
1305	1020	27.4
1405	980	27.2
1545	780	26.8

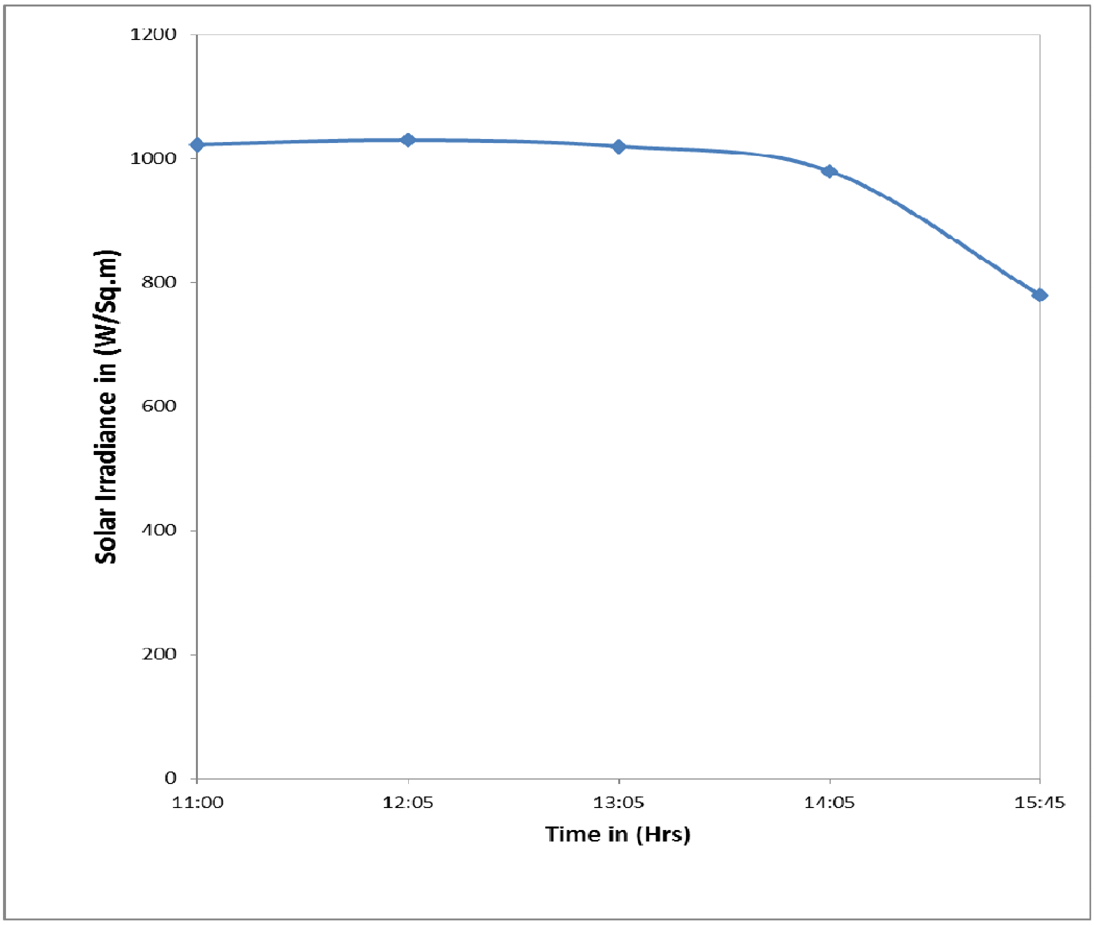

Figure 8.1 Agraph showing variation of average solar radiation with time of the day during the experiment period.

Appendix A2: Solar Drier

Drying the maize grains using solar dryer

DAY ONE
Avg. Amb. Temp. 27.4°C
Air Flow Vel. 15.5m/s

	Solar chamber			**Drying chamber**		
	T_{in}	**T_{out}**	**ΔT**	**T**		
Time, Hrs	**^0C**	**^0C**	**^0C**	**^0C**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00	27.4	31.7	4.3	30.4	4.100	19.3%
11:10	27.7	30.7	3	29.8		
11:20	27.4	31.1	3.7	29.3		
11:30	27.4	31.3	3.9	30.3		
11:40	27.4	31.7	4.3	30.3		
11:50	27.4	31.3	3.9	30.8		
12:00	27.4	31.2	3.8	30.7		
12:10	27.2	31.4	4.2	30.4		
12:20	27.1	29.3	2.2	28.8		
12:40	27.1	29	1.9	28.4		
13:00	27.1	29.2	2.1	28.1		
13:20	27.1	29.1	2	28.5		
13:40	27	29.2	2.2	28.8		
14:00	26.9	28.7	1.8	28.5		
14:20	26.9	28.1	1.1	28		
14:40	26.7	28	1.3	27.8		
15:00	26.5	28	1.5	28	3.92	14.9%

Initial moisture content = 19.3%; Final Moisture Content =14.9%

Initial weight of grains = 4.1kg; Final Weight of grains = 3.92kg

DAY TWO

Avg. Amb. Temp. 28.1°C

Air Flow Vel. 15.5m/s

	Solar chamber			**Drying chamber**		
Time, Hrs	**T_{in}**	**T_{out}**	**ΔT**	**T**		
	^0C	**^0C**	**^0C**	**^0C**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	28	32.7	4.7	30.4	3.92	14.9%
11:10:00	27.9	32.8	4.9	29.8		
11:20:00	28.3	32.8	4.5	31.3		
11:30:00	28.2	33.1	4.9	31.7		
11:40:00	28.2	33	4.8	31.8		
11:50:00	28.2	33.1	4.9	31.7		
12:00:00	28.2	33.2	5	31.7		
12:10:00	28.2	33	4.8	31.4		
12:20:00	28.1	33.1	5	31.7		
12:40:00	28.1	33	4.9	31.9		
13:00:00	28.1	32.8	4.7	31.1		
13:20:00	28	31.2	3.2	30		
13:40:00	27.8	30.8	3	29.5		
14:00:00	27.8	30.3	2.5	29.4		
14:20:00	27.3	29.3	2	28.7		
14:40:00	26.8	28.1	1.3	28		
15:00:00	26.1	27.4	1.3	27.3	3.87	13.7%

Initial moisture content = 14.9%; Final Moisture Content =13.7%

Initial weight of grains = 3.92kg; Final Weight of grains = 3.87kg

DAY THREE

Avg. Amb. Temp. 28.0°C

Air Flow Vel. 15.5m/s

	Solar chamber			**Drying chamber**		
Time, Hrs	$\mathbf{T_{in}}$	$\mathbf{T_{out}}$	**ΔT**	**T**		
	^{0}**C**	^{0}**C**	^{0}**C**	^{0}**C**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	27.6	31.3	3.7	30.2	3.87	13.7%
11:10:00	27.9	31.7	3.8	30.6		
11:20:00	28	32.4	4.4	31.3		
11:30:00	28.1	32.6	4.5	31.2		
11:40:00	28	32.6	4.6	31.4		
11:50:00	28	32.4	4.4	31.2		
12:00:00	28	32.5	4.5	31.7		
12:10:00	28	32.6	4.6	31.4		
12:20:00	28.1	32.8	4.7	31.8		
12:40:00	28.1	32.9	4.8	31.9		
13:00:00	28.1	32.8	4.7	32.1		
13:20:00	28	32.7	4.7	32		
13:40:00	27.6	32	4.4	31.2		
14:00:00	27.6	31.7	4.1	31		
14:20:00	27.5	31.6	4.1	31		
14:40:00	27.3	31	3.7	30.5		
15:00:00	27	30.7	3.7	30.1	3.83	13.2%

Initial moisture content = 13.7%; Final Moisture Content =13.2%

Initial weight of grains = 3.87kg; Final Weight of grains = 3.83kg

Drying the maize grains using solar dryer in the month of August 2012

DAY	ONE
DATE	18-Aug-12
Avg. Ambient Temp.	26.9°C
Air Flow Velocity	15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00	27.8	32.1	4.3	30.8	4.10	19.3%
11:10	28.1	30.9	2.8	30		
11:20	27.6	32	4.4	30.2		
11:30	27.5	31.4	3.9	30.4		
11:40	27.5	32	4.5	30.6		
11:50	27.4	31.3	3.9	30.8		
12:00	27.5	31.4	3.9	30.9		
12:10	27.7	31.2	3.5	30		
12:20	27.4	29.5	2.1	29		
12:40	27.3	29.2	1.9	28.6		
13:00	27.4	29.5	2.1	28		
13:20	27.3	29.3	2	28.7		
13:40	27.2	29.6	2.4	29.2		
14:00	27.1	28.9	1.8	28.6		
14:20	27	28.2	1.2	27.8		
14:40	26.6	28	1.4	27.8		
15:00	26.3	28.1	1.8	27.4	3.93	15.0%

Initial moisture content = 19.3%; Final Moisture Content =15.0%

Initial weight of grains = 4.1kg; Final Weight of grains = 3.93kg

DAY	TWO
DATE	19-Aug-12
Avg. Ambient Temp.	27.0°C
Air Flow Velocity	15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize, kg**	**Moisture Content, %**
11:00:00	28.4	33.5	5.1	30.5	3.93	15.0%
11:10:00	28.3	33.5	5.2	29.9		
11:20:00	28.6	33.2	4.6	31.4		
11:30:00	28.3	33.3	5	31.9		
11:40:00	28.4	33.8	5.4	32		
11:50:00	28.5	34.1	5.6	31.7		
12:00:00	28.6	33.9	5.3	31.7		
12:10:00	28.7	32.8	4.1	31.5		
12:20:00	28.2	33	4.8	31.9		
12:40:00	28.2	33.1	4.9	32.2		
13:00:00	28.3	32.9	4.6	31.1		
13:20:00	28.1	31.3	3.2	29.5		
13:40:00	27.9	30.9	3	29.4		
14:00:00	28	30.4	2.4	29.4		
14:20:00	27.3	29.1	1.8	28.8		
14:40:00	26.8	28	1.2	28		
15:00:00	25.8	27.1	1.3	27.4	3.86	13.6%

Initial moisture content = 15.0%; Final Moisture Content =13.6%

Initial weight of grains = 3.93kg; Final Weight of grains = 3.86kg

DAY	THREE
DATE	20-Aug-12
Avg. Ambient Temp.	27.3°C
Air Flow Velocity	15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize, kg**	**Moisture Content, %**
11:00:00	27.8	31.5	3.7	30.4	3.86	13.6%
11:10:00	28.1	32	3.9	31.1		
11:20:00	28	32.5	4.5	31.5		
11:30:00	28.2	33.9	5.7	31.4		
11:40:00	27.9	32.8	4.9	32		
11:50:00	28	31.4	3.4	31.5		
12:00:00	28.1	31.9	3.8	32.1		
12:10:00	28.2	32.8	4.6	31.6		
12:20:00	28.3	33.2	4.9	32.2		
12:40:00	28.1	32.9	4.8	32.3		
13:00:00	27.9	33.1	5.2	32.3		
13:20:00	28.2	32.7	4.5	32		
13:40:00	27.8	31.8	4	31.4		
14:00:00	27.8	31.9	4.1	31.1		
14:20:00	27.5	31.9	4.4	31.1		
14:40:00	27.1	31	3.9	30.4		
15:00:00	27.4	31	3.6	30.6	3.83	12.9%

Initial moisture content = 13.6%; Final Moisture Content =12.9%

Initial weight of grains = 3.93kg; Final Weight of grains = 3.83kg

<u>Drying the maize grains using solar dryer in the month of September 2012</u>

DAY	ONE
DATE	19-Sep-12
Avg. Ambient Temp.	26.7°C
Air Flow Velocity	15.5m/s

	Solar chamber			Drying chamber		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize, kg**	**Moisture Content, %**
11:00	27.1	31.4	4.3	30.1	4.100	19.3%
11:10	27.4	30.6	3.2	29.7		
11:20	27.3	30.8	3.5	29		
11:30	27.4	31.4	4	30.4		
11:40	27.4	31.6	4.2	30.2		
11:50	27.4	31.4	4	30.9		
12:00	27.3	31	3.7	30.5		
12:10	26.9	31.8	4.9	30.8		
12:20	27	29.4	2.4	28.9		
12:40	27.1	29	1.9	28.4		
13:00	27	29.3	2.3	28.2		
13:20	27.1	29.2	2.1	28.6		
13:40	27	29.2	2.2	28.8		
14:00	26.8	28.6	1.8	28		
14:20	26.9	28.2	1.3	27.8		
14:40	26.8	28.1	1.3	26.5		
15:00	26.7	28	1.3	26.3	3.910	14.7%

DAY TWO

DATE 20-Sep-12

Avg. Amb. Temp. 27.4°C

Air Flow Velocity 15.5m/s

	Solar chamber			Drying chamber		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	27.7	32.4	4.7	30.3	3.91	14.7%
11:10:00	27.6	32.7	5.1	29.7		
11:20:00	28.2	32.5	4.3	31.2		
11:30:00	28.2	33.2	5	31.5		
11:40:00	28.2	32.9	4.7	31.6		
11:50:00	28.2	33.2	5	31.7		
12:00:00	28.1	33	4.9	31.7		
12:10:00	27.9	33.4	5.5	31.3		
12:20:00	28	33.2	5.2	31.5		
12:40:00	28.1	33	4.9	31.6		
13:00:00	28	32.9	4.9	31.1		
13:20:00	28	31.3	3.3	30.5		
13:40:00	27.8	30.8	3	29.6		
14:00:00	27.7	30.2	2.5	29.4		
14:20:00	27.3	29.4	2.1	28.6		
14:40:00	26.9	28.2	1.3	28		
15:00:00	26.3	27.4	1.1	27.2	3.87	13.8%

DAY THREE

DATE 21-Sep-12

Avg. Amb. Temp. 26.8°C

Air Flow Velocity 15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	27.5	31.2	3.7	30.1	3.87	13.8%
11:10:00	27.8	31.5	3.7	30.2		
11:20:00	28.1	32.4	4.3	31.2		
11:30:00	28.1	31.5	3.4	31		
11:40:00	28.2	32.4	4.2	31.2		
11:50:00	28	33.4	5.4	30.9		
12:00:00	27.9	33.2	5.3	31.5		
12:10:00	27.9	32.4	4.5	31.2		
12:20:00	28	32.6	4.6	31.6		
12:40:00	28.1	32.9	4.8	31.5		
13:00:00	28.2	32.7	4.5	32		
13:20:00	28	32.7	4.7	32		
13:40:00	27.5	32.1	4.6	31		
14:00:00	27.4	31.5	4.1	30.8		
14:20:00	27.5	31.4	3.9	30.8		
14:40:00	27.4	31	3.6	30.6		
15:00:00	26.8	30.5	3.7	29.9	3.840	13.1%

Drying the maize grains using solar dryer in the month of October 2012

DAY ONE

DATE 8-Oct-12

Avg. Ambient Temp. 27.0 ^{0}C

Air Flow Velocity 15.5m/s

	Solar chamber			Drying chamber		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00	27.3	31.6	4.3	30.3	4.100	19.3%
11:10	27.6	30.6	3.0	29.7		
11:20	27.3	30.5	3.2	28.7		
11:30	27.3	31.1	3.8	30.1		
11:40	27.3	31.5	4.2	30.1		
11:50	27.4	31.2	3.8	30.7		
12:00	27.4	31.2	3.8	30.7		
12:10	27	31.2	4.2	30.4		
12:20	26.9	29.0	2.1	28.5		
12:40	26.9	28.8	1.9	28.2		
13:00	26.9	28.8	1.9	28.1		
13:20	26.9	28.8	1.9	28.2		
13:40	26.8	28.8	2.0	28.4		
14:00	26.8	28.6	1.8	28.2		
14:20	26.8	27.9	1.1	27.3		
14:40	26.7	27.9	1.2	27.4		
15:00	26.5	27.9	1.4	27.4	3.928	15.10%

DAY TWO

DATE 9-Oct-12

Avg. Amb. Temperature 27.2 ^{0}C

Air Flow Velocity 15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	27.9	32.2	4.3	30.4	3.928	15.1%
11:10:00	27.8	32.2	4.4	29.8		
11:20:00	28.1	32.7	4.6	31.3		
11:30:00	28.1	32.8	4.7	31.7		
11:40:00	28.0	32.3	4.3	31.8		
11:50:00	27.9	32.0	4.1	31.7		
12:00:00	27.9	32.7	4.8	31.7		
12:10:00	28.0	32.8	4.8	31.4		
12:20:00	28.1	33.1	5.0	31.7		
12:40:00	28.0	32.9	4.9	31.9		
13:00:00	28.0	32.6	4.6	31.1		
13:20:00	27.9	31.0	3.1	30.0		
13:40:00	27.7	30.7	3.0	29.5		
14:00:00	27.7	30.3	2.6	29.4		
14:20:00	27.3	29.4	2.1	28.7		
14:40:00	26.7	28.1	1.4	28.0		
15:00:00	26.2	27.7	1.5	27.3	3.870	13.70%

DAY THREE

DATE 10-Oct-12

Avg. Ambient Temp. 26.7 ^{0}C

Air Flow Velocity 15.5m/s

	Solar chamber			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T (^{0}C)**	**Wt. of Maize,kg**	**Moisture Content, %**
11:00:00	27.5	31.2	3.7	30.1	3.870	13.7%
11:10:00	27.8	31.6	3.8	30.5		
11:20:00	27.9	32.3	4.4	31.2		
11:30:00	28.0	32.4	4.4	31.2		
11:40:00	27.9	32.6	4.7	31.0		
11:50:00	28.0	32.4	4.4	31.2		
12:00:00	28.0	32.4	4.4	31.5		
12:10:00	27.9	32.6	4.7	31.4		
12:20:00	28.0	32.6	4.6	31.6		
12:40:00	28.1	32.9	4.8	31.9		
13:00:00	28.2	32.6	4.4	32.0		
13:20:00	27.8	32.7	4.9	32.0		
13:40:00	27.5	32.1	4.6	31.2		
14:00:00	27.6	31.7	4.1	31.1		
14:20:00	27.5	31.5	4.0	31.1		
14:40:00	27.4	31.0	3.6	30.5		
15:00:00	26.8	30.6	3.8	29.8	3.835	12.8%

Appendix A3: Biomass Heater as source of heat in the dryer

DATE 21-Aug-12

Avg. Ambient Temp. 25.5°C

Air Flow Velocity 15.5m/s

	Heater Chamber			Drying chamber		
Time, Hrs	**T_{in}**	**T_{out}**	**∆T**	**T**		
	^0C	**^0C**	**^0C**	**^0C**	**Wt. of Maize, kg**	**Moisture Content, %**
11:00:00	26.0	40.2	14.2	35.2	4.1	19.3%
11:10:00	27.3	43.5	16.2	36.4		
11:20:00	27.4	42.7	15.3	35.2		
11:30:00	27.5	41.0	13.5	34.3		
11:40:00	27.4	39.5	12.1	36.8		
11:50:00	27.4	40.4	13.0	37.3		
12:00:00	27.1	44.3	17.2	40.1		
12:10:00	27.2	45.5	18.3	41.0		
12:20:00	28.2	46.0	17.8	41.3		
12:40:00	27.0	42.4	15.4	40.5		
13:00:00	27.1	45.0	17.9	41.6		
13:20:00	27.1	43.0	15.9	40.6		
13:40:00	26.8	41.8	15.0	40.7		
14:00:00	26.5	41.8	15.3	40.8		
14:20:00	26.5	42.3	15.8	41.2		
14:40:00	26.3	42.9	16.6	42.7		
15:00:00	26.3	42.6	16.3	42.4		
15:20:00	26.1	42.6	16.5	42.4		
15:40:00	26.0	41.6	15.6	41.5	3.86	13.5%

Appendix A3: Biomass Heater as source of heat in the dryer

DATE 22-Sep-12

Avg. Ambient Temp. 26.8°C

Air Flow Velocity 15.5m/s

	Heater Chamber			Drying chamber		
Time, Hrs	T_{in}	T_{out}	ΔT	T		
	^0C	^0C	^0C	^0C	**Wt. of Maize, kg**	**Moisture Content, %**
11:00:00	27.3	40.1	12.8	35.3	4.1	19.3%
11:10:00	27.6	43.5	15.9	36.7		
11:20:00	27.3	42.6	15.3	35.3		
11:30:00	27.2	41.4	14.2	34.3		
11:40:00	27.4	40.0	12.6	37.0		
11:50:00	27.4	40.0	12.6	37.2		
12:00:00	27.3	44.2	16.9	40.3		
12:10:00	27.2	45.6	18.4	41.1		
12:20:00	28.0	45.8	17.8	41.4		
12:40:00	27.1	42.2	15.1	40.4		
13:00:00	27.0	42.8	15.8	41.2		
13:20:00	26.9	41.8	14.9	40.6		
13:40:00	26.7	41.6	14.9	40.7		
14:00:00	26.9	41.8	14.9	40.7		
14:20:00	26.4	42.3	15.9	41.1		
14:40:00	26.5	43.0	16.5	42.7		
15:00:00	26.2	42.7	16.5	42.4		
15:20:00	26.1	42.5	16.4	42.4		
15:40:00	25.9	41.7	15.8	41.6	3.84	13.0%

Appendix A3: Biomass Heater as source of heat in the dryer

DATE 11-Oct-12

Avg. Ambient Temp. 26.5°C

Air Flow Velocity 15.5m/s

	Heater Chamber			Drying chamber		
Time, Hrs	T_{in}	T_{out}	ΔT	T		
	^0C	^0C	^0C	^0C	Wt. of Maize, kg	Moisture Content, %
11:00:00	28.9	40.6	11.7	35.7	4.1	19.3%
11:10:00	28.2	44.4	16.2	37.3		
11:20:00	27.5	42.8	15.3	35.4		
11:30:00	27.5	42.1	14.6	34.3		
11:40:00	27.4	40.5	13.1	37.2		
11:50:00	27.4	39.6	12.2	37.4		
12:00:00	27.8	45.0	17.2	40.5		
12:10:00	27.2	46.0	18.8	40.9		
12:20:00	28.1	45.9	17.8	41.5		
12:40:00	27.2	42.0	14.8	40.6		
13:00:00	27.2	40.9	13.7	40.8		
13:20:00	27.0	40.6	13.6	40.6		
13:40:00	26.9	41.7	14.8	40.7		
14:00:00	27.3	41.8	14.5	40.9		
14:20:00	26.6	42.6	16.0	41.3		
14:40:00	26.7	43.1	16.4	42.7		
15:00:00	26.4	42.8	16.4	42.4		
15:20:00	26.1	42.7	16.6	43.0		
15:40:00	26.1	41.8	15.7	41.7	3.85	13.2%

Appendix A4: Solar drier assisted by biomass heater (Both sources of heat engaged)

DATE	22-Aug-12
Avg. Amb. Temp.	27
Air Flow Vel.	15.5m/s ;
Avg. RH	70%

	Solar chamber			**Heater chamber**			**Drying chamber**		
Time	**T_{in}**	**T_{out}**	**ΔT**	**T_{in}**	**T_{out}**	**ΔT**	**T_{out}**	**Wt. of Maize, kg**	**Moisture**
(Mins)	**^0C**	**^0C**	**^0C**	**^0C**	**^0C**	**^0C**	**^0C**		**(%)**
12:00:00	27.00	28.50	1.50	28.5	48.4	19.9	33	4.1	19.3
12:10:00	27.17	28.50	1.33	28.5	47.1	18.6	34.2		
12:20:00	27.07	30.10	3.03	30.1	46.2	16.1	36.5		
12:30:00	27.00	30.10	3.10	30.1	47.1	17	45.3		16.3
12:40:00	26.93	30.40	3.47	30.4	47.7	17.3	44.8		
12:50:00	26.97	30.30	3.33	30.3	49.2	18.9	47.5		
13:00:00	27.07	30.20	3.13	30.2	48.0	17.8	46.6		14.7
13:10:00	27.20	30.10	2.90	30.1	45.0	14.9	44.4		
13:20:00	26.97	28.30	1.33	28.3	42.0	13.7	39.4		14.1
13:40:00	26.87	28.00	1.13	28	44.6	16.6	43.9		
14:00:00	26.87	28.20	1.33	28.2	44.5	16.3	44.3		13.8
14:20:00	26.87	28.10	1.23	28.1	44.6	16.5	44.2		13.7
14:40:00	26.63	28.20	1.57	28.2	44.6	16.4	44		13.6
15:00:00	26.63	27.20	0.57	27.9	44.3	16.4	43.5	3.87	13.3

Appendix A4: Solar drier assisted by biomass heater (Both sources of heat engaged)

DATE 25-Sep-12

Avg. Ambient Temp. 26.5^{0}C

Air Flow Velocity 15.5m/s

Avg. RH 69%

	Solar chamber			**Heater chamber**			**Drying chamber**		
Time, hrs	**T_{in}(^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T_{in} (^{0}C)**	**T_{out} ^{0}C)**	**ΔT (^{0}C)**	**T_{out} (^{0}C)**	**Wt. of Maize, kg**	**Moisture (%)**
12:00:00	27.2	31.5	4.3	31.5	43.4	11.9	36.2	4.1	19.3
12:10:00	27.5	30.5	3	30.5	46.6	16.1	34.7		
12:20:00	27.2	31.3	4.1	31.3	46.6	15.3	35.3		
12:30:00	27.4	31.4	4	31.4	46.5	15.1	36		
12:40:00	27.4	32.7	5.3	32.7	46.8	14.1	41		
12:50:00	27.5	33.2	5.7	33.2	48.5	15.3	42.1		
13:00:00	27.4	31.2	3.8	31.2	49	17.8	45.2		
13:10:00	27.1	31.5	4.4	31.5	49.6	18.1	46		
13:20:00	27.8	29.3	1.5	29.3	47	17.7	45.2		
13:40:00	27.1	29.1	2	29.1	44.2	15.1	42.5		
14:00:00	27	29.2	2.2	29.2	44.7	15.5	44.2		
14:20:00	27	28	1	28	44.8	16.8	44.5		
14:40:00	26.7	27.9	1.2	27.9	44.7	16.8	44.6		
15:00:00	26.7	28	1.3	28	44.7	16.7	44.6	3.88	13.8

Appendix A4: Solar drier assisted by biomass heater (Both sources of heat engaged)

DATE 14-Oct-12

Air Flow Vel. 15.5m/s

Avg. RH . …70%

	Solar chamber			**Heater chamber**			**Drying chamber**		
Time, hrs	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T_{in} (^{0}C)**	**T_{out} (^{0}C)**	**ΔT (^{0}C)**	**T_{out} (^{0}C)**	**Wt. of Maize, kg**	**Moisture (%)**
12:00:00	27.6	31.9	4.3	31.9	43.8	11.9	36.6	4.1	19.3
12:10:00	27.9	30.9	3	30.9	47	16.1	34.9		
12:20:00	27.6	30.9	3.3	30.9	46.8	15.9	35.3		
12:30:00	27.4	31.2	3.8	31.2	46.5	15.3	36.6		
12:40:00	27.4	32.7	5.3	32.7	49.2	16.5	39		
12:50:00	27.3	32.8	5.5	32.8	47.5	14.7	42.5		
13:00:00	27.4	31.2	3.8	31.2	48	16.8	45.4		
13:10:00	27.3	31.3	4	31.3	49.8	18.5	46		
13:20:00	28.4	29.3	0.9	29.3	46.8	17.5	45.6		
13:40:00	27.1	28.9	1.8	28.9	44.2	15.3	44.5		
14:00:00	27.2	29.2	2	29.2	45.1	15.9	44.2		
14:20:00	27	28	1	28	44.8	16.8	44.7		
14:40:00	26.9	27.7	0.8	27.7	44.7	17	44.8		
15:00:00	27.1	27.8	0.7	27.9	44.9	17	44.8	3.87	13.6

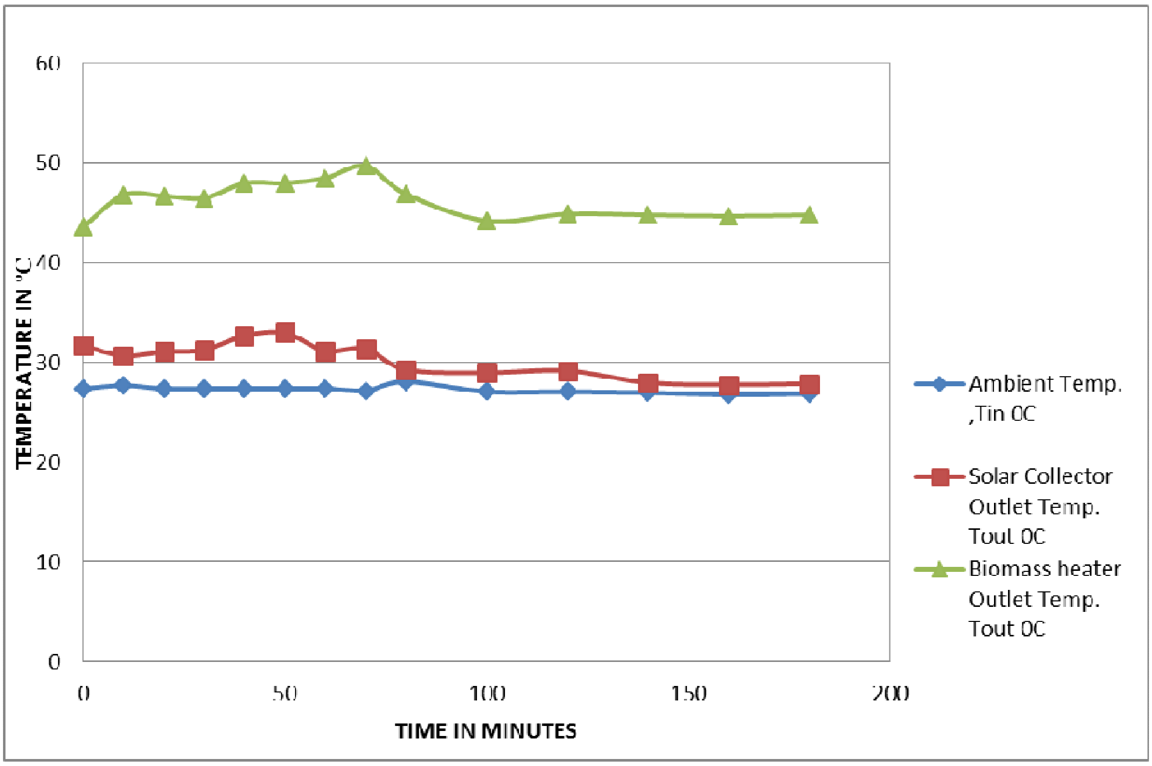

Figure 8.2: A graph of variations in ambient temperature, Solar collector outlet temperature and biomass heater outlet temperature with time in a day for a typical experimental run during solar assisted drying of maize.

Appendix A5.1: The static pressure chart for maize grain

Fan/Heater Application **PRESSURE CHART**

STATIC PRESSURE CHART FOR CORN (W/STIRRING)

Static Pressure (inches of water column)

GRAIN DEPTH FEET	Airflow Rate (cfm per bushel)											
	3	2	1	3/4	1/2	1/3	1/4	1/5	1/7	1/10	1/15	1/20
2	0.56	0.54	0.52	0.51	0.51	0.51						
4	0.80	0.68	0.58	0.55	0.53	0.52	0.52	0.51	0.51	0.51		
6	1.29	0.95	0.69	0.63	0.58	0.55	0.54	0.53	0.52	0.51	0.51	0.51
8	2.10	1.40	0.86	0.75	0.65	0.60	0.57	0.55	0.54	0.53	0.52	0.51
10	3.28	2.04	1.09	0.91	0.75	0.65	0.61	0.59	0.56	0.54	0.53	0.52
12	4.90	2.90	1.41	1.12	0.87	0.73	0.66	0.63	0.59	0.56	0.54	0.53
14	7.00	4.02	1.81	1.39	1.03	0.82	0.73	0.68	0.62	0.58	0.55	0.54
16	9.63	5.41	2.30	1.71	1.21	0.93	0.80	0.73	0.66	0.61	0.57	0.55
18	12.86	7.10	2.88	2.10	1.43	1.06	0.89	0.80	0.71	0.64	0.59	0.57
20	16.72	9.11	3.58	2.55	1.69	1.21	1.00	0.88	0.76	0.67	0.61	0.58
22		11.47	4.38	3.08	1.98	1.37	1.11	0.97	0.82	0.71	0.64	0.60
24		14.20	5.31	3.68	2.32	1.57	1.24	1.07	0.88	0.75	0.66	0.62
26		17.32	6.35	4.36	2.69	1.78	1.39	1.18	0.95	0.80	0.69	0.64
28			7.53	5.12	3.11	2.02	1.55	1.30	1.03	0.85	0.72	0.66
30			8.85	5.97	3.58	2.28	1.73	1.43	1.12	0.91	0.76	0.69
32			10.31	6.91	4.09	2.57	1.92	1.57	1.21	0.97	0.80	0.72
34			11.92	7.94	4.66	2.88	2.13	1.73	1.32	1.03	0.84	0.75
36			13.69	9.07	5.27	3.22	2.36	1.90	1.42	1.11	0.88	0.78
38			15.62	10.30	5.93	3.59	2.61	2.08	1.54	1.18	0.93	0.81
40			17.72	11.63	6.65	3.99	2.88	2.28	1.67	1.26	0.98	0.85
42			19.99	13.08	7.43	4.42	3.16	2.49	1.80	1.35	1.03	0.88
44				14.63	8.27	4.87	3.47	2.71	1.95	1.44	1.08	0.92
46				16.30	9.16	5.36	3.79	2.95	2.10	1.53	1.14	0.96
48				18.09	10.11	5.88	4.13	3.20	2.26	1.63	1.20	1.01
50				19.99	11.13	6.44	4.50	3.47	2.43	1.74	1.27	1.05
52					12.21	7.02	4.89	3.75	2.61	1.85	1.34	1.10
54					13.36	7.64	5.30	4.05	2.80	1.97	1.41	1.15
56					14.57	8.30	5.73	4.37	2.99	2.09	1.48	1.20
58					15.85	8.99	6.18	4.70	3.20	2.22	1.56	1.26
60					17.20	9.72	6.66	5.04	3.42	2.36	1.64	1.32
62					18.63	10.48	7.16	5.41	3.65	2.50	1.73	1.38
64					20.13	11.29	7.69	5.79	3.89	2.65	1.81	1.44
66						12.13	8.24	6.18	4.13	2.80	1.90	1.50
68						13.01	8.81	6.60	4.39	2.96	2.00	1.57
70						13.93	9.41	7.03	4.66	3.13	2.10	1.64
72						14.90	10.04	7.49	4.94	3.30	2.20	1.71
74						15.90	10.69	7.96	5.24	3.48	2.31	1.78
76						16.95	11.37	8.45	5.54	3.67	2.42	1.86
78						18.04	12.08	8.95	5.85	3.86	2.53	1.94
80						19.17	12.81	9.48	6.18	4.06	2.65	2.02
82						20.35	13.57	10.03	6.52	4.27	2.77	2.11
84							14.36	10.60	6.87	4.48	2.89	2.19
86							15.18	11.18	7.23	4.70	3.02	2.28
88							16.03	11.79	7.60	4.93	3.15	2.37
90							16.91	12.42	7.99	5.16	3.29	2.47
92							17.82	13.07	8.39	5.40	3.43	2.57
94							18.75	13.74	8.80	5.65	3.58	2.67
96							19.72	14.43	9.22	5.91	3.72	2.77
98								15.15	9.66	6.17	3.88	2.87
100								15.88	10.11	6.44	4.03	2.98

.50" Water Column have been Added To Static Pressure to Account for System Loss
Static Pressures are Calculated Using a 1.15 Factor Applied to Shedd's Data

Appendix A5.2: Reported aflatoxin poisoning cases in Kenya (1960-2010)

Year	Those affected	Numbers affected	Locality (Location/District)	Sources of the toxin	Observed complications/ effects
1960	Ducklings	16,000	White settler farmer Rift Valley	Aflatoxin contaminated groundnut feed	Death
1977	Dogs/poultry	Large numbers	Nairobi, Mombasa/Eldoret	Contaminated products due to poor storage	Death
1981	Humans	12	Machakos	Contaminated maize	Death
		numbers		imported maiize	
1988	Human	3	Meru North	contaminated maize	Death and acute effects
2001	Humans	3 26	Meru North Maua	Mouldy maize Contaminated maize	Death 16 death
2002	Poultry/Dogs	Large numbers	Coast	Contaminated feed	Death
2003	Humans	6	Thika	Mouldy maize	Death
2004	Humans	331	Eastern,Central Makueni Kitui	Aflatoxin contaminated	Acute poisoning 125 deaths
2005	Humans	75	Machakos ,makueni, kitui	Aflatoxin contaminated maize	Acute poisoning, 75 cases with 32 deaths
2006	Humans	20	Makueni, Kitui, Machakos	Contaminated maize	Acute poisoning 10 deaths
2007	Humans	4	Kibwezi, Makueni	Aflatoxin contaminated maize	2 deaths
2008	Humans	5	Kibwezi, Kajiado, mutomo	Contaminated maize	3 hospitalized, 2 deaths
2010	Humans		29 districts in Eastern Kenya	Suspected contaminated maize	Price spiraldown and grain trade breakdown unconfirmed dog cases.

(Source: Erastus, 2011)

Appendix A5.3: Fan performance specifications

FAN PERFORMANCE SPECIFICATIONS

Fan/Heater Application

VANE AXIAL FANS									
			STATIC PRESSURE IN INCHES						
MODEL NO	H.P	FAN DIA	0.0	1.0	2.0	3.0	4.0	5.0	6.0
AF-.75	3/4	12"	2050	1050	500				
AF-12	1	12"	2000	1100	650	250			
AF-14	1	14"	3200	1850	1200	500			
AF-1.5	1.5	18"	4650	3600	2300	1050			
AF-3	3	18"	6300	5200	3700	2000	700		
AF-7	7	24"	12750	11200	9500	7200	3600	950	
AF-10	10	24"	13600	12300	10900	8900	5250	3150	
AF-156	15	26"	17000	15350	13700	12000	9500	6400	4500
AF-158	15	28"	19500	18000	16400	14500	12400	9700	6400

Appendix A5.4: Meteorological data

REPUBLIC OF KENYA
MINISTRY OF ENVIRONMENT & MINERAL RESOURCES
KENYA METEOROLOGICAL DEPARTMENT
Dagoretti Corner, Ngong Road, P. O. Box 30259, 00100 G.P.O. Nairobi, Kenya.
Telephone: 254-020-3867880-5, Fax: +254-020-[illegible]
Mobile: 0724 255 153/4, 0738 120 045/6
E-mail: director@meteo.go.ke WWW: http://www.meteo.go.ke

Attention: VITALIS KIBIWOTT TOO **26th May, 2011**

Please find the following data as requested.

1. Nakuru Maximum and Minimum temperatures for the years 2007-2010
2. Nakuru relative humidity for 2007-2010 (0600z and 1200z)
3. Nakuru radiation 2007-2010

Please note that all the data given is in the form of monthly values.

Kind regards,
Christine O. Mahonga.

For Director KMD

For: DIRECTOR
KENYA METEOROLOGICAL DEPARTMENT
P. O. Box 30259 - 00100, GPO.
NAIROBI.

Please address all replies to the Director of Meteorological Services

Station_ID: 9036261

Station_Name: NAKURU METEOROLOGICAL STATION - NEW

Element_Name Temperature, Maximum and Minimum, (Deg.C)

Month >>>>

YEAR		1	2	3	4	5	6	7	8	9	10	11	12
	Max	25.8	26.6	27.6	25.9	25	23.4	23.1	23.6	24.7	24.7	24.6	26.1
2007	min	12.1	12.2	11.1	12.7	13.2	13.3	12.4	12.1	11.8	10.4	11.3	10.5
	Max	27.1	28.4	27.8	25.5	25.7	25.4	24.4	24.7	25.5	24.5	25	26.5
2008	min	11.2	11.8	12.5	13.2	13	11.7	12	12.7	12.4	13.4	12.3	12.8
	Max	27.5	29	30.1	27	25.7	26.3	26.1	26.9	28	25.8	25.8	25.7
2009	min	11.2	11.8	12.5	13.2	13	11.7	12	12.7	12.4	13.4	12.3	12.8
	Max	26.3	27.3	25.8	25.5	24.8	24.4	24	24.2	24.9	25	24.8	26.9
2010	min	12.2	13.6	13.4	13.8	13.8	12.9	12.7	12.8	12.1	12.8	11.5	11.2

Element_Name Relative humidity at 06Z and 12Z in (%)

Month >>>>

YEAR		1	2	3	4	5	6	7	8	9	10	11	12
	06z	75	76	73	79	80	84	83	83	77	78	77	67
2007	12z	44	41	35	54	54	59	57	54	50	51	49	36
	06z	66	62	68	74	76	75	77	76	79	81	75	64
2008	12z	32	24	33	47	45	43	48	48	47	58	48	35
	06z	62	54	56	73	78	72	67	68	67	69	70	74
2009	12z	30	22	23	47	50	38	35	37	36	47	44	44
	06z	71	77	81	84	83	81	80	80	76	79	77	69
2010	12z	36	41	53	56	55	54	51	52	50	54	53	31

Element_Name Solar Irradiation in (MJ/M²/day)

Month >>>>

YEAR	1	2	3	4	5	6	7	8	9	10	11	12
2007	26.46	24.94	24.85	21	22.99	19.88	20.1	21.7	22.44	22.16	21.92	24.23
2008	24.38	26.92	23.46	21.5	22.61	22.17	20.46	22.11	22.82	21.38	24.06	26.42
2009	25.26	25.48	26.38	22.49	22.64	24.93	23.86	24	23.1	20.32	23.61	22.6
2010	25.09	24.14	23	23.53	22.51							

Appendix A5.5: Kenya: Investors Target Harvest With Mobile Maize Dryers

Press Release : Kenya: Investors Target Harvest With Mobile Maize Dryers

BY ELIZABETH WANJIRU, 2 AUGUST 2011 { Business daily)

Entrepreneurs are positioning themselves for a piece of the grain drying business fuelled by **farmers' growing demand for modern technology** as they race to tame heavy losses occasioned by **grain contamination**. Lesiolo Grain Handlers Limited (LGHL), which exhibited its mobile drier at the ninth edition of the annual agribusiness fair by the Eastern Africa Grain Council (EAGC), is the latest to join other players eyeing this window.

Poor drying due to overreliance on heat from the sun has been cited as a **major cause of Aflatoxin contamination in the country**, which is estimated to claim up to **30 per cent of harvests every season.** "This is a new technology which has been introduced to help farmers avoid issues related to food poisoning as a result of improper moisture extraction from grains," said LGHL market linkages team leader Michael Kimani.
He said that their machine, which uses a mortar, is three months old in the market. Close to 20,000 farmers attending the fair at Rift Valley Institute of Science and Technology flocked the LGHL stand to see the machine.

This comes at a time when **the government and donor partners are advocating adoption of modern drying** techniques to replace roadside drying and mitigate against rising cases of grain contamination. Last year the government condemned maize from about **30 districts** in Coast and Eastern provinces after tests confirmed Aflatoxin contamination. Reports from the World Health Organization (WHO) indicate that the country has suffered from contamination at least six times, including in 1982, 2001, 2004, 2005, 2006 and 2009.
This saw Finance minister Uhuru Kenyatta, in last year's budget**, allocate Sh 400 million and Sh360 million towards buying of fixed and mobile maize driers respectively to reduce post-harvest losses.** The project, which is still in the pilot phase, is yet to be fully implemented after the Agriculture ministry diverted the funds to other areas creating space for private entrepreneurs.

USAid has been testing a mobile dryer in Eastern Kenya as part of an initiative to support food stability in the country. The two-day event, which ended Monday, attracted over 70 exhibitors drawn from the dairy, agrochemical, fertiliser, farm machinery, maize production, banking and storage industries. Running under the theme Enhancing Returns in Agribusiness Investments Opportunities and Challenges, the fair came at a time when the country is facing starvation.

According to EAGC representatives, the fair aimed at creating a forum to address factors contributing to famine and providing mitigation measures on challenges to sustainable food production.

Ministry of Agriculture official Zakayo Magara, who was the chief guest, said the ministry would use such exhibitions to educate more farmers.

Productivity

"With such exhibitions, both public and private sectors like financial institutions come together to enable farmers enhance agricultural productivity which is why the ministry is supporting them," Mr Magara said.

He said through such fairs, farmers are given opportunities to invest in tangible products that penetrate the food market and enhance food insecurity.

EAGC was using the fair to expand commercial small holder agriculture, through building capacity of producers in structured training that would offer access to market information. EAGC executive director Gerald Masila said the fair provided farmers and other attendees' access to relevant and up to date farming techniques. The techniques are expected to enhance grain trade and by extension agricultural production, leading to a multiplier effect on allied industries

Appendix B1: Assorted Photos

Plate 1: Sample of spoiled (rotten) maize affected by Aflatoxin

Plate 2: Solar irradiation measurement during the performance of the experiment and the gadget used (Daystar DS-05A Solar Digital Meter)

Plate 3: Maize sample preparations; measuring the mass of the grains using weighing balance

Plate 4: Woodfuel burning in the back-up heater to supplement the solar collector heat during the performance of the experiment

Plate 5: Hygrometer used in determining ambient relative humidity

Plate 6:Illustration of (a) sliding doors in the drying chamber, (b) flange air regulator mechanism and (c) installed vane axial fan in the assembled maize dyer.

Plate 5. Illustration of plan view of solar assisted maize dryer

Drawing layouts