# DESIGN, CONSTRUCTION AND PERFORMANCE EVALUATION OF A SOLAR DRYING SYSTEM FOR CROPS

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## ABSTRACT

This research presents the design, construction, and analysis of the performance of a mixed-mode solar dryer for crops. A mixed-mode solar dryer utilizes direct solar radiation from the sun as well as input heat ducted from the solar collector inlet which is directly connected to the dryer. Such dryers have been shown to outperform passive solar dryers as it was also shown in this work using drying kinetics.

Tomatoes were dried in the drying chamber under the mixed-mode condition. The maximum dryer temperature obtained was 39.2, while the lowest relative humidity in the dryer was 32%. These conditions are shown to be only fair for drying of tomatoes as it prolongs drying time. The system's performance was largely affected by poor insolation and high heat losses during chosen drying days. Based on drying kinetics, a drying rate of 2.88*units/day* was obtained during the chosen drying days. With this rate, the dryer can dry 2*kg* of tomatoes within three days.

The dryer can reduce the moisture content of 1*kg* of tomatoes from 95% to 14% within 45 hours of drying time. The capacity of the dryer is 1*kg* of products per tray.

A simplified 2D transient heat transfer model of the temperature distribution in the drying chamber is presented. Results obtained show that material selection, insolation, and inlet temperature play a crucial role in the solar dryer performance.

## ACKNOWLEDGMENT

I want to use this opportunity to thank God for his many blessings upon my life, the abundance of provisions, and good health all through this academic sojourn. Firstly I extend my appreciation to the Head of Department Professor Azikiwe Peter Onwualu and co-supervisor (Professor Zabaze Kana). In addition, I would like to acknowledge the support of my entire family residing in Liberia and the United States of America, for their financial support during this difficult period. Finally, my unreserved appreciation goes to my friend and brother, Dr. Fashina Adebayo for the many computer skills he embedded in me, and the encouragement that helped to keep me focused all through this program. May God bless you all!

## DEDICATION

To: Mr. and.Mrs. Momolu F.Guzeh, Deddeh Kolu Pettiquoi, Miss Wenwu M.Weefar and Mr.Thomas Guzeh.

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# CHAPTER 1

## INTRODUCTION

The use of solar drying systems for agricultural products to preserve fruits, vegetables and other crops has been proven to be cheap, reliable, and environmentally friendly [1]. These solar dryers offer another option for processing vegetables and fruits under safe conditions that conform to standards. Some of the good qualities of these solar dryers are minimal maintenance cost, no fuel costs, time saving, occupying less area, improvement of the product quality, environmental protection, and control of required air condition [2].

The availability of satisfactory information regarding efficient solar dryers is lacking in many countries where the food processing methods like indirect solar drying are needed. To eliminate the risk of spoilage during drying and quality production of the products, indirect drying with forced convection air flow is one of the best options [3].

Although the solar air collector is a very important component in the solar drying system, much attention has not been drawn to it during dryer design. In principle, the performance of the solar dryer depends on several operating conditions such as the climatic condition, collector orientation, the thickness of the cover material, wind speed, length and depth of the collector, and the type of material used for the absorber [4].

For this reason, this research has dealt with the optimization of the design, material selection, and required parameters to enhance the efficiency of the designed solar dryer. Drying is one of the methods used to preserve food products for longer periods. Drying helps in the preservation of food, fruits, and vegetables for a long time with good quality. It is a process of moisture removal due to simultaneous heat and mass transfer.

Drying of most agriculture products, especially fruits and vegetables requires hot air in the temperature range of 40 – 60 degrees for safe drying. Direct solar energy coupled with the wind has been used to dry food for years. Sun drying of crops is the widest spread method of food preservation in a lot of African countries due to solar irradiation being very high for the most part of the year. There are some drawbacks relating to the traditional method of drying i.e. placing the crops on mats, trays or paved grounds and exposing the product to the sun and wind. These include poorer quality food caused by contamination by dust, insect attack, enzymatic reactions, and infection by micro-organisms. This system is labor and time intensive as crops have to be covered at night and during bad weather, and the crops continually have to be protected from attack by domestic animals. Non-uniform and insufficient drying is noted, resulting in deterioration of the crop during storage in this method. Fierce drying problems occur especially in humid tropical regions where some crops have to be dried during the rainy season.

Solar air heaters are devices that heat air by utilizing solar energy. It is employed in applications requiring a low temperature below 80 degrees, such as crop drying and space heating. High prices and shortages of fossil fuels have increased the emphasis on using alternative renewable energy resources. Drying products using renewable energy such as solar energy is environmentally friendly and has less environmental impact [5, 6]. Different types of solar dryers have been designed, developed, and tested in the different regions of the tropics and subtropics. The principal categories of the dryers are natural and forced convection solar dryers. In the natural convection solar dryers, the airflow is established by buoyancy induced airflow, while in forced convection solar dryers the airflow is provided by using solar-powered fans or generator-powered fans.

To ensure a continuous supply of healthy and affordable food to the public, efficient and affordable drying methods are necessary. The high-temperature dryers used in industrialized countries are found to be economically viable in developing countries only on large plantations or big commercial establishments. The lower cost of locally manufactured solar dryers offers a promising alternative to reduce the tremendous post-harvest losses. The need to produce high-quality marketable products seems to be a chance to improve the economic situation of the not-so-commercial farmers.

Because solar energy is readily available, environmentally clean, and recognized as one of the promising options for alternative energy, Bal et al decided to introduce solar energy systems, in particular, the design of an indirect solar dryer that would enhance the drying of fruits, vegetables, aromatic plants, spices, fungi and other edible products [6].

Vegetable and fruits form an integral part of the human diet. Post-harvest losses of approximately 40% [7] have become a principal challenge and there is a transient ability to preserve and store foods for off-season consumption due to the lack of proper storage systems.

Optimization of the selection process for the solar dryer can reasonably enhance the longevity of the solar dryer, and the material required for construction must be of high performance, available, and of reasonable cost. The construction materials selected for designing solar dryers in times past include plastic, wood, and sheet. Metals are the best and most often used materials due to their low cost and availability.

## 1.1 Problem Statement

Nowadays drying has become very important in the agricultural sector. In order to maintain the quality of most agricultural products after harvest, they need to be dried and preserved. Proper care of produce during post-harvest time is paramount to preservation with respect to the quality of the products. One of the hampering problems has been designing a solar dryer that is relatively simple using available local materials. Solar dryers at all times have unceasingly been too expensive and have not been built for long term use. This concern can be addressed by using locally available materials to curtail the cost and design a dryer that will have an almost equivalent performance in all weather conditions. This will help to overcome the "out of order due to weather conditions" matter, which has restricted the performance or efficiency of solar dryers in developing countries. Regardless of all these challenges, I propose to optimize the collector design which will be subjected to an increased efficiency. In this research work, the selected product will be adequately dried to prevent spoilage.

## 1.2 Objectives

The specific objectives of this study are to:

1. Design and construct a forced convection solar energy dryer with energy storage.
2. Evaluate the performance of the dryer using several parameters.
3. Study the drying process of at least one high moisture content fruit or vegetable (tomatoes).

## 1.3 Scope

This work is limited to the design of the mixed-mode type of solar dryer, its construction, and testing, using tomatoes as the test crop. From our new design and analysis of the drying process, it means that the experiment and simulation are used to investigate the performance of the dryer under certain conditions. In the material selection process, materials will be selected on the principles of material properties that are relevant to the performance of the solar dryer. However, we will focus mainly on tomato drying. Drying rates of the tomatoes in this mixed-mode condition will also be studied.

# CHAPTER 2

## LITERATURE REVIEW

The sun drying approach may be efficient and cheap but has disadvantages such as exposure to foreign matters, microbial and creepy-crawly insect infestation, and loss due to wetting by rain squalls. To adequately protect the products from the mentioned disadvantages and accelerate the time for drying the products, reduce the moisture and hence wastage through microbial action, different types of solar dryers have been developed. During the 1970's oil and natural gas became a problem, increase in the cost of fossil fuels and the depletion of other fossil fuel resources stimulated effort in the development of solar energy as a practical power source. This led to an interest in harnessing solar energy for heating, cooling, generation of electricity and other purposes. Some other areas of practical application include crop drying, thermal processes in food industries, and drying irrigation [8].

Tomatoes are among the widely used food in most African countries. But its storage poses a big problem for farmers and sellers. It has a high moisture content and this has subjected it to microbial and mechanical damage after harvest. All these factors have led to post-harvest losses, thereby necessitating drying of the portion of the production that will not be readily consumed. However, drying faces a big challenge because of the rising energy cost.

The basic essence of drying is to reduce the moisture content of the product to a level that prevents deterioration after harvest. This has created awareness of renewable energy sources, which has an important role to play in the extension of solar thermal technology to address these challenges.

However, several factors are contributing to post-harvest losses, and some of the technological factors include faulty harvesting and handling practices, poor packaging and transport systems, lack of storage facilities and poor processing techniques. One of the objectives of this work is to design a solar dryer that can optimize drying of crops (e.g. tomatoes) in order to serve the rural farmer in addressing the problems of preservation of high moisture content crops.

However, the performance of the dryer depends on the performance of the solar collector. A number of studies have been conducted in order to improve the performance of the solar dryers. Bennamoum et al [9] studied a simple, efficient and inexpensive solar batch dryer for agricultural products. During periods of low sunshine, a heater is used. An onion was chosen as the dried product because of its swift deterioration characteristic. The overall result indicated that drying was affected by the collector surface, the product characteristics, and the air temperature. El-Shiatry et al [10] designed and constructed a dryer with a collector area of $16.8m^2$, which was expected to dry $195.2kg$ of fresh mango from a moisture content of 81.4% to 10% wet basis, in two days, and under ambient conditions during the harvesting period. Majumdar et al [11] studied briefly the emerging drying methods and selected recent developments applicable to post-harvest processing. They included a heat pump assisted in drying with a multi-mode and time-varying heat inputs, low and atmospheric pressure superheated stream drying, modified atmospheric drying, intermittent batch drying, osmotic pretreatments, microwave-vacuum drying etc. Bolaji et al [12] were able to develop a simple mixed-mode dryer from locally available materials. With the help of experimental analysis, Bolaji et al [13] were able to evaluate the performance of a mixed solar dryer for food preservation. The temperature increase inside the drying cabinet was up to 74% for about 3h immediately after 12 noon. The rate of drying and the efficiency of the system were $0.62kg/h$ and 57.5% respectively. An assisted forced convection solar dryer was developed by Sarsavadia et al [14] to study the effect of flow rate (8.09, 5.25, 2.43kg/*min*), air temperature ($70^oC$, 65oC, 55oC) and fraction of the air recycled (up to 90%) on the total energy requirement in drying of onion slices.

## 2.1 Drying of Agricultural Products

Crop drying is among the most energy-consuming processes on a farm. The objective of drying is to remove moisture from the agriculture produce. Subsequently, it can be processed suitably or stored for an extended period of time. Crops are furthermore dried before storage or during storage by forced circulation of air to prevent spontaneous combustion by inhibiting fermentation. It is estimated that 20% of the world's grains production is lost after harvest because of inefficient handling and poor implementation of post-harvest technology [15].

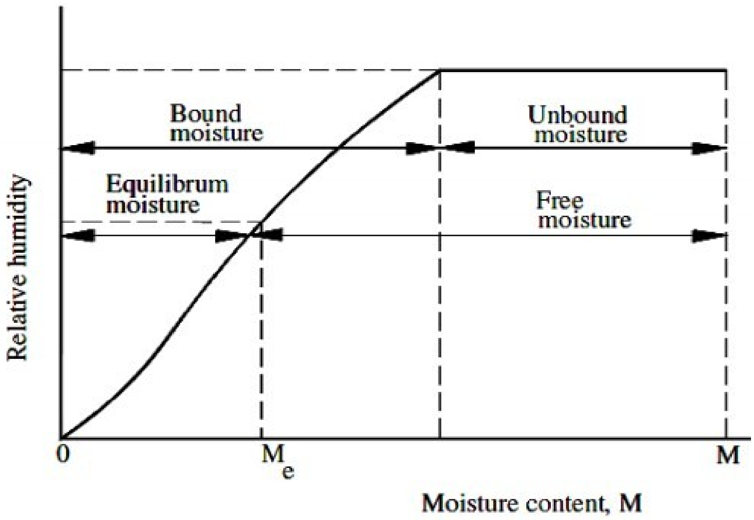



**Figure 2.1**: Relative humidity versus moisture content [15]

Most products are normally harvested at a moisture level between 18% and 40% depending on the nature of the crop. The drying range for the harvested crops is between 7% to 11% depending on the application and the market demand. Some crops are harvested and stored for a certain duration before they are sold or marketed. This storage time depends on the condition in which the crop was harvested and the storage condition being utilized. Crops stored at lower temperature and moisture contents can be kept in storage for a longer period of time before its quality drops. Examples are rice, beans and maize [15]. In all drying processes, the driving force is heat. It is the heat that can evaporate moisture from the material, and the mass flow rate of the air which removes the evaporated moisture. This is possible in two ways namely: the removal of the moisture from the surface of the material to the air by means of evaporation and the other is, the movement of moisture from the interior of the material or product to the surface. This drying process is described as a heat mass transfer process which is dependent upon other essential factors. These factors can be described as both, external and internal factors. The external factors include temperature, humidity and velocity of the air stream whereas the internal factors include the characteristic of the surface (smooth or rough), chemical composition (sugar, starches etc.), physical structure (porosity, density, etc.) and size and shape of the products. However, the rate of moisture removal from the inner part of the product to that of the outer part differs from one product to the other, depending on whether the product is hygroscopic or non-hygroscopic. For the hygroscopic products or materials, there will always be residual moisture content. This residual moisture content can either be a bound moisture which remained in the material as a result surface forces or closed capillaries and unbound moisture which remained in the material due to the surface tension of the water.

Depending on the relative humidity of the air, hygroscopic materials will either absorb or desorb water. Equilibrium moisture content will reach when the vapor pressure of water in the material is equal to the partial pressure of water in the surrounding air [15]. The equilibrium moisture content, therefore, is very important in drying because it is the minimum moisture to which a material can be dried under a particular drying condition. This is illustrated by plotting the moisture content against time. From the above curves, both the hygroscopic and non-hygroscopic material have a constant drying rate but terminating at the critical moisture content. This point is followed by the falling rate. However, for both hygroscopic and non-hygroscopic materials, there is a constant drying rate that is the same, while the period of falling rate is different.

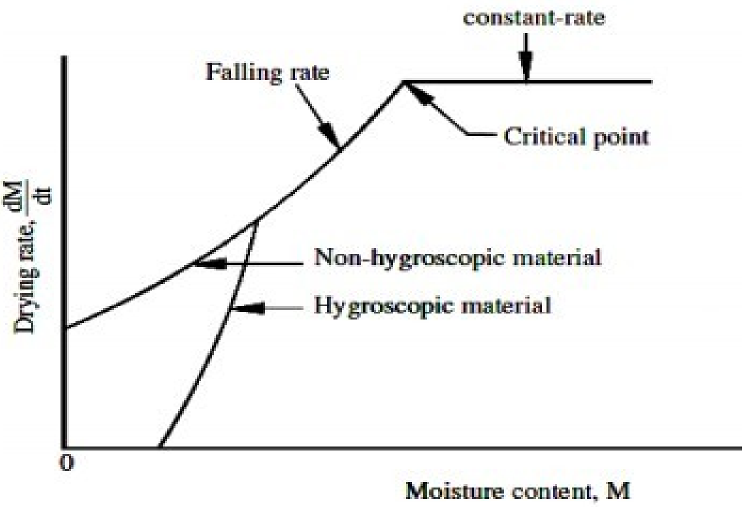



**Figure 2.2**: Rate of moisture loss [15]

For non-hygroscopic materials, the period of falling rate goes on decreasing to the extent where the moisture content will certainly become zero. For the hygroscopic materials, the period of falling rate is similar, until the unbound moisture content is removed; the drying rate further reduces and some bound moisture is removed and continues to till an equilibrium is established between the vapor pressure of the material and that of the vapor pressure of the drying air. When this equilibrium reaches, the rate of drying becomes zero.

The falling rate period for most organic materials is of more interest which depends on the rate at which moisture is removed. In the falling rate, moisture is migrated by diffusion thus causing products with a high moisture content to have slower diffusion due to turgid pressure and filled interstices. For most agricultural products, there is sugar and some other minerals in the liquid phase that also migrate to the surface, increasing viscosity hence reducing the surface vapor pressure and then reducing the moisture evaporation rate [15].

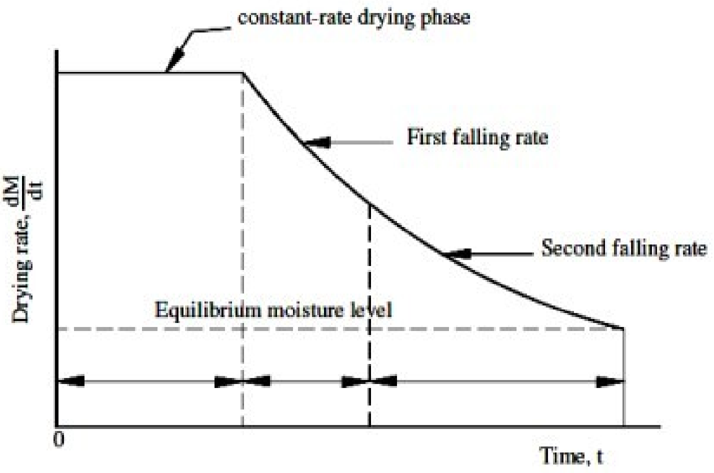



**Figure 2.3**: Drying rate against time [15]

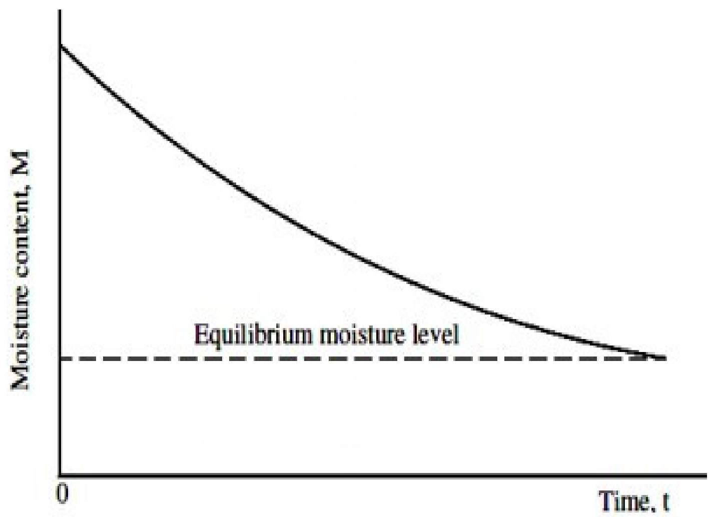



**Figure 2.4**: Typical drying rate curve [15]

## 2.2 Solar Crop Dryers

A new and acceptable technology that addresses the issues of deterioration or loss of quality in product, is the solar drying technology. It is gradually gaining acceptance. Direct and indirect types of solar drying are the two main classifications of this technology.

Solar drying can be done in two forms; either as direct or indirect drying but, the indirect one is by far more efficient than the direct with respect to the quality of the products after drying [15].Direct drying is the conventional and most primitive way of drying crops and other products. This method involves direct exposure of the products to solar radiation, enabling the release of the moisture to the atmospheric air.

The movement of the air is due to the difference in density. This method is achieved in two ways: direct and indirect means.

### 2.2.1 Direct Solar Drying

This has a transparent cover which protects the products from rain and other natural phenomena. This method is mainly passive. This method involves thin layer drying; the products are usually spread over a large space to enable them to be exposed to solar radiation [16]. This process lasts for a long time until the products dry to a required moisture level. It also involves open air solar drying.

The outdoor direct solar drying is mainly useful for grains. Products are mostly spread on floors for usually between $10 - 30$ days [16]. It is the simplest method, but has some drawbacks:

1. It dependent on the climatic conditions and requires very large surface areas and long exposure to the sun.
2. The condition of the final products implies that the production is unskilled.

3. The final condition of the dried products can never be controlled easily.

4. Products may be lost quantity-wise e.g. due to bird, animal and rodent disturbance.

5. Products are most often exposed to all types of weather and changes.

6. Slow drying rate.

7. Direct exposure of products reduces the level of nutrients such as vitamins.

The only advantage is that it is less costly compared to the indirect type. In the direct type of solar dryers, the air heater contains the grains and solar energy which passes through a transparent cover and absorbed by the grains. Clearly, most of the heat required for drying is provided by radiation to the upper layers and gradually into the grains and bed.

### 2.2.2 Indirect Solar Drying

Indirect solar drying has proven to be more effective and efficient relative to the direct type of solar drying. In this type of solar dryer, the air is heated by the flat-plate solar collector or the concentrated type of solar collector. The heating process could be active or passive. The hot air goes to the cabin where the products are stored; the moisture from the products may be lost through convection or diffusion. This method avoids direct solar radiation; it reduces the drawback of the direct type of solar drying. The advantages of the indirect solar dryer are:

1. Drying rate is high, relative to direct solar drying.

2. The final condition of the product can be controlled easily.

3. Losses in products are avoided due to circumstances of natural phenomena.

4. Floor surface area required is very minimal for the same amount of materials in the direct solar dryer.

5. Preservation of nutrient content is better in products since direct exposure to solar radiation is avoided.

6. The same dryer can be used for different seasonal products.

The main disadvantage of the indirect type is the high initial cost. In an indirect dryer, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed. However, 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 energy directly through the transparent walls or the roof.

All drying systems can be classified according to their operating temperature ranges, high-temperature dryers, and low-temperature dryers. The heat source is another important tool for further classification, i.e. into fossil fuel dryer and solar energy dryer. All high-temperature dryers are powered by fossil fuel and are known as conventional dryers. Unlike the low-temperature dryers, that are powered by fossil fuel or solar energy.

### 2.2.3 Classification of Solar Dryers

Solar dryers are classified on the basis of the modes of operation of some important principles [17]. The following criteria helps to classify solar dryers:

1. Direction of air flow

2. Arrangement of the dryer

3. Exposure to insulation

4. Status of the solar distribution

5. Mode of air movement

The mode and manner in which the solar heat is utilized enables the classification to be done in two forms namely: an active solar energy drying system or a forced convection dryer, and passive energy drying system or natural circulation drying system as shown in **Fig. (2.5)**. There are three distinct sub-classes of either the active or passive type of solar dryers which is basically dependent on the design arrangement of the system components and utilization of the solar heat. There are the integral-type of solar dryers, distributed type of solar dryers, and mixed-mode type of solar dryers as illustrated in **Fig. (2.6)**.

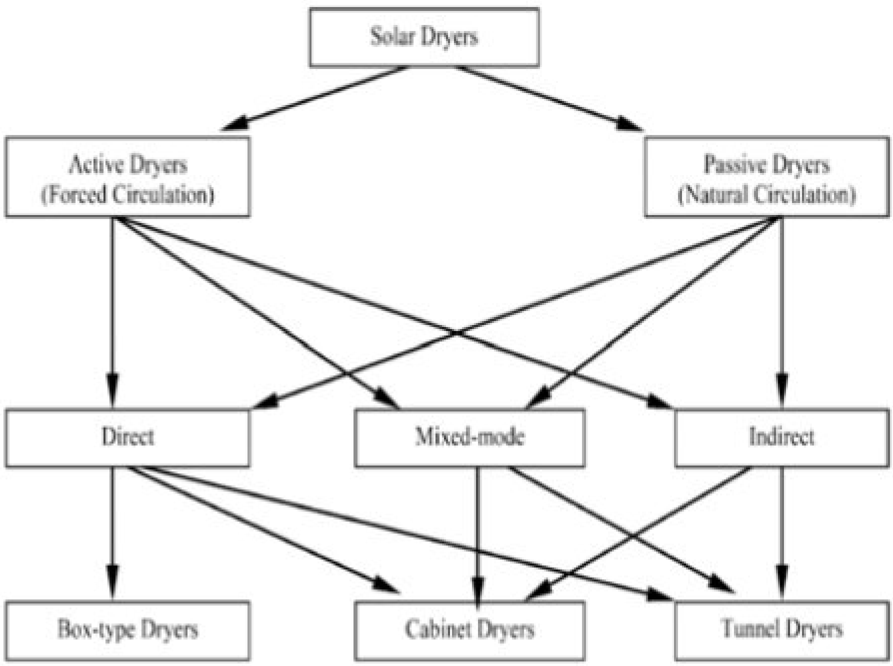



**Figure 2.5**: Classification of solar dryers [17]

Natural convection dryers can be used separately without using electricity supply. In this system, there may be a problem with the adequate amount of airflow to penetrate crop in bulk. However, the difference in specific weight between the drying air and the ambient air promotes a vertical air flow. Another critical issue associated with this system is that the air flow comes to a standstill during the night time and other adverse weather conditions. The risk of product deterioration due to mold attack and enzymatic reactions is high.

The mode of drying can be divided into direct, indirect or mixed-mode depending on whether the product is directly exposed to solar radiation or dried in the shade. Indirect (integral) mode, the product itself serves as the absorber, i.e. the heat transfer is affected not only by convection and radiation according to the product surface. It can be concluded that the surface area of the product being dried has to be maximized by spreading the crop in thin layers. In order to have a uniform final moisture content, the crop has to be turned frequently.

In the integral (direct) mode of drying, the sunlight may affect components in the product; an example is chlorophyll that quickly decomposes. Such a dryer needs large ground surface area due to the limitation of the bulk depth. So if space is scarce, indirect mode type of dryers are preferred for drying larger quantities [17].

Natural circulation or natural convection systems are sometimes called passive solar dryers. Their size is appropriate for farm use; they also can be direct or indirect solar dryers. These type of systems depend on solar energy entirely for their operation. The heated air in this system is circulated through the crop by buoyancy forces or as a result of wind pressure, acting singly or in combination. The table below was developed to give an explanatory summary of the comparison of the integral and distributed types of dryers, using their principal mode of heat transfer to crops, their components, construction, operation and maintenance, and efficiency [18].

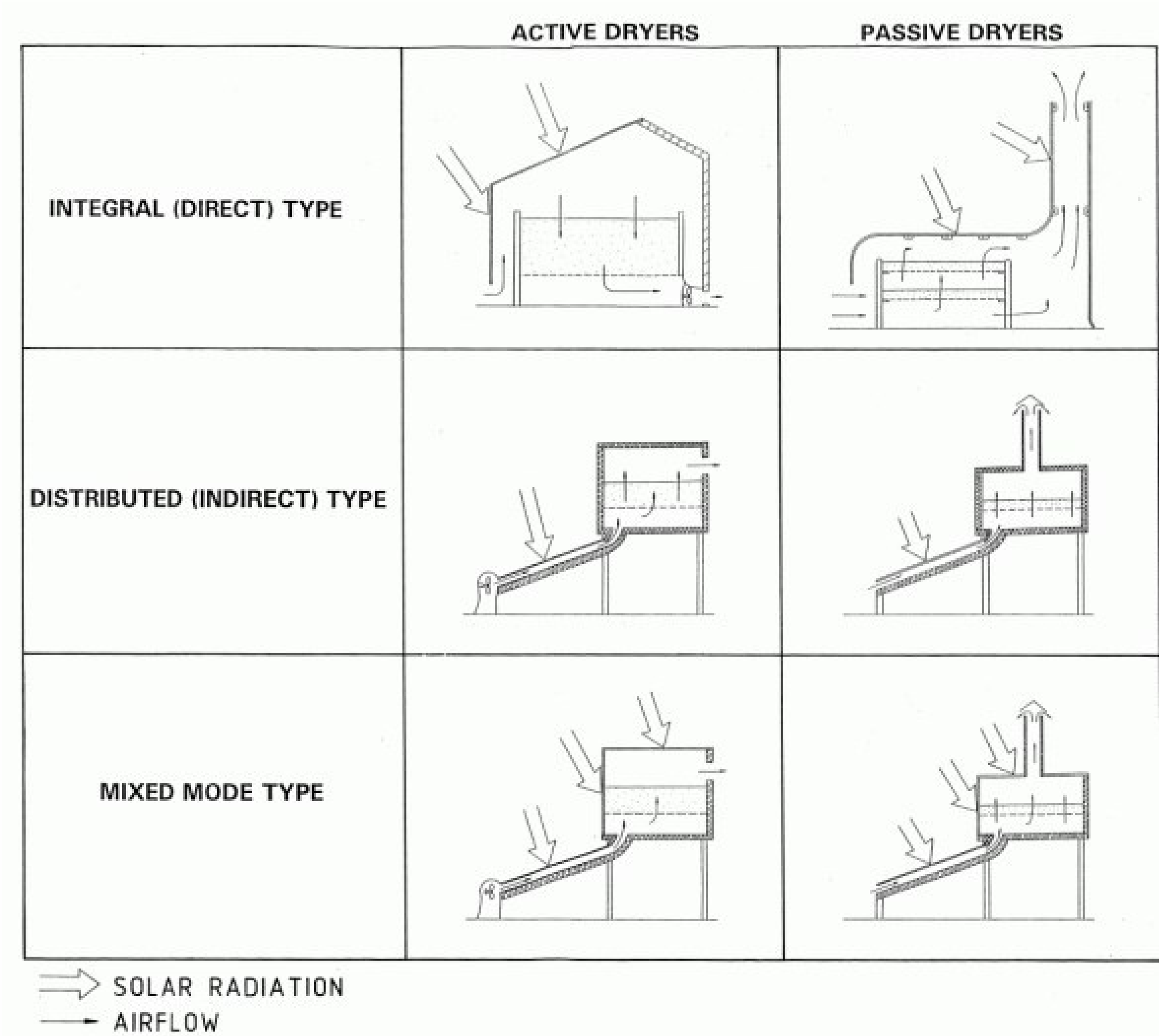



**Figure 2.6**: Sub-classes of solar dryers [17]

## 2.3 Material Selection for Solar Dryers

The material selection process for a solar dryer should be based on certain criteria namely: performance, material availability and cost, and durability. Care must also be taken because of the hygienic state of the products, mainly agricultural products. Similar care is taken for the drying chamber because of the possibilities of recontamination of the products.

The following materials should be selected for the construction of an indirect solar dryer:

1. Hinges and handles for the dryer's door

**Table 2.1**: Comparison of the integral and distributed type of solar dryer [18]

| Types | Integral | Distributed |
|---|---|---|
| Mode of heat transfer | Radiation(i.e. by direct absorption of solar radiation) and convection(i.e. from heated surrounding air) | Convection from preheated air in an air heating solar energy collector. |
| Components | Glazed drying chambers and chimney | Air heating solar energy collector, ducting, drying chamber and chimney. |
| Initial cost | Increasing cost | Increases with this type |
| Construction, operation and maintenance | Simple construction, (i.e. on the site of construction and operation). Requires little maintenance | Comparative requires elaborate structures. It requires more capital investment in materials and large running costs, operational loading is difficult, including the stirring process, since the crops are dried in deep layers. |
| Efficiency | Little knowledge about comparison of performance with | Higher efficiency as a result of the design of the individual components for |

| | | |
|---|---|---|
| | distributed types dryer. Efficiency is low due to the lack of control of drying and its simplicity. | optimal performance |

2. Nails and Glue as fasteners and adhesives.

3. Paint–black and another color for the solar dryer outlook.

4. Insect net at air inlet and outlet mainly meant to prevent insects from entering into the dryer.

5. A net cloth (cheese cloth or metal mesh) and wooden frames for constructing the trays.

6. Wood - the casing (housing) of the entire system; wood is selected because it is a good Insulator and relatively cheaper than metals. Having low thermal conductivity than other materials, so the heat transfer is less.

7. Glass - the solar collector cover and the cover for the drying chamber. It allows the solar radiation into the system but resists the flow of heat energy out of the system. It has a higher transmittance than others materials.

8. Mild steel or galvanize or aluminum sheets of $1mm$ thickness painted black for maximum absorption of solar radiation.

In the fabrication process of this work, there are factors to consider in selecting the engineering materials for this solar dryer, they are:

1. Cost of fabrication.

2. Ease of fabrication (e.g. forming, nailing, bending, cutting, etc.).

3. Service requirement.

4. Mechanical properties of the materials (e.g. stress, creep, fatigue, etc.).

5. Corrosion resistance.

Considerations were given to the most economic materials that satisfy both process and mechanical requirements over the working life of the solar dryer, allowing for easy loosening, maintenance, and replacement. However, the selected materials to be used must have sufficient strength and easy to work with [19].

## 2.4 Major Challenges of Existing Dryers

There have been many challenges with existing dryers from design to performance. One of the major challenges is intermittent weather conditions. These changes cause limitations to the drying process, i.e. preventing the continuation of the drying process at night or on a rainy day when there is not enough sun light [20]. However, for the absorber plate which is a major component of the solar dryer; there is a low heat transfer coefficient between the absorber plate and air stream due to poor thermal conductivity and the low heat capacity of the air. In addition, the even distribution of the heated air within the drying chamber has become a major problem for most designs.

Another challenge is the durability of the dryer, which is a reflection of how long it can last. Most solar dryers used by farmers for drying agricultural products do not often last longer than seven years. Such a problem can most likely be attributed to the material selection for the construction of the dryers [20]. Reduction in drying time has become a paramount issue which is dependent on other factors such as collector area, mass flow rate and the nature of the absorber plate. Lastly, several indirect solar dryers have limited applications due to their unreliable performance and high investment cost relative to their production capacity. Another problem that has affected solar dryers over the years has been how to reduce heat losses and thus increase the efficiency of the dryer.

## 2.5 Knowledge Gap and Need for Current Research

In the past, the designs of most indirect solar dryers are based on one solar collector. In the dryer chamber there are usually trays in the number range between 3− 5, and the heated air flow from the lower inlet has a mass flow rate and can gradually move to the products in the trays.

The drying rate of the above is very slow compared to our new design with one collector and two solar-powered fans. It increases the efficiency of the design and will possibly address other improved parameters. Another reason for the current research is to possibly address the limitation of the dryer due to weather conditions. On a humid day, most solar dryers turn to be limited due to lack of sunshine.

One possible way our research can help to resolve this issue is the use of composite structures that have a honeycomb structure as the absorber. Performance-wise, collectors made of composite materials are more efficient and suitable for almost all weather conditions.

CHAPTER 3

# METHODOLOGY

## 3.1 Design Criteria

The following criteria guided the design of the dryer:

1. Small scale service.
2. Ability to reduce moisture.
3. Exclusion of insects within the drying chamber.
4. Heat energy storage.
5. Forced convection to improve efficiency.
6. Availability of charging point, and solar PV system for powering the blowers.

## 3.2 Description of the dryer

The dryer is made up of the solar collector, drying chamber, chimney, and solar photovoltaic system, as shown in **Figures** (**3.3**), (**3.1**), and (**3.2**).
A detailed description of the component parts of the dryer is given below:

1. The solar collector
2. The drying chamber
3. The chimney
4. The solar PV system

The components of the dryer are listed in **Table** (**3.1**):

**Table 3.1**: Components of the dryer

| s/n | Component |
|---|---|
| 1 | Solar collector: this is made up of the glazing, the absorber plate, the absorber, the blowers, the insulation, and the collector sides. |
| 2 | Drying chamber: this is made up of the air duct, the glass sides, the glass base, and the top glazing. |
| 3 | Chimney |
| 4 | Solar PV system |

### 3.3 Material Selection for the dryer

Material selection for each part of the dryer was done based on the following factors:

1. Functionality requirements
2. Processability
3. Cost
4. Reliability requirements

Based on the above factors, **Tables** (**3.2**) and (**3.3**) were devised. The serial number(s/n) for each of the parts represents the number given to each part of the dryer during the engineering drawing in the construction stage.

**Table 3.2**: Parts of the drying chamber: their functions, processing, cost, and reliability

| s/n | Part | Material(s) | Function | Processing | Cost | Reliability |
|---|---|---|---|---|---|---|
| 2 | Drying chamber | silica glass | It holds the tray | Cutting, Joining | Costly | fairly reliable |
| 3 | Chimney | Aluminum | Outlet | Fastening | Costly | Strong |
| 4 | Tray | wood, wire mesh | It holds the product | Carpentry | Cheap | Strong |

**Table 3.3**: Parts of the solar collector, their functions, processing, cost, and reliability

| s/n | Part | Material(s) | Function | Processing | Cost | Reliability |
|---|---|---|---|---|---|---|
| 4 | Absorber plate | Mild steel | Space heating | Cutting | Cheap | Strong |
| 5 | Collector side | Mild steel | Reduces heat losses | Cutting, Welding | Cheap | Strong |
| 8 | Supporting stand | Mild steel | Reduces heat losses | Cutting, Welding | Cheap | Strong |
| 2 | Inlet | Mild steel | Reduces heat losses | Cutting, Welding | Cheap | Strong |
| 3 | Fan | Rubber blades | Air blower | | Cheap | Strong |
| 1 | Glazing | Perpex glass | Transmits light | Casting, Extrusion | Cheap | Strong |
| 7 | Black pebbles | special rocks | Heat storage | Crushing | Cheap | Strong |

## 3.4 Design of the dryer

Based on the materials selection discussed previously, the three major parts of the dryer were designed as follows:

### 3.4.1 Solar collector:

The solar collector is made up of the glazing (perspex glass), the absorber plate, black-painted pebble rocks, insulation, inlet, collector side, solar PV system, fans, and stand as shown below.

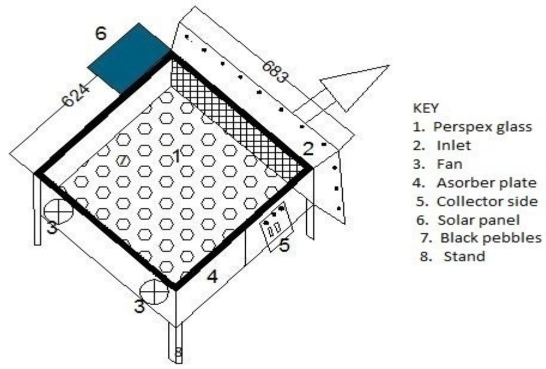



**Figure 3.1**: The solar collector

### 3.4.2 Drying chamber:

The drying chamber consists of the chimney, the glass roof, the glass walls, the trays, and the glass floor. Below is the engineering drawing showing the three parts (i.e. the trays, the solar collector, and the drying chamber) in the coupled form. The tray: The drying tray is made up of a wire mesh and wood. The wood is fastened to the mesh to form a rectangular shape when viewed from the top as shown below.

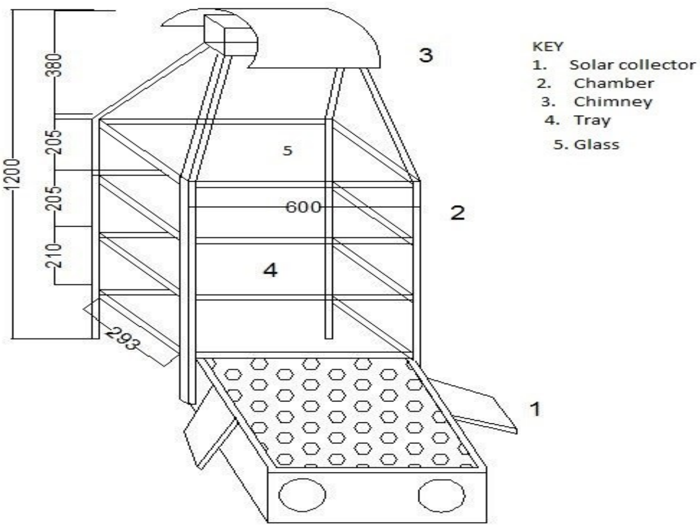



**Figure 3.2**: Design of the mixed-mode solar dryer

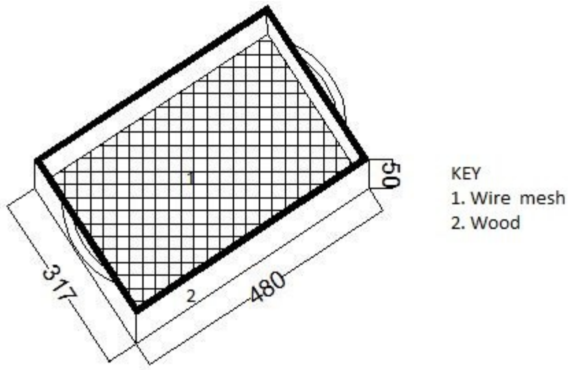



**Figure 3.3**: Design of the tray

## 3.5 Construction of the dryer

### 3.5.1 The solar collector:

**Figure 3.4**: Front and back views of the solar collector

### 3.5.2 The solar PV system:

**Figure 3.5**: Front and back views of the solar PV system

### 3.5.3 The drying chamber:

**Figure 3.6**: Front and side views of the drying chamber

### 3.5.4 The solar dryer:

**Figure 3.7**: Front and side views of the dryer

### 3.6 Experimental Procedure for Performance Evaluation

The experiment comprised of three parts:

1. Temperature measurements: The hourly temperature variation of the major parts of the solar dryer were measured in the presence of the product (tomatoes) starting on 17*th June* 2016. The procedure was repeated for two more days; 18*th* and 19*th* of June, 2016. This was achieved using a digital thermometer that measures temperatures in the range -50 to 500.

2. Relative humidity measurements: The hourly relative humidity variation of the major parts of the solar dryer were calculated on each of the chosen days in the presence of the product (tomatoes) by using the **August-Roche-Magnus (ARM) approximation** also known as the *Magnus formula*. According to the *ARM* approximation:

Relative humidity (RH) is given by: $RH \approx \frac{exp(17.625Td/243.04+Td)}{exp(17.625T/243.04+T)} \times 100\%$

*RH* = Relative humidity, *Td* = dew point, *T* = [$-20^oC$, 50oC]. *T* is the temperature range within which the formula holds.

The most accurate method of measuring relative humidity is through the use of a hygrometer. The ARM method was used because we had to improvise since the instrument was not available.

3. Moisture content/Weight loss/Mass loss measurements: The hourly weight loss or mass loss of the product were measured using a weighing balance, and converted to percentage moisture content loss.

Two extra measurements that were also made during the experimental procedure included:

1. Insolation measurements: Another parameter of importance is insolation. It is the amount of radiant heat striking a unit area of a surface per unit time. Insolation fluctuates rapidly with time and depends on weather conditions. We can measure the amount of insolation on the solar collector surface, and that of the glass walls and roof of the drying chamber. It is measured with a *solarimeter*. It is an essential parameter since the performance of the dryer depends largely on it.

2. Wind speed measurement: Wind speed in the ambient temperature can affect the parameters such as the overall top loss coefficient and the overall edge loss coefficient by altering the value of the convective heat transfer coefficient and the radiative heat transfer coefficient between the top and edge of the solar collector and the ambient temperature. This is measured with an *anemometer*.

## 3.7 Modeling Performance of the Dryer

The three most important parameters for a solar collector include the collector efficiency, the overall heat loss coefficient, and the heat removal factor. The theoretical background for these parameters is given as follows [23]:

1. Collector efficiency (for flat-plate air heaters):

   The collector efficiency is a dimensionless parameter that measures the ratio of heat output from the inlet to the heat input from the solar collector surface at any given time. It is a time-varying parameter and depends on insolation, collector area, and the quantity of heat extracted from the heated air per unit time. It is given as follows:

. $\eta_c = \frac{\dot{Q}}{A_c S}$ .

, where $Q = m_a c_p\ (T_{ab} - T_a)$

where $\dot{m}_a$= mass flow rate of heated air, $c_p$ = constant pressure specific heat capacity of air, $T_{ab}$ = absorber or plate temperature, $T_a$ = heated air temperature or

inlet temperature, $A_c$ = collector area, $Q$ = heat extracted from the heater per unit time, and $\eta_c$ is the collector efficiency.

2. Overall heat loss coefficient:

   The overall heat loss coefficient measures the total heat loss from the solar collector in three areas: the top, the edge, and the back contact or insulation. It is given as follows: $U_l = U_t + U_b + U_e$,

$$U_e \propto \frac{1}{A_c}, U_b \propto \frac{1}{\delta_b}, U_t \propto \frac{1}{R_t}$$

   where $U_l$ = overall heat loss coefficient, $U_t$ = overall top loss coefficient, $U_b$ = overall back contact loss coefficient, $U_e$ = overall edge loss coefficient, $R_t$ = thermal resistance through the collector top, $\delta_b$ = thickness of back contact or insulation, and $A_c$ = area of the collector.

3. Heat removal factor:

   The heat removal factor is a dimensionless parameter that measures the ease at which heat is removed through the duct (the inlet) of the air heater. It is given as follows:

$$F = \frac{Q}{[S - U_l(T_a - T_{am})]}$$

where $F$ = heat removal factor, $S$ = insolation, and $T_{am}$ = ambient temperature, $T_a$ = heated air temperature or inlet temperature, $U_l$ = overall heat loss coefficient, and $Q$ = heat extracted from the heater per unit time.

**Table 3.4**: Performance optimization of major dryer parts

| Material | General properties | Thermal properties | Optical properties | Mechanical properties |
|---|---|---|---|---|
| Perspex glass (glazing) | Density: 1.16 to 1.22$kg/m^3$ Price: cheap | low thermal conductivity | Transparent | Fracture toughness: 0.7 to 1.6$MPa$ |
| Silica glass (chamber) | Density: 2.15 to 2.2 × $10^3 kg/m^3$ Price: cheap | low thermal conductivity | Transparent | Fracture toughness: 0.6 to 0.8$MPa$ |
| Aluminum (Chimney and chamber) | Density: 2.5 to 2.9 × $10^3 kg/m^3$ Price: Costly | high thermal conductivity | Opaque | Ductile |
| Mild steel (Absorber plate) | Density: 7.8 to 7.9 × $10^3 kg/m^3$ Price: cheap | high thermal conductivity | Opaque | Ductile |

## 3.8 Heat Distribution in the Drying Chamber

We studied a simplified model of the two-dimensional transient heat transfer in the drying chamber using the heat equation.
The aim of this model is to obtain the transient temperature distribution in the drying chamber when some initial conditions have been prescribed.

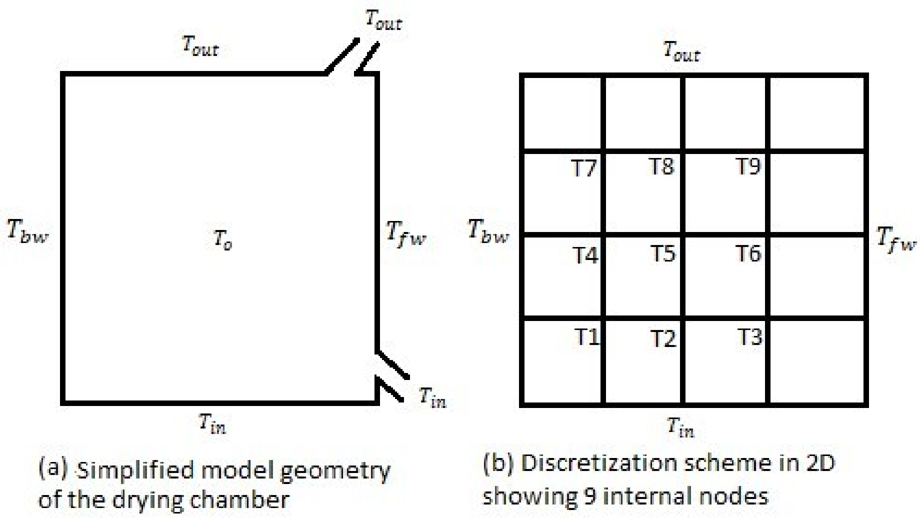
Here the temperature distribution is in 2D i.e. $T = T(x,y,t)$

The following assumptions were made in this model:

1. The chamber is irradiated by the sun through the front wall.

2. The inlet temperature is the same as the temperature of the base of the dryer.
3. The outlet temperature is the same as temperature of the top of the dryer.
4. The temperature of the back wall is less than that of the front wall.
5. The length of the dryer and the width are equal.

**Figure 3.8**: 2D model geometry of the transient heat distribution in the drying chamber




In the sketch above, $T_{fw}$ = temperature of the front wall of the drying chamber in, $T_{bw}$ = temperature of the back wall of the drying chamber in, $T_{out}$ = outlet temperature, $T_{in}$ = inlet temperature in, and $T_o$ = initial temperature inside the drying chamber.

The heat equation in 2D is given by:

$$\frac{\partial T(x,y,t)}{\partial t} = \frac{k}{\rho c}\left(\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2}\right)$$

In the heat equation above, $k$ is the thermal conductivity of the chamber in $W/mK$, $c$ is the specific heat capacity of the chamber in $J/kgK$, and $\rho$ is the density of the chamber in $kg/m^3$.

The heat equation was transformed to a nodal equation using the forward time central difference scheme (FCTS) also called the *matching scheme* which was consequently applied to each node in **Figure** (**3.4**) to arrive at nine nodal equations which were solved simultaneously in MATLAB.

# CHAPTER 4

# RESULTS AND DISCUSSION

## 4.1 Operation of the dryer

The amount of insolation i.e. the amount of radiant heat received by the dryer per unit area of a given surface per unit time fluctuates rapidly. For instance, on a sunny say, insolation is high during sunrise, in the afternoon hours, and just before sunset. The dryer receives insolation in three ways namely from the transparent glass roof (top glazing), from the transparent walls of the drying chamber, and from the solar collector's cover. A dryer that receives insolation through these ways is said to be operating in the *mixed-mode condition*.

Heat energy is constantly exchanged (lost or gained) between the sky and the different regions of the dryer through radiation, convection, and conduction. Hence, the total energy of the system is conserved i.e. heat gained by the dryer per unit time equals heat input in the dryer per unit time *minus* heat output in the dryer per unit time *plus* heat generated within the dryer per unit time.

Heat is generated in the dryer in the solar collector region i.e. in the absorber, and in the drying chamber. When the solar collector's glazing receives insolation, it heats up the surrounding air directly below it causing them to be less dense. The absorber stores the radiant heat used to heat up air in this way. The blowers (the two fans) in front of the duct help blow heated air toward the duct, where the hot air is ducted to the drying chamber through convection. The solar collector losses heat through conduction in the insulation region, through the glazing by convection due to flow of wind over the surface, and by radiation between the absorber and the ambient.

In the drying chamber, the products to be dried receives heat directly through the top glazing and the transparent walls through convection, and from the inlet connected to the solar collector's duct through convection. At the same time, heat is lost from the products through evaporation when occurs as they dry, and through radiation between the ambient and the products.

## 4.2 Temperature Measurement Results

The transient temperature distribution in each of the following parts of the dryer was determined: the glazing or cover (Tcov), the absorber (Tab), the inlet (Tin), the two trays in the drying chamber; tray 1(upper tray) (Tdcu) and tray 2(lower tray) (Tdcd), the outlet (Tout), and the ambient (Tam). The Tables below show the results obtained for each of the three days respectively: The temperatures are in degrees Celsius ( ) and the time is recorded in 24 hour format.

**Table 4.1**: Temperature data for day 1: 17th June, 2016

| t(hrs) | Tab | Tdcu | Tdcd | Tout | Tin | Tcov | Tam |
|---|---|---|---|---|---|---|---|
| 8.5 | 28.5 | 26.2 | 26.2 | 27.8 | 25.8 | 25.8 | 25.8 |
| 9.5 | 37.2 | 35.3 | 35.1 | 29.6 | 25.6 | 30.1 | 23.1 |
| 10.5 | 32.7 | 31.7 | 31.6 | 31.1 | 29.6 | 27.5 | 27.1 |
| 11.5 | 38.7 | 35.1 | 35.2 | 34.1 | 32.0 | 32.1 | 30.5 |
| 12.5 | 32.4 | 32.0 | 31.8 | 31.3 | 29.3 | 31.6 | 28.5 |
| 13.5 | 31.2 | 30.8 | 30.8 | 28.8 | 28.7 | 31.3 | 29.3 |
| 14.5 | 30.2 | 30.5 | 31.2 | 30.5 | 29.8 | 33.3 | 31.3 |
| 15.5 | 35.5 | 31.0 | 31.6 | 32.3 | 30.3 | 30.8 | 29.3 |
| 16.5 | 31.8 | 30.1 | 29.6 | 30.7 | 30.7 | 28.8 | 28.6 |

**Table 4.2**: Temperature data for day 2: 18th June, 2016

| t(hrs) | Tab | Tdcu | Tdcd | Tout | Tin | Tcov | Tam |
|---|---|---|---|---|---|---|---|
| 9.5 | 28.1 | 31.3 | 30.1 | 27.7 | 27.5 | 29.2 | 26.5 |
| 10.5 | 40.0 | 35.5 | 36.3 | 38.5 | 38.0 | 30.0 | 27.0 |
| 11.5 | 38.6 | 39.2 | 38.1 | 40.0 | 36.1 | 35.5 | 30.5 |
| 12.5 | 43.0 | 36.9 | 36.9 | 37.6 | 38.8 | 38.3 | 32.8 |
| 13.5 | 33.0 | 28.4 | 30.0 | 33.6 | 31.7 | 24.7 | 21.7 |
| 14.5 | 29.2 | 28.5 | 28.0 | 28.0 | 26.7 | 24.3 | 22.7 |
| 15.5 | 29.6 | 27.9 | 27.7 | 28.2 | 27.7 | 26.6 | 26.0 |
| 16.5 | 30.7 | 24.0 | 24.2 | 30.6 | 27.8 | 21.7 | 21.7 |

**Table 4.3**: Temperature data for day 3: 19th June, 2016

| t(hrs) | Tab | Tdcu | Tdcd | Tout | Tin | Tcov | Tam |
|---|---|---|---|---|---|---|---|
| 9 | 31.0 | 30.2 | 30.2 | 30.4 | 31.0 | 29.7 | 28.0 |
| 10 | 28.8 | 28.6 | 28.7 | 28.3 | 28.4 | 28.8 | 28.0 |
| 11 | 28.7 | 27.0 | 26.5 | 26.8 | 26.3 | 26.6 | 25.8 |
| 12 | 30.1 | 27.4 | 27.4 | 27.0 | 27.0 | 26.7 | 26.1 |
| 13 | 43.0 | 38.7 | 38.5 | 32.1 | 31.6 | 29.0 | 27.0 |
| 14 | 33.5 | 31.5 | 32.5 | 24.8 | 24.0 | 30.0 | 26.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 15 | 34.0 | 32.5 | 32.0 | 25.6 | 23.5 | 31.4 | 25.6 |
| 16 | 34.5 | 32.6 | 32.4 | 23.7 | 21.5 | 30.4 | 25.6 |
| 17 | 31.7 | 27.7 | 27.5 | 24.4 | 22.5 | 31.1 | 24.5 |

The following graphs were plotted based on the above data:

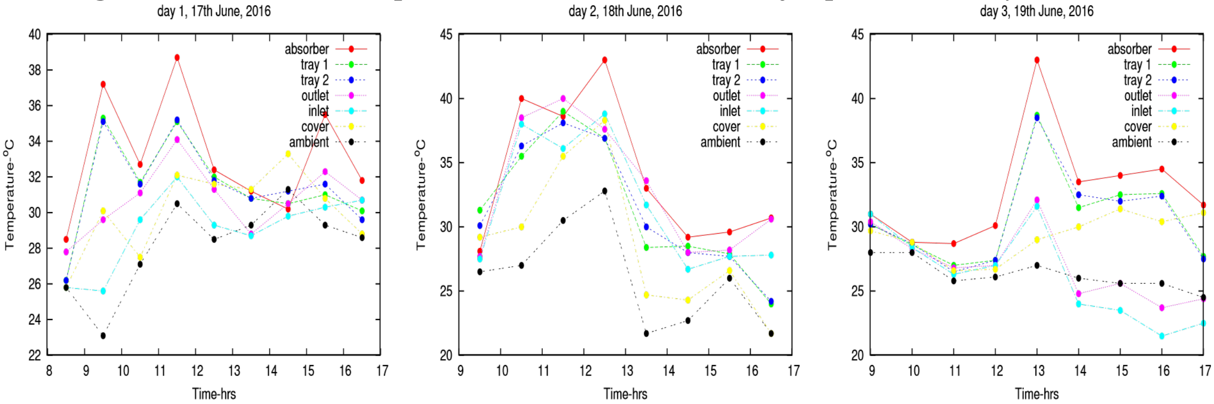



**Figure 4.1**: Transient temperature distribution in the major parts of the dryer

## 4.3 Simulation Results

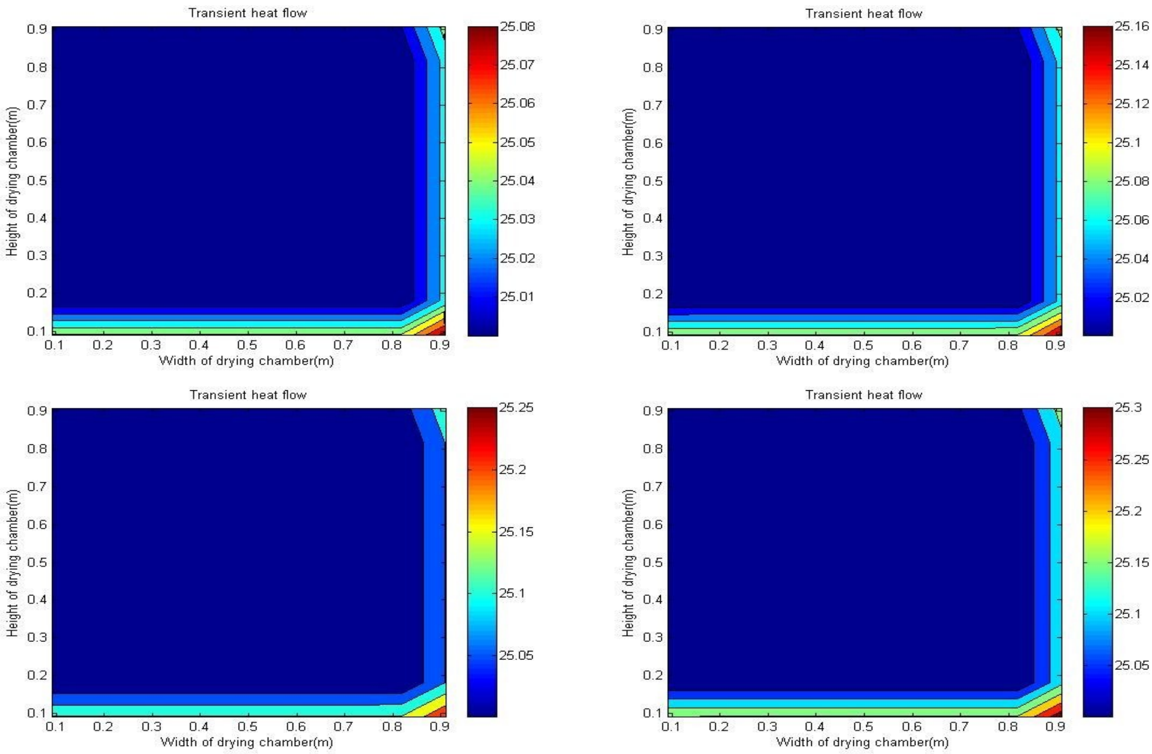
The contour plots in **Fig. (4.2)** represent the temperature distribution in the drying chamber obtained after (a) 30 seconds (b) 60 seconds (c) 90 seconds and (d) 120 seconds respectively. The contour plots above show that the temperature in the drying chamber increases gradually with time. Starting with an initial temperature $T_o = 25$ in the dryer, we set:

$T_{in} = 40$, $T_{fw} = 35$, $T_{bw} = 25$, and $T_{out} = 28$ as boundary conditions. Heat flows from the inlet and front wall to the outlet and back wall.

The contour plots also show that to get an appreciable temperature which can affect drying of products in the drying chamber, the inlet temperature and front wall temperatures need to be increased. The front wall temperature is directly affected by insolation while the inlet temperature is directly affected by the solar collector performance.

This simplified model has shown that temperature changes in the dryer can be improved if the material of the drying chamber has high thermal conductivity, low density, and low specific heat. For example, by using aluminum instead of silica glass, this feat might be achieved through aluminum is far more expensive. However, using aluminum throughout will affect the front wall insolation since aluminum is opaque. One way to prevent poor insolation in the chamber is to use glass in the front wall.

**Figure 4.2**: Contour plot of the temperature distribution in the dryer




To enable the temperature in the chamber to build up to the optimal level required for tomato drying, the drying should be allowed to run empty for a while before putting products into it.

Again, heat distribution is slow in larger dryers compared to smaller ones running on the same collector size. This is expected. For instance, reducing the length and width of the dryer will result in an increase in heat distribution.

## 4.4 Relative Humidity Measurement Results

The relative humidity in the ambient (rha) and the drying chambers (rhu and rhd in the two trays) were estimated using the ARM approximation discussed in the previous chapter. The following data were obtained with respect to each of the drying days. The relative humidity is in % and the time is in 24-hour format.

**Table 4.4**: Relative humidity data for day 1: 17th June, 2016, dew point: 21

| t(hrs) | Tdcu | Tdcd | Tam | Rhu | rhd | rha |
|---|---|---|---|---|---|---|
| 8.50000000 | 26.2000008 | 26.2000008 | 25.7999992 | 73.1009216 | 73.1009216 | 74.8520203 |
| 9.50000000 | 35.2999992 | 35.0999985 | 23.1000004 | 43.4532585 | 43.9367905 | 87.9843979 |
| 10.5000000 | 31.7000008 | 31.6000004 | 27.1000004 | 53.1618958 | 53.4645576 | 69.3270721 |
| 11.5000000 | 35.0999985 | 35.2000008 | 30.5000000 | 43.9367905 | 43.6942558 | 56.9253159 |
| 12.5000000 | 32.0000000 | 31.7999992 | 28.5000000 | 52.2654495 | 52.8611794 | 63.8847618 |
| 13.5000000 | 30.7999992 | 30.7999992 | 29.2999992 | 55.9570618 | 55.9570618 | 60.9919243 |
| 14.5000000 | 30.5000000 | 31.2000008 | 31.2999992 | 56.9253159 | 54.6947861 | 54.3842812 |
| 15.5000000 | 31.0000000 | 31.6000004 | 29.2999992 | 55.3218613 | 53.4645576 | 60.9919243 |
| 16.5000000 | 30.1000004 | 29.6000004 | 28.6000004 | 58.2458687 | 59.9453964 | 63.5148354 |

**Table 4.5**: Relative humidity data for day 2: 18th June, 2016, dew point: 20

| t(hrs) | Tdcu | Tdcd | Tam | Rhu | rhd | rha |
|---|---|---|---|---|---|---|
| 9.50000000 | 31.2999992 | 30.1000004 | 26.5000000 | 54.3842812 | 58.2458687 | 71.8178558 |
| 10.5000000 | 35.5000000 | 36.2999992 | 27.0000000 | 42.9757233 | 41.1240273 | 69.7353592 |

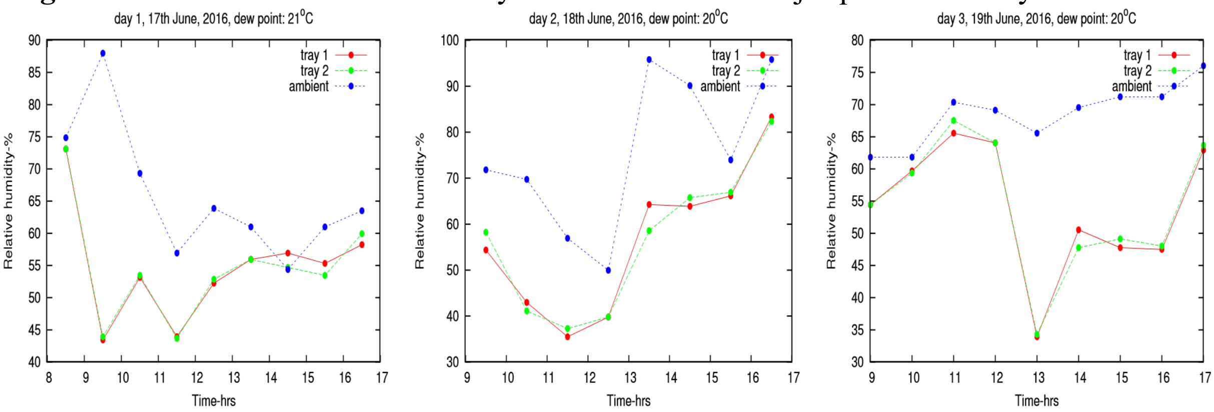
| | | | | | | |
|---|---|---|---|---|---|---|
| 11.5000000 | 39.0000000 | 38.0999985 | 30.5000000 | 35.5092087 | 37.2783394 | 56.9253159 |
| 12.5000000 | 36.9000015 | 36.9000015 | 32.7999992 | 39.7943687 | 39.7943687 | 49.9571877 |
| 13.5000000 | 28.3999996 | 30.0000000 | 21.7000008 | 64.2571335 | 58.5813828 | 95.8011246 |
| 14.5000000 | 28.5000000 | 28.0000000 | 22.7000008 | 63.8847618 | 65.7711945 | 90.1420364 |
| 15.5000000 | 27.8999996 | 27.7000008 | 26.0000000 | 66.1559830 | 66.9331436 | 73.9706345 |
| 16.5000000 | 24.0000000 | 24.2000008 | 21.7000008 | 83.3387833 | 82.3442917 | 95.8011246 |

**Table 4.6**: Relative humidity data for day 3: 18th June, 2016, dew point: 20

| t(hrs) | Tdcu | Tdcd | Tam | Rhu | rhd | rha |
|---|---|---|---|---|---|---|
| 9.00000000 | 30.2000008 | 30.2000008 | 28.0000000 | 54.4486351 | 54.4486351 | 61.8372612 |
| 10.0000000 | 28.6000004 | 28.7000008 | 28.0000000 | 59.7158585 | 59.3703232 | 61.8372612 |
| 11.0000000 | 27.0000000 | 26.5000000 | 25.7999992 | 65.5643158 | 67.5222549 | 70.3749390 |
| 12.0000000 | 27.3999996 | 27.3999996 | 26.1000004 | 64.0439529 | 64.0439529 | 69.1360626 |
| 13.0000000 | 38.7000008 | 38.5000000 | 27.0000000 | 33.9296188 | 34.2980652 | 65.5643158 |
| 14.0000000 | 31.5000000 | 32.5000000 | 26.0000000 | 50.5531044 | 47.7700081 | 69.5462723 |
| 15.0000000 | 32.5000000 | 32.0000000 | 25.6000004 | 47.7700081 | 49.1393280 | 71.2147141 |
| 16.0000000 | 32.5999985 | 32.4000015 | 25.6000004 | 47.5013657 | 48.0404015 | 71.2147141 |
| 17.0000000 | 27.7000008 | 27.5000000 | 24.5000000 | 62.9297104 | 63.6700821 | 76.0400009 |

The following graphs were plotted based on the above data:

**Figure 4.3**: Transient relative humidity distribution in the major parts of the dryer




## 4.5 Mass Loss/Moisture Content

The loss in mass or mass loss $ml$ of the tomatoes were calculated during the drying hours with the formula:

$$ml = m_i - m_f$$

where $ml$ = mass loss, $m_i$ = initial mass, and $m_f$ = final mass. To calculate the loss in mass of the product over a given time interval, the product is first weighed with a weighing balance to determine its initial mass $m_i$ at a particular time. After the time interval, the product is weighed again to determine the final mass $m_f$. Observation shows that $m_f < m_i$ which means that drying takes place.

The percentage moisture content $\%MC$ is calculated based on the following formula:

$$\%MC = \frac{m_i}{m_f} - 1 \times \frac{100}{1}$$

$$= \frac{ml}{m_f} \times \frac{100}{1}$$

where $\%MC$ = percentage moisture content, $m_i$ = initial mass, and $m_f$ = final mass.

**Table 4.7**: Decrease in product's mass as a function of time

| t(hrs) | 0 | 4 | 5 | 8 | 18 | 19 | 20 | 21 | 22 | 24 | 41 | 43 | 44 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m(kg) | 1.00 | 0.95 | 0.85 | 0.75 | 0.50 | 0.46 | 0.35 | 0.32 | 0.30 | 0.24 | 0.22 | 0.21 | 0.21 |

**Table(4.7)** shows that the mass of the product was reduced from its initial value of $1.00kg$ to a final value of $0.21kg$ when the change in the product's mass is negligible and the desired color is obtained. Beyond this value, over-drying sets in which leads to excessive drying and wrinkling of the products.

### 4.5.1 Drying Kinetics

Drying kinetics study the rate of drying of products under certain conditions. For the drying of tomatoes, three major drying models usually used to obtain the drying rate constant of tomatoes include [22, 24]:

1. Henderson and Pabis (1974) : $MR = exp(-kt^n)$, where $k$ = drying rate constant, $n$ = drying coefficient, $1 \leq n \leq 2$

In this model, effects of temperature and time on the rate of drying were considered.

2. Newton(1985) : $MR = exp(-kt)$, where $k$ = drying rate constant, $MR$ = moisture ratio, $t$ = time

   This is a special case of the Henderson and Pabis model (when $n$ = 1).

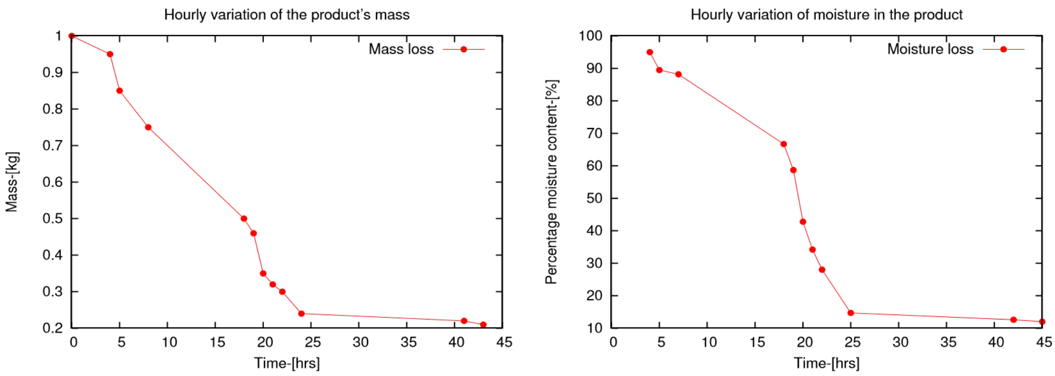
3. Midilli et al(2002): $MR = aexp(-k^n t) + bt$, $k,b$ = drying rate constants, $a,n$ = drying coefficients, $1 \leq n \leq 2$, $a \geq 1$

   This model studied effects of temperature, relative humidity, dew point, and time on the rate of drying.

$MR = \frac{M}{M_o}$, $M_o$= initial moisture content of the product,

$M$ = moisture content of the product at any time. By fitting our experimental data on

**Figure 4.4**: Drying results




the drying models using the least-squares regression method, the following results were obtained; the Newton model gave the best fit.

Henderson and Pabis: $k = 0.25units/h = 6.00units/day$, $n = 1.44$

**Newton**: $k = 0.12units/h = 2.88units/day$

Midilli et al: $k = 0.32units/h = 7.68units/day$, $a = 1.01$, $n = 1.43$, $b = 0.0135units/h = 0.324units/day$

## 4.6 Analysis of Results

The optimal drying chamber temperature range for tomato drying is $40^oC - 80^oC$ [24]. From our results in **Tables** (**4.1**, **4.2**, and **4.3**) and **Fig**. (**4.1**), the temperature in the drying chamber reached a maximum value of $35.3^oC$ at 9: 30*am* on day 1, a maximum of $39.2^oC$ at 11: 30*am* on day 2, and a maximum of $38.7^oC$ at 1: 00*pm* on day 3. These values show that insolation and dryer performance are both affected by time and weather conditions. Day 1 was a rainy day with low insolation, while day 2 and day 3 were not rainy and insolation was high after sunrise. Hence, the drying chamber temperature on day 2 and day 3 are comparable to the optimal drying chamber temperature range.

The relative humidity of the drying chamber is the amount of moisture content of the air within the drying chamber at a given time. It depends on dew point and temperature. The optimal drying chamber relative humidity range for tomato drying is $20\% - 60\%$ [24]. From our results in **Tables** (**4.4**, **4.5**, and **4.6**) and **Fig**. (**4.3**), the relative humidity in the drying chamber reached a minimum value of $43.5\%$ at $9{:}\ 30am$ on day 1, a minimum of $35.5\%$ at $11{:}\ 30am$ on day 2, and a minimum of $33.9\%$ at $1{:}\ 00pm$ on day 3. Hence, the drying chamber relative humidity on day1, day 2 and day 3 respectively fall within the optimal drying chamber relative humidity range.

**Fig.** (**4.4**) shows that the dryer can reduce the moisture content of $1kg$ of tomatoes from 95% to 14% within 45 hours of drying time. The capacity of the dryer is $1kg$ of products per tray.

The experimental results show that while the relative humidity in the dryer was adequate for tomato drying, the temperature in the drying chamber did not rise up to the optimal limit. One possible cause of this is poor insolation on the chosen drying days, heat losses through the glass walls and roof, and high relative humidity in the ambient.

# CHAPTER 5

## Conclusion and Recommendation

### 5.1 Conclusion

1. We have successfully shown that the mixed-mode solar dryer out-performed passive solar dryers since it gave a higher drying rate constant for tomatoes based on drying kinetics. For example, using the mixed-mode solar dryer in this research work, a drying rate constant of 2.88*units/day* for tomatoes was achieved, while the drying rate constant of tomatoes reported in Ojike et al [21] lie between 1*unit/day* and 2*units/day* for different passive solar dryers based on the Newton model.

2. The temperature of the drying chamber remained higher than the ambient temperature throughout the experiment while the relative humidity remained high in the ambient temperature.

3. The drying chamber reached a maximum temperature of $39.2^oC$ while the relative humidity reached a minimum value of 33.9% within active drying hours, which is a good condition for drying of tomatoes.

4. The dryer can reduce the moisture content of 1*kg* of tomatoes from 95% to 14% within 45 hours of drying time. The capacity of the dryer is 1*kg* of products per tray.

5. Based on our drying experiment, drying of tomatoes can last up to three or more days during rainy season before equilibrium is attained.

### 5.2 Recommendation

1. Real-time insolation and relative humidity measurements should be performed using a *solarimeter* and a hygrometer respectively to monitor fluctuations in

solar irradiation during drying days. Based on such insolation measurements, the collector efficiency can then be calculated.

2. More research on the design should be carried out in order to minimize heat losses in the drying chamber and to ward off insects that enter the outlet through the chimney.

3. Simulation of transient heat transfer in the mixed-mode solar dryer to study the dependence of the dryer performance on temperature, heat transfer coefficients, and insolation still needs to be explored.

4. Pre-treatment of the tomatoes with some standard reagents is recommended before resuming drying to prevent contamination by microbes during days with poor insolation, and at night hours.

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