PROJECT TITLE: DESIGN OF A SOLAR DRYER SYSTEM FOR DRYING PARCHMENT COFFEE

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A Report Submitted in Partial Fulfillment for the Requirements of the Degree of Bachelor of Science in Environmental and Biosystems Engineering, of the University Of Nairobi

MAY, 2015
DECLARATION

I declare that this project is my original work and has not been submitted for a Degree in any other institution of higher learning.

Signature………………………….. Date…………………………………….

MWANGI JEREMIAH

This design project report has been submitted for examination with my approval as University supervisor.

Signature……………………………… Date……………………………………

ENG. DR. GICHUKI MUCHIRI
DEDICATION

I dedicate this project to the Almighty God for graciously guiding me throughout my studies. This project is also dedicated to my late Father, my Mother, Brother, and sisters for the inspiration and support that they showed me throughout my study at the University of Nairobi; your contribution towards my education will forever live.

I salute you all.
ACKNOWLEDGEMENT

First and foremost, I wish to acknowledge my supervisor Eng. Dr. Gichuki Muchiri of the University of Nairobi for his endearing guidance and supervision while I was undertaking this project. The project would not have been a success without his strong input. My appreciation also goes to J.K. Mburu, the Field station manager at Coffee research Foundation for availing useful meteorological data that was extensively used in the design of this project.

I acknowledge the entire staff and fellow students at the Department of Environmental and Biosystems Engineering for their tremendous contributions and positive criticisms in the many discussions we held together. Your input was crucial for the overall success of this project.

Finally, I wish to thank Coffee Research Foundation fraternity for being supportive while I acquired design data for my project. I am grateful to you all.
ABSTRACT

The conventional way of drying coffee in Kenya is by spreading wet parchment on drying beds up to depths of 25 mm. This method of drying coffee demands large labour force, vast drying space, and extended drying time. Moreover, the final product is of low quality since the parchment is exposed to environmental contaminants. The solar dryer system designed in this project tries to minimize these requirements.

The solar dryer has a collector efficiency of 32.5%, a pick-up efficiency of 25%, and a system efficiency of 24%. The system efficiency is within the range of efficiency for forced convection dryers, that is, 20-30%. The collector efficiency is within the range of 30-40% for the given collector area. The Cost-Benefit ratio is 3.52 compared with a biomass fired dryer of the same capacity and 1.12 compared to natural sun drying. This implies that the project is economically feasible and a desirable option.

The system is composed of a solar collector, a duct for conveying heated air, a duo-fan, a drying chamber, and a drying bin. The solar collector has a surface area of 10 m² and is an enclosed airspace with the upper side covered with a transparent glass which allows the solar energy into the collector. The sides of the collector are made of wood and the bottom of the collector is made of a blackened sheet of metal which acts as the absorber of solar insolation. All the sides and the underside of the collector are covered with a (10 cm-minimum) layer of insulating material. This helps to minimize loss of thermal energy.

The air duct is 3 m long and 20 cm in diameter. It is a T-type duct and connects the solar collector to the drying bin. The duct is made of PVC material since plastic is a good thermal insulator. A regulating device is fitted perpendicular and connected to this duct. It aids in regulating temperature, by allowing more cold-air into the system when the temperatures of the system exceed the required temperature values.

The drying chamber is essentially a batch dryer and measures 2.5 m × 2.5 m × 1.5 m. It accommodates a drying bin which act as the holding compartment for the wet parchment to be dried. The roof of the chamber is sloping to allow rainfall to drain away from the dryer. The base of the drying chamber is made of a block of wood material 0.5 m deep, since wood is a good thermal insulator. The wood must be well seasoned and pre-treated to ensure it is protected from the humid environment. The chimney is fitted at the top of the drying chamber. This chimney serves as the exit for the moisture ridden air. It is important since it ensures that moisture does not condense at the top of the drying chamber and also speeds up the rate of drying through creating the suction effect.

The drying bin measures 2 m × 2 m × 0.5 m. It is linked to the collector by the means of a T-type duct which conveys heated air to the wet parchment. The bottom of the drying bin is made of special type of coffee grit which has openings of 1% the size of the bottom surface area. This
ensures that the heated air passes smoothly through the coffee to be dried with minimal resistance. The sides of the drying bin are covered with a layer of insulating material to minimize the heat loss through the sides of the bin compartment.

The system designed can handle a capacity of up to 86 kg of wet parchment per m² at a depth of 100 mm. However, the system can be scaled upwards in the case of commercial applications to meet the required capacity.

The average sunshine at the experimental site was found to be 12 hours per day. The daily solar insolation at the site was found to be 0.451 kW/ m² of surface per day. By utilizing the solar collector in question and assuming a collector efficiency of 20 %, the total solar energy received is 3.608 kW-hrs/m²/day or 36.08 kW-hours per day (assuming the sunshine hours per day to be 8 hours).

When the system is loaded with 86 kg of wet parchment at 55 % M.C. and dried to 10.5 M.C., 42.76 kg of water is removed. This requires 22.45 kW-hours per day of energy to evaporate. Taking the collector efficiency as 20 %, the drying operation would take about 4 days. The drying time, however, will vary according to the actual conditions at the site. The system dries 3.4 times faster compared to natural air circulation system.

In determination of the drying air flow rate, the drying potential and capacity of the air were the two important properties to consider. The air flow rate was found to be 8.63 m³/min and the maximum velocity at the center of the pipe was found to be 4.58 m/s.

This design is based on data obtained from coffee research foundation (CRF), at Ruiru. The site was picked due to the ease of obtaining timely and accurate design data. However, the design can be adopted easily to any region in Kenya since the coffee growing regions fall within the same agro-ecological zone.
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<tr>
<td>d.b</td>
<td>Dry basis</td>
</tr>
<tr>
<td>W.b</td>
<td>Wet basis</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra violet</td>
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<tr>
<td>Pa</td>
<td>Pascal</td>
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<tr>
<td>M</td>
<td>meters</td>
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<tr>
<td>M.C.</td>
<td>Moisture content</td>
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<td>Hrs</td>
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<td>RH</td>
<td>Relative humidity</td>
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<td>°C</td>
<td>Degrees centigrade</td>
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<td>%</td>
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CHAPTER 1

1.0 INTRODUCTION

1.1 Background

After oil, coffee is the second largest volume commodity sold in the world. Coffee goes through a series of processing stages before it reaches the cup. Each of these processing stages contributes significantly to the final quality of coffee and hence there is need for careful and skillful handling. The drying of coffee is a step in coffee processing that is required, as for many other food crops, to stabilize an otherwise unstable product. Depending on the processing method employed, the whole fruit, the crushed fruit, parchments (bean enclosed by the inner integument), or naked beans may be dried. It is very important to note that, the processes of drying and fermentation are the key stages that influence coffee quality.

Coffee drying entails moisture reduction from about 60% to about 11% wet basis (w.b) to achieve a stable product. For coffee producers, the drying process of coffee grain is critical for obtaining a good quality and a good price for their product. The drying process is very important for keeping the quality of the coffee, because it reduces the humidity content of the grain in order to store and impedes the microbial action that is responsible for spoilage.

The conventional way of drying coffee is open beds at 25mm depth, and the mandatory requirement of exposing coffee to sunshine in Kenya, demands high labour input, vast drying space, and longer drying periods. Sun drying is still widely practiced in many tropical and subtropical countries. It is the cheapest method of drying coffee but the quality of the dried products is far below the international standards.

In recent years, solar drying technologies have become a preferred option for drying majority of agricultural-based products. Solar drying of agricultural products in enclosed structures by forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional open sun-drying methods (Jain and Tiwari, 2003). In many rural locations in most developing countries, grid-connected electricity and supplies of other non-renewable sources of energy are non-existent, unreliable or, too expensive. In such conditions, solar dryers appear increasingly to be attractive as commercial propositions (Mekhilefa et al., 2011; Xingxing et al., 2012).

1.2 Problem statement and Problem Analysis

Currently, parchment coffee is dried in open drying beds in the sun. Manual labour is employed in transporting both the wet and dry parchment to and fro during the drying process, and for the
frequent turning of the coffee on the beds. Labour is also required in covering and uncovering the coffee on the beds whenever necessary. Furthermore, during the peak picking period, the need for more drying beds increases, but owing to the lack of space for expansion, it is not always possible to satisfy this requirement.

Chapman et al. (2006) reported that poor coffee quality in Southern Thailand which was contaminated with Ochratoxin A (OTA), was due to extended and poor drying conditions.

Sun drying is also prone to other in-built problem, such as, degradation due to biochemical or microbiological reactions; the coffee is unprotected from rain, storm, windborne dirt, dust, and infestation by insects, rodents, and other animals. This method of drying may result in physical and structural alterations in the final product, including shrinkage, case-hardening, loss of volatile nutrient components and lower water re-absorption during rehydration. Consequently, sun drying yields low quality product that in most instances does not meet the desired international standards.

Mechanized coffee drying systems have greatly speeded-up the overall drying rate, but face a major limitation in the sense that complete drying by machine is not feasible. In Kenya, for instance, it is mandatory to expose parchment coffee at the black stage to the sun for at least 48 to 50 hours. Solar drying technology provides a suitable method of drying crops, particularly for low temperature systems. Solar energy is especially very efficient in “sun-belt” regions, that is, tropical and sub-tropical zones. Through the solar dryer option, the key challenges of sun drying, namely, large labour force, vast drying space, and extended drying periods, are effectively minimized. This in turn contributes to improved quality of dried coffee and better market prices for the product.

Solar drying is however, not a substitute for sun-drying. It is a complement for sun-drying by speeding-up the drying process. In both systems, the parchment coffee has to be exposed to sun during the soft black stage (it’s mandatory in Kenya).

1.3 Problem Justification

The justification for solar dryer is that they dry products rapidly, uniformly and hygienically, the prerequisites for industrial food drying processes.

1.4 Site Analysis and Inventory

The case study of this project was at Coffee Research Foundation (CRF), Ruiru, Kenya. This station is situated at latitude 1° South and longitude of 37° East. It experiences cool temperatures (less than 24 °C) between June and August. The rain falls in two seasons, March to May and October to November with maximum in April and November. These seasons, unfortunately, coincide with coffee harvesting and processing season.
Coffee Research Foundation (CRF) is located in Ruiru, adjacent the Coffee Research Institute (CRI) as shown on the google earth image below.
1.5 Overall Objective

The overall objective was to design an affordable solar dryer system for drying parchment coffee to replace or reduce dependence on fuel fired mechanical driers.

1.5.1 Specific Objectives

- To analyze the coffee drying requirements.
- To design a solar collector that absorbs solar radiation for heating air to the recommended coffee drying limit.
- To design a drying chamber that can hold a given amount of coffee to be dried by a given volume of air.
- To design the air-ducting system
- To prepare a bill of quantities and perform Cost-Benefit Analysis

1.6 Statement of scope

The scope of the project was to design a solar dryer for drying coffee within the recommended range of temperatures (i.e. 30°C to 40°C), and for coffee depths not more than 100 mm. The project covered the design of the solar collector, air vent, and a bin for holding the coffee to be dried. All this was done by utilizing locally available materials.
CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Mechanism of Drying

Drying basically comprises of two fundamental and simultaneous processes: (i) heat is transferred to evaporate liquid, and (ii) mass is transferred as a liquid or vapour within the solid and as a vapour from the surface. The factors governing the rates of these processes determine the drying rate. The different dryers may utilize heat transfer by convection, conduction, radiation, or a combination of these. However, in almost all solar dryers and other conventional dryers heat must flow to the outer surface first and then into the interior of the solid, with exception for dielectric and microwave drying (G.L. Visavale, 2012).

The drying phenomenon follows the psychrometric principles since drying rate is governed by air-water vapour relationship. Several factors affect the drying process such as; the drying method adopted, the drying air temperature, the relative humidity, the drying air velocity, and the drying time. The removal of water from foods provides microbiological stability and reduces deteriorative chemical reactions. Also, the process allows a substantial reduction in terms of mass, volume, packaging requirement, storage and transportation costs with more convenience (Okos et al., 1992).

2.2 Drying of wet processed coffee

The drying and fermentation operations are the two main stages which significantly influence the flavor and final quality of the coffee. Unlike grain, coffee has a high moisture content of about 60% w.b at the start of drying (i.e. immediately after fermentation or soaking). There is therefore, more water to be removed during the drying operation; this makes the process slower and more difficult to mechanize. The solution to complete mechanization is further complicated due to the requirement of sunlight exposure at the soft black stage, when the bean moisture content is between 32% and 22%.

2.2.1 Drying stages

There are six stages that coffee goes through during drying:

i) Skin drying stage
The moisture content is reduced from 55% to 45%. It is recommended that this reduction in moisture content be done as quickly as possible; any delay will result in the formation of onion flavor and sourness. This drying stage may be done by heated air or sun drying. A coffee layer thickness of 12 mm on skin drying tables is recommended in sun drying and 45 mm in forced air drying. At this stage, the water held between the parchment and the bean is removed. This stage is identified as a constant rate of drying phase. The coffee beans on the drying tables are constantly stirred to avoid cracking of the parchment. It is important not to allow the parchment to crack at this stage because it is considered necessary for filtering sun rays in later stages of drying.

ii) White stage drying

The moisture is reduced from 45% to 33% in this stage. Research has shown that this process must be done slowly and controlled in order to avoid the cracking of the parchment. Thickness of 25 mm is recommended in sun drying. Thorough aeration is essential in order to avoid stinkers. The falling rate drying starts at this stage and the temperature should be lowered in forced air drying systems. It is recommended that the above two stages take between two to three days.

iii) Soft black stage drying

In this stage the moisture is reduced from 33% to 22%. This stage is recommended to last for at least 48 to 50 hours. Sun drying is considered a must in this stage for better cup quality. The apparent importance of the sun’s irradiation makes the process of handling coffee in Kenya labour intensive and expensive.

iv) Medium black stage drying

The moisture is reduced from 21% to 16% in this stage. The coffee at this stage is dark in colour and may be dried either mechanically or in the sun. Unlike in the previous two stages, coffee may now be dried quickly without adverse effect on the quality. This drying is done on the sun drying beds in most factories of Kenya.

v) Hard black stage drying

The moisture is brought down to 12%. Drying continues in the sun or by heated air and may be done fast.

vi) Fully dry and conditioning stage

The moisture is further reduced from 12% to 10.5%. The parchment at this stage may be in a store. Dry air is blown through the perforated wooden floors to even up the moisture at a given relative humidity, normally recommended to be 60%.

2.3 Drying methods
There are two broad methods of drying coffee, that is, natural sun-drying and forced air drying. Sometimes a combination of both methods may be used. However, each method has its limitations depending on the location and effects on the coffee quality.

2.3.1 Natural sun drying

This is the oldest method of drying and is used to dry a wide variety of agricultural products. In this method, immediately after the coffee is removed from the soak tanks, the wet coffee is spread out on wet parchment drying tables where most of the water is allowed to drip off. This is the skin drying stage and may last up to two days in the sun. Drying will continue until moisture content of about 11% is achieved. However, this method suffers the key draw-backs mentioned earlier hence yielding low quality coffee.

2.3.2 Force-Air drying/ Mechanical drying

Mechanical dryers using forced air systems are the best alternative at present, particularly for large estates which handle large amounts of coffee. Though different mechanical drying methods are available, they are expensive, need technical skill and many of them produce low quality coffee. The dryers are mainly fueled through petroleum products, biomass or electricity for their drying applications. Of the world’s total energy requirements, 80% comes from fossil fuels and only a dismal 2-3% from renewable energy sources (WEA, 2000). This trend raises serious environmental concerns which make these systems unsustainable in the long-run.

2.4 Solar dryers

The major two categories of solar dryers are the natural convection solar dryers 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 inflow is provided by using fan operated either by electricity/solar module or fossil fuels. These dryers fall within two main groups, that is, high temperature dryers and low temperature dryers.

Further, solar-energy drying systems are classified primarily according to their heating modes and the manner in which solar heat is utilized (El-Sebaii et al, 2002):

- Passive solar-energy drying systems (conventionally termed natural-convection solar drying systems); and
- Active solar-energy drying systems (most types of which are often termed hybrid solar dryers).

A coffee solar dryer transforms solar energy into heat that helps diminish the humidity of the coffee grains; the quantity of water that can be reduced by evaporation from the coffee grains depends mainly on the air temperature and velocity of air circulation.
2.4.1 Passive solar-dryer

In passive solar dryers, air is heated and circulated naturally by buoyancy force or as a result of wind pressure or combination of both. They are also referred to as Natural convection solar dryers and do not require supplemental energy sources. They consist of a solar collector with a transparent cover on top and a drying unit with an opaque cover on top. The crop to be dried is contained within a cabinet in a relatively thin bed. The heated air from the collector flows as a result of the buoyancy forces resulting from the temperature gradient up through the crop thus drying it in the process.

![Diagram of Passive Solar Dryer](image)

**Figure 2.4 (a) Distributed-type natural-circulation solar maize dryer**

(Ekechukwu and Norton, 1999)

The passive dryers are best suited for drying small batches of fruits and vegetables such as banana, pineapple, mango, potato, and carrot (Hughes et al., 2011).

2.4.2 Active solar-drying systems

Active solar drying systems are designed incorporating external means, like fans or pumps, for moving the solar energy in the form of heated air from the collector area to the drying beds. Thus all active solar dryer are, by their application, forced convection dryer. A typical active solar dryer depends on solar-energy only for the heat source, while for air circulation uses motorized fans or ventilator (G.L. Visavale, 2012).

Normally, the air at required flow-rate is provided by two dc fans operated by one photovoltaic module.
Examples of active solar drying systems include:

i) Solar tunnel drier (Esper and Muhlbauer, 1993 and Janjai, 2004),
ii) Indirect forced convection solar drier (Oosthuizen, 1996),
iii) Greenhouse type solar drier (Janjai, 2004),
iv) Roof-Integrated solar drier (Janjai, 2004),
v) Solar assisted dryer (SmitaBhindu, 2004).

Active solar dryers are known to be suitable for drying higher moisture content foodstuffs such as papaya, kiwi fruits, coffee, brinjal, cabbage and cauliflower slices (G.L. Visavale, 2012).

2.5 Factors Affecting the Rate of Drying and Quality of Coffee

- **Drying Temperature**
  Temperature has a direct effect on the rate of drying and hence is considered to be one of the key factors for consideration in any drying system. In coffee drying, it is the temperature of the coffee, not of the drying air, that is of importance in the drying process. The recommended range for coffee drying temperatures is 30°C to 40°C.

- **Air Drying Potential**
  The drying potential of air is defined as the drying force that accomplishes drying and is measured by the difference between the water vapour pressure of the material to be dried and that of the drying air. The excess of the material vapour pressure over that of air, constitutes the drying potential and influence the rate of drying. When the material vapour pressure equals that of the drying air, the drying potential becomes zero and drying ceases.
• **Relative Humidity**
  Relative humidity is the ratio of the partial pressure of the water vapour to the equilibrium vapour pressure of water at the same temperature. The relative humidity of air is an indicator of the drying capacity of the air. A low value of RH is generally an indication of a high drying capacity.

• **Velocity of Drying Air**
  In general, for high moisture content coffee, as the air velocity increases, the drying rate increases and is more uniform. Therefore, at the initial phase of drying, high velocity of drying air will ensure faster rate of moisture removal from the wet parchment coffee.
CHAPTER 3

3.0 THEORETICAL FRAMEWORK

3.1 Physical Modeling

3.1.1 Assumptions

a) The air flow in thermal balance close to surface of the product and in space between particles to the layer is laminar with an almost null speed and moisture does not condense on the surface of the product.

b) The water of the product migrates on the surface of the product along the conduits of sap (xylems). This transport of water and the thermal flow has a cylindrical symmetry. Consequently, the different thickness of the wet agricultural produce can be modeled as cylindrical particles.

3.2 Mathematical modeling

a) The dehydration of thin layers of wet agricultural produce

Taking account of the symmetry of the system and applying the diffusion equation, we can show that:

$$\frac{\delta y}{\delta x} = D \frac{\delta^2 \eta}{\delta x^2}$$ ................................. (1)

This equation is called the dehydration equation of thin layers of wet agricultural products. The dehydration equation of thin layers of wet agricultural products admits as solution, the relation:

$$\eta_1(t) = \eta_0 e^{-kt}$$ ................................. (2)

Where;

$$\eta_0$$ is the water content of wet agricultural products,

K the time constant of diffusion

b) The dehydration of thin layer of wet agricultural produce with hull

In the case of dehydration of thin layers of wet agricultural produce with hull, we can show that the equation of dehydration is:

$$\frac{\delta \eta_2}{\delta t} + k_2 \eta_2 = k \eta_1$$ ................................. (3)
Where;

\( \eta_2 \) is the water content of hull part and \( k_2 \) is its time constant of diffusion’

\( \eta_1 \) is the water content of the part without hull and \( k \) is its time constant of diffusion.

The equation of the thin layers of the wet agricultural produce with hull admits as solution the relation:

\[
\eta_2 = \eta_0 \alpha \cdot e^{-kt} \quad \ldots \quad (4)
\]

With, \( \alpha = \frac{k}{k_2 - k} \)

### 3.3 Determination of the various drying parameters

**a) Available solar energy approximation**

This is estimated by employing the Angstrom’s expression

\[
Q = Q_0 (a + b \frac{s}{s_0}) \quad \ldots \quad (5)
\]

Where, \( Q \)=average daily radiation received on a horizontal surface, kW/m\(^2\)

\( Q_0 \)=solar radiation constant per day, kW/m\(^2\)

\( S \)=hours of sunshine recorded at the site per day

\( S_0 \)=maximum possible number of hours of sunshine at the site per day

\( a, b \)=constants which depend on location, \( a \) being relatively constant and \( b \) is dependent on latitude.

**b) Energy requirement**

The following two equations will be applied:

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

\[
Q = m_w \times h_{fg} \quad \ldots \quad (6) \quad a
\]

Where;
Q=the amount of energy required for the drying process, kJ

\( m_w = \text{mass of water, kg} \)

\( h_{fg} = \text{latent heat of evaporation, kJ/kg.} \)

\[(2) \quad m_w = m_p \frac{m_i - m_f}{100 - m_f} \]

Where, 

- \( m_i = \text{initial moisture content, \% wet basis;} \)
- \( m_f = \text{final moisture content, \% wet basis;} \)
- \( m_w = \text{Amount of water to be removed of water, kg;} \)
- \( m_p = \text{initial mass of product to be dried, kg.} \)

The amount needed is a function of temperature and moisture content of the crop. The latent heat of vaporization is calculated from Youcef-Ali et al. (2001) as follows:

\[ h_{fg} = 4.186 \times 10^3 (597-0.56 (T_p) ) \]

Where, \( T_p = \text{product temperature, \^{\degree}C} \)

c) **Estimation of the area of the solar collector**

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

\[ A_c I_\eta = m' (h_f - h_i) t_d \]

Therefore, area of the solar collector is:

\[ A_c = \frac{E}{I_\eta} \]

Where:

- \( E = m' (h_f - h_i) t_d \)
- \( m' = \text{mass flow rate of air, kg/hr} \)
- \( A_c = \text{the solar drying system collector area, } m^2 \)
- \( E = \text{the total useful energy received by the drying air, kJ} \)
I is the total global radiation on the horizontal surface during the drying period, kJ/m²

η is the collector efficiency, 20% (Vincent Serem, 1987).

d) **Estimation of the air-flow rate**

The mass of air, m, needed for drying is calculated using equation given by Sodha et al. (1987) as follows:

\[
m = \frac{m_{dr}}{W_f - W_i} \]

\[\text{(8)}\]

Where;

- \(m_{dr}\) = average drying rate, kg/hr
- \(W_f - W_i\) = final and initial humidity ratio, respectively, kg water/ kg dry air

Volumetric airflow rate, \(V_a\) is obtained by dividing mass of water lost, \(m_w\) by the drying potential, \(d_p\), given as;

\[
V_a = \frac{m_w}{d_p} \]

\[\text{(9)}\]

e) **Air vent dimension**

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

\[
A_v = \frac{V_a}{V_w} \]

\[\text{(10)}\]

Where;

- \(A_v\) is the area of the air vent, m²,
- \(V_w\) is the wind speed, m/s.

f) **Dynamic pressure**

The pressure difference across the coffee bed will be solely due to the speed of the heated air and the density difference between the hot air inside the dryer and the ambient air.

The operation of a fan is often expressed in the terms of pressure;

\[
P_t = P_s + P_d = constant \]

\[\text{(11)}\]

Where;
\[ P_t = \text{total pressure (Pa, N/m}^2 \text{)} \]
\[ P_s = \text{static pressure (Pa, N/m}^2 \text{)} \]
\[ P_d = \text{dynamic pressure (Pa, N/m}^2 \text{)} \]

The dynamic pressure can be expressed as:

\[ P_d = \frac{\rho V^2}{2} \ldots (12) \]

Where:
\[ \rho = \text{density of air (kg/m}^3 \text{)} \]
\[ V = \text{flow velocity (m/s)} \]

### 3.3 Drying Efficiencies

- **Efficiency of a solar collector**

  The efficiency of a solar collector is defined as the quotient of usable thermal energy versus the received solar energy. The performance evaluation of the collector, which is significant for its dimensioning, is based on the Hottel-Whiller equation on the assumption that it is applicable to this design. In the steady state, the thermal efficiency \( \eta_c \) is defined by:

\[
\eta_c = \frac{M C_p (T_d - T_a)}{A_c I_t} \ldots (13)
\]

Where:
- \( M \) is the mass of the product in Kg;
- \( C_p \) is the specific heat of the product in kJ Kg\(^{-1}\)K\(^{-1}\);
- \( T_d \) is the dryer temperature in °C;
- \( T_a \) is the ambient temperature in °C;
- \( A_c \) is the collector surface area in m\(^2\);
- \( I_t \) is the total incident radiation in kW/m\(^2\)

- **Pick up Efficiency**

  The pick up efficiency, \( \eta_p \) is defined as the ratio of the moisture removed or picked-up by the drying air to the theoretical capacity of the air to absorb moisture. Mathematically;

\[
\eta_p = \frac{W_o - W_i}{W_a - W_i} \ldots (14)
\]

Where, \( W_i \) and \( W_o \) is the absolute humidity of air entering and leaving the drying chamber respectively.
$W_a$ is the adiabatic saturation humidity of air entering the dryer.

The numerator of this equation could also be written as:

$$\frac{M_o - M_t}{V \rho}$$

Where:

$m_o$ and $m_t$ are the mass of the commodity at time $t=0$ and $t=t$ respectively.

$V$ is the volume flow rate

$\rho$ is the density of air

- **System Efficiency**
  The system drying efficiency $\eta_s$ or system efficiency is the ratio of the energy required to evaporate the moisture of the commodity to the heat supplied by the dryer. Mathematically;

$$\eta_s = \frac{W_o L}{I A_c} \quad \cdots \cdots \quad (15)$$

Where:

$W_o$ is the mass of moisture evaporated;

$L$ is the latent heat of vaporization of water at the dryer temperature

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

$A_c$ is the solar drying system collector area, m$^2$

**NOTE:** System efficiency is a measure of the overall effectiveness of the drying system. Typical values are 10-15 % for natural convection dryers, while a system efficiency of 20-30 % could be expected for forced convection dryers. This is approximately 3.4 times compared to natural sun drying.
CHAPTER 4

4.0 METHODOLOGY

4.1 Data Collection

4.1.1 Meteorological Data

The following data was collected regarding the weather conditions at the proposed site for the months of May and November, that is, when peak rainfall is experienced:

- Sun duration (hrs)
- Solar radiation (mj)
- Wet-bulb temperature (°C)
- Dry bulb temperature (°C)
- Relative humidity (%)

The weather information for the months of May and November was collected at the Meteorological station based at the site (i.e. Coffee Research Foundation). This data was requested from the field-station manager. (See Appendix A1 Tables A1-2 & A1-3).

While the general recommendation is that the temperature of the drying coffee should not be more than 35 °C but an upward tolerance of 5 °C for short periods may not be harmful on the quality. The solar collector was therefore designed to raise the temperature from the ambient value (about 24°C to 35 °C. The ambient temperature varies according to the weather conditions prevalent each day.

4.2 Design

Two important factors were covered during the design:

a) Design Calculations
b) Design system components

4.2.1 Design Calculations

a) Solar Energy Approximation

From Angstroms’s expression:

\[ Q = Q_0 (a + b \frac{s}{s_0}) \]

At coffee Research Foundation (CRF):

\[ Q_0 = \text{Ranges from 1.101 kW/m}^2 \text{ to 1.390 kW/m}^2 \]
Taking $S = 8\ \text{hrs/day}$

\[ S_0 = 12\ \text{hrs} \]

\[ b=0.25 \]

\[ b=0.24, \text{values for Kisangani, Zaire, lying on the same latitude with the station (Williams, 1974).} \]

\[ Q=1.1[0.25+0.24(8/12)] \]

\[ =0.451\ \text{kW/m}^2/\text{hr} \]

\[ =0.451\ \text{kW/m}^2/\text{hr} \times 8\ \text{hrs} \]

\[ = 3.608\ \text{kW-hrs/m}^2/\text{day} \]

Area of solar collector= 10 m$^2$

Therefore, total daily potential= $3.608\ \text{kW-hrs/m}^2/\text{day} \times 10\ \text{m}^2$

\[ = 36.08\ \text{kW-hrs} \]

The normal range of collector efficiency is 30-40\%.

However, for design purposes, it is common to use a theoretical collector efficiency of 20\% (Bala, 1997).

Therefore, assuming collector efficiency as 20%:

\[ \frac{20}{100} \times 36.08\ \text{kW-hrs} \]

\[ = 7.216\ \text{kW-hrs/day (Available)} \]

\[ \text{b) Energy Requirement} \]

The following two equations were applied:

\[ Q=m_w \times h_{fg} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ ld
Taking initial moisture content of coffee= 55%, and
Final moisture content=10.5%
Then; \(m_w = 86 \times \left(\frac{55-10.5}{100-10.5}\right) = 42.76 \text{ kg (water lost)}\)

Latent heat of vaporization= 1890 kJ/kg at 25 °C
Therefore, the energy required= 1890 \times 42.76 = 80,816.4 \text{ kJ}
= 22.449 \text{ kW-hrs}

c) **Estimation of the area of the solar collector**

Total energy to evaporate 42.76 kg of water= 22.45 kW-hrs
Assuming that drying can be accomplished in 4 days, and that 8 hours of sunshine are available per day;
Total energy= 0.451 \times 8 \times 4 = 14,432 \text{ kW-hrs/m}^2
If collector efficiency= 20%
Heat energy from the collector= 2.8864 kW-hrs/m²
\[
A_c = \frac{E}{E_{\text{eq}}}
\]
\[
= \frac{22.45}{(2.8864 \times 0.76)}
\]
\[
= 10.234 \text{ m}^2
\]
d) **Estimation of the air flow rate**

Assuming that average daily rise in temperature= (25-30) °C;
Ambient relative humidity= 90%;
Taking the drying air relative humidity= 60% and exhaust air relative humidity= 50 %
At 25 °C, and 90 % R.H….a.h=0.119 kg water per kg dry air
At 30 °C, and 60% R.H.,a.h=0.0142 kg water per kg dry air
Therefore, the drying potential= (0.0142-0.0119) =0.0023 kg water per kg dry air
Specific volume of air at these conditions= 0.891 m³/kg

Hence the drying potential= \[
\frac{2.3 \times 10^{-3} \text{ kg}}{0.891 \text{ m}^3}
\]
\[
= 2.58 \times 10^{-3} \text{ kg water/m}^3 \text{ air}
\]
42.76 kg water requires:
\[ (42.76/2.58) \times 1000 \text{ m}^3 \text{ air} \]
\[ = 1.657 \times 10^4 \text{ m}^3 \text{ air} \]

If the drying period is 4 days (8 hours per day), air flow rate will be;

\[
V_a = \frac{m_w}{d_p} = \frac{1.657 \times 10^4}{32 \times 60} 
\]

Air flow rate = 8.63 m$^3$/min or 0.1438 m$^3$/s

**e) Air vent dimensions**

The maximum velocity at the center of the duct in a forced air-dryer system should be in the range of 4.7-6.2 m/s (Mekhilefa, 2011).

Taking a velocity of 4.7 m/s and applying the continuity equation of pipe flow:

\[
Q = VA = V \frac{\pi D^2}{4} 
\]

Substituting:

\[
0.1438 = 4.7 \times A = (4.7 \times \pi \times D^2) / 4
\]

\[D^2 = 0.0389\]

\[D = 0.197 \text{ m}\]

Take a diameter of 20 cm or 0.2 m for the design.

Pipe diameter, \( D = 0.20 \text{ m} \)

Cross sectional area, \( A = 0.0314 \text{ m}^2 \)

Air flow rate, \( V_a = 0.1438 \text{ m}^3/s \)

Maximum velocity at the center of the pipe was calculated as follows:

\[A_v = \frac{V_a}{V_w}\]
\[ V_{\text{max}} = \frac{0.1438}{0.0314} \]

\[ = 4.58 \text{ m/s} \]

f) Dynamic Pressure

The dynamic pressure can be expressed as:

\[ P_d = \frac{\rho V^2}{2} \]

\[ = \frac{1.215 \times 4.58^2}{2} \]

\[ = 12.741 \text{ Pa} \]

(Mekhilefa, 2011) The loss of thermal energy is directly proportional with the length of the ducting pipe. However, the loss of thermal energy is negligible within the first 5 m length of pipe used (only applicable to u-PVC pipes).

For this design, a duct length of 3 m was used.

4.2.2 Drying Efficiencies

➤ Solar Collector Efficiency

The following formula was used to compute the collector efficiency:

\[ \eta = \frac{M C_p (T_d - T_a)}{A_c I_t} \]

Where:

- \( M \) is the mass of the product in Kg;
- \( C_p \) is the specific heat of the product in kJ Kg\(^{-1}\) K\(^{-1}\);
- \( T_d \) is the dryer temperature in °C;
- \( T_a \) is the ambient temperature in °C;
- \( A_c \) is the collector surface area in m\(^2\);
- \( I_t \) is the total incident radiation in kW/m\(^2\)

\[ \eta = \frac{86 \times 12.395 \times (35 - 24)}{10 \times 36.08} \]

\[ = 32.5\% \]

This is the collector efficiency at full capacity, that is, 100 mm.

➤ Pick-up Efficiency
The pick-up efficiency was determined from the formula below:

\[ \eta_p = \frac{W_o - W_i}{W_a - W_i} \]

Where, \( W_i \) and \( W_o \) is the absolute humidity of air entering and leaving the drying chamber respectively.

\( W_a \) is the adiabatic saturation humidity of air entering the dryer.

Substituting;

\[ \eta_p = \frac{60 - 50}{90 - 50} = \frac{10}{40} = 25\% \]

**System Efficiency**

The system efficiency was determined from the following formula:

\[ \eta_s = c \frac{W_o L}{IA_c} \]

Where;

\( W_o \) is the mass of moisture evaporated;
\( L \) is the latent heat of vaporization of water at the dryer temperature
\( I \) is the total global radiation on the horizontal surface during the drying period, kJ/m²
\( A_c \) is the solar drying system collector area, m²
\( c = 10-12 \) for forced convection dryers

Substituting:

\[ \eta_s = 10 \times \frac{42.76 \times 2.025}{3.608 \times 10} \]

\[ = 23.99\% \]

Take System efficiency as 24 %.

This is within the range of forced convection dryers, that is, 20-30 %.

### 4.2.3 Design System components
1) Solar collector unit

From theoretical computations, a collector area of 10 m$^2$ was arrived at. To achieve this collector area, a collector measuring 4 m by 2.5 m, was designed. The solar collector unit measuring 4 m long by 2.5 m wide and 0.5 m deep, was designed utilizing locally available materials. The various collector components are as follows:

- A transparent glass top to allow solar irradiation into the collector unit and prevent loss of thermal energy.
- The bottom of the collector unit is composed of an absorber. The absorber is made of a thick black painted galvanized iron sheet (1” thick). This is the surface used to absorb incoming solar radiation. The under-side of the absorber is covered with a 10 cm insulating foam material to prevent loss of thermal energy.
- An insulation (10 cm thick) at the bottom and on the sides of the collector to prevent loss of thermal energy. The insulating material utilized for all the linings was dense foam.

The design incorporated a cold air inlet positioned perpendicular to air-flow duct and connected to the duct before the blower. The device was for regulating the temperature of the air by letting in cold air whenever the temperature become higher than required. It was to be operated manually.

The angle of inclination of the solar collector was taken as 12°, which lies between -9° and 15° recommended for maximum solar energy collection (Gbaha et al, 2007).

2) The Air duct

The design made provision for an air duct to convey heated air to the drying chamber. From computations done above, the diameter of the duct was found to be 0.2 m and the length to be 3 m. It is made of PVC pipe since plastic is a good thermal insulator. The air inlet device is connected perpendicular to this duct (as earlier mentioned).

3) Drying Chamber

A ton of coffee cherry requires an area of 40 m$^2$ of drying space on the open drying beds for wet parchment at a depth of 12.5 mm. For main drying tables, the requirement is 20 m$^2$ per ton of cherry at a depth of 25 mm. When natural circulation system is used the area requirement reduces by 5:1 compared to main beds limit. The forced convection system requires the same area per ton of coffee for an extra depth in the ratio 1:4. It is common practice in coffee factories to base the sizing of these drying bins per ton of cherry.

Therefore, for forced convection system an area of 4 m$^2$ will be needed for a depth of 100 mm of wet cherry. A bin drying area of 2 m by 2 m was provided to meet this requirement. It can dry up to a ton of coffee, but can be scaled upwards to meet more capacity. To dry 86 kg of wet cherry at
100 mm, a demarcation grate which is fitted into the drying bin is used to confine the area to the required one. This way, any quantities less than a ton, can be confined in proportional areas of the drying bin and drying conducted. The drying chamber houses the coffee-holding bin measuring 2.0 m × 2.0 m × 0.5 m. The drying chamber is 2.5 m long by 2.5 m wide, and 1.5 m high. Its foundation is made of 0.5 m wooden block which is treated and properly cured to ensure it can withstand environmental elements. The wooden base is ideal for preventing thermal loss through the cold floor.

The dual-way fan is connected to the hot-air duct just below the drying bin. The fan speeds up the flow of heated air through the wet coffee berries, reducing the drying time by three times compared to the natural circulating system.

The whole chamber and the holding bin are made of 30 gauge galvanized sheets which are forged and soldered into the required shapes. There is a chimney at the roof of the chamber to allow moisture ridden exhaust air to escape. This is important to ensure the moisture does not accumulate at the top of the chamber and to create the suction effect ideal for faster drying.

The sides of the holding bin are insulated using 10 cm foam material to prevent loss of thermal energy. The floor of the bin was made from a coffee tray wire material. The openings of the tray wire were much greater than 1 % of the area of the floor and hence resistance to air-flow was negligible. The top side of the container bin was left open for moisture to escape.

The various properties of the drying air were to be measured along the duct. The measuring devices were inserted into an inlet made in the duct for the measurement of temperature, relative humidity, and the air-flow rate.

**4.2.4 Soft Black Stage**

The system is not a complete replacement of sun drying. In Kenya, it is mandatory to expose coffee to sun-light for at least 45-50 hours at the soft black stage (i.e. when moisture is gradually reduced from about 33 % to 22 %). This is desirable since it improves the cup-quality of coffee. Therefore, for this system, coffee has to be exposed to the sun when this stage is reached.
CHAPTER 5

5.0 RESULTS AND ANALYSIS

5.1 Performance of the solar collector

The solar collector has an efficiency of 32.5 % when the system is operating at full capacity (i.e. 86 kg of wet parchment at 100 mm depth). This efficiency is well within the range of 30-40 % for the corresponding collector area.

As the collector heats up, thermal losses from it will reduce its efficiency, resulting in increased radiation, primarily infrared. This is countered in two ways. First, the glass top helps to create the green-house effect. It readily transmits solar radiation in the visible and ultraviolet spectrum, but does not transmit the lower frequency infrared re-radiation very well. Second, the glass top also traps air in the space, thus reducing the heat loss by convection.

Parchment coffee is dried in the months of May and June and again in November and December. Most of the days within these months have moderate weather conditions and are sunny.

The incident angle of solar radiation varies throughout the year. However, the difference in the amount of energy received is small during most of the time in a year. This is because of the fact that Kenya is situated near the equator with the sun near the zenith year round and the tilted angle of the collector is small, 12°.

5.2 Performance of the solar dryer

The solar dryer has a collector efficiency of 32.5 %, a pick-up efficiency of 25 %, and a system efficiency of 24 %. The system efficiency is within the range of efficiency for forced convection dryers, that is, 20-30 %. The collector efficiency is within the range of 30-40 % for the given collector area.

The drying air is forced through the coffee parchment with an air speed of 4.58 m/s. The pressure of the drying air drops but it depends on the depth of the bed of the products. For this case, a depth of 100 mm is recommended. For 86 kg of fresh parchment coffee, its bed depth will decrease due to shrinkage of the coffee parchment.

For moderate weather conditions, the moisture content of the parchment in the drying bin will be reduced from an initial value of 55 % w.b. to 10.5% w.b. within 4 days (8 hours daily), or with an effective drying time of approximately 32 solar hours. The drying time, however will vary according to the actual conditions at the site.

The average sunshine hours at the site was found to be 12 hours per day. By using Angstrom equation, the daily solar radiation at the site was found to be 0.451 kW/m². By using a solar
collector with a surface area of 10m², the total solar received was 3.608 kW-hrs/m²/day or 36.08 kW-hrs assuming 8 sunshine hours daily.

When the system is loaded with 86 kg of wet parchment at 55.5 % M.C. and dried to 10.5 % M.C., 42.76 kg of water is removed. This requires 22.45 kW-hrs of energy for evaporation. If 20 % collector efficiency is assumed, the drying operation would take about 4 days. The drying time however, will vary according to the actual conditions at the site.

The air flow rate into the drying bin was found to be 0.1438 m³/s. It was assumed further in this calculation that the drying would take 8 hours a day, and that the rate of drying was constant.

5.3 Weather conditions Analysis

From the meteorological data for May and November collected at the Ruiru Field station (Tables A1-2 and A1-3):

- The mean average day temperature in May= 18.62 °C (d.b) and 19.58 °C (w.b)
- The average relative humidity for May= 92.7 %
- From the Psychrometric chart (Appendix A2, figure A2-2), the humidity ratio for May= 0.0127 kg Water/kg dry air.
- The mean average temperature in November= 20.23 °C (d.b) and 18.32 °C (w.b.)
- The average relative humidity for November= 92.1 %

Table 5.3 Average weather conditions for the year 2014 (CRF, Meteorological station)

<table>
<thead>
<tr>
<th>Month</th>
<th>D.b Temp. (°C)</th>
<th>W.b temp. (°C)</th>
<th>Relative humidity (%)</th>
<th>Sun duration (hrs/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>18.62</td>
<td>19.58</td>
<td>92.7</td>
<td>6.65</td>
</tr>
<tr>
<td>June</td>
<td>21.45</td>
<td>20.5</td>
<td>89.6</td>
<td>7.71</td>
</tr>
<tr>
<td>July</td>
<td>19.0</td>
<td>18.4</td>
<td>90.4</td>
<td>6.80</td>
</tr>
<tr>
<td>November</td>
<td>20.23</td>
<td>18.32</td>
<td>92.1</td>
<td>7.59</td>
</tr>
<tr>
<td>December</td>
<td>22.86</td>
<td>21.5</td>
<td>91.4</td>
<td>7.88</td>
</tr>
</tbody>
</table>

Source: CRF, Ruiru, Meteorological Station.
### 5.4 Economic Analysis

#### 5.4.1 Engineering Bill of Quantities

Table 5.4 (a) BOQ

<table>
<thead>
<tr>
<th>ITEM</th>
<th>DESCRIPTION</th>
<th>UNIT</th>
<th>QUANTITY</th>
<th>RATE (Ksh)</th>
<th>AMOUNT (Ksh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Solar Collector Unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transparent glass top, 28 gage (4m × 2.5m)</td>
<td>m²</td>
<td>10</td>
<td>400</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>Timber frame (sides): 10 “ × 2 ”</td>
<td>M</td>
<td>5</td>
<td>250</td>
<td>1,250</td>
</tr>
<tr>
<td></td>
<td>5 “ × 2 ”</td>
<td>M</td>
<td>3</td>
<td>170</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>3 “ × 2 ”</td>
<td>M</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Iron Metal sheet, 30 gage (4 m × 2.5 m).</td>
<td>m²</td>
<td>10</td>
<td>799</td>
<td>7,990</td>
</tr>
<tr>
<td></td>
<td>Insulating Material (10 cm thick foam)</td>
<td>m³</td>
<td>2.65</td>
<td>500</td>
<td>1,325</td>
</tr>
<tr>
<td></td>
<td>Nails</td>
<td>Kg</td>
<td>1</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><strong>Air-duct Unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 mm DIA. 3m u-PVC pipe</td>
<td>M</td>
<td>4</td>
<td>1,748</td>
<td>6,992</td>
</tr>
<tr>
<td></td>
<td>Regulating screw shutter GI</td>
<td>Kg</td>
<td>1</td>
<td>450</td>
<td>450</td>
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<td>3</td>
<td><strong>Drying Chamber</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iron Metal sheets, 30 gage</td>
<td>m²</td>
<td>40</td>
<td>799</td>
<td>31,960</td>
</tr>
<tr>
<td></td>
<td>Wooden Base (25 “ by 25 ’)</td>
<td>M</td>
<td>3</td>
<td>400</td>
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<td></td>
<td>Damp-proof membrane (dpm)</td>
<td>M</td>
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<td>2,105</td>
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<tr>
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<td>Insulating material (10 cm thick foam)</td>
<td>m³</td>
<td>5</td>
<td>500</td>
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</tr>
<tr>
<td>4</td>
<td><strong>Drying Bin</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Iron metal sheet, 30 gage</td>
<td>m²</td>
<td>20</td>
<td>799</td>
<td>15,980</td>
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<tr>
<td></td>
<td>Coffee grill plate</td>
<td>kg</td>
<td>1</td>
<td>1,230</td>
<td>1,230</td>
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<td></td>
<td>Insulating material (10 cm thick foam)</td>
<td>m³</td>
<td>3</td>
<td>500</td>
<td>1,500</td>
</tr>
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<td>5</td>
<td><strong>Duo-way fan/Blower</strong> (Flow rate = 2.99 kg/s)</td>
<td>Rpm</td>
<td>1</td>
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<tr>
<td></td>
<td><strong>TOTAL</strong></td>
<td></td>
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<td><strong>85,242</strong></td>
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Table 5.4 (b) Other costs involved:

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<th>S/N</th>
<th>PARAMETER</th>
<th>AMOUNT</th>
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<tbody>
<tr>
<td>1</td>
<td>Land clearing and flooring</td>
<td>12,580</td>
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<td>2</td>
<td>Installation and labor cost</td>
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<td>3</td>
<td>O &amp; M (30% of construction cost)</td>
<td>25,572</td>
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<td>4</td>
<td>Auxiliary power source (electricity)</td>
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<td>5</td>
<td>Insurance Cost (2% of fixed cost)</td>
<td>1,705</td>
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<tr>
<td></td>
<td>TOTAL</td>
<td>76,773</td>
</tr>
</tbody>
</table>

TOTAL COST OF PUTTING THE SYSTEM = (85,242 + 76,773) = KSH. 162,015

5.4.2 Cost-Benefit Analysis

The Capital cost (FC) of the solar drying system is the sum of all the components as collector, drying chamber, blower, the auxiliary heater, and installation costs. The cost of drying (products) can be divided into fixed costs and direct costs. Direct costs comprise the labor cost control, electrical, maintenance and insurance. The cost of the product can be written as follows (Yahya, 2007):

\[ PC = MC + LBC + ELC + EXC \]

Where;
\[ EXC = MC + IC \]

With
\[ PC = \text{production cost} \]
\[ MC = \text{cost of materials} \]
\[ LBC = \text{labor costs} \]
\[ ELC = \text{electricity costs} \]
\[ IC = \text{maintenance cost} \]
\[ IC = \text{cost of insurance} \]

The Future Value \( P_f \) of the system can be calculated from the Present Value \( P_v \), assuming the interest rate to be 5% and the Project lifetime 40 yrs:

\[ P_v = \frac{P_f}{(1 + r)^t} \]

\[ 162,015 = \frac{P_f}{(1+0.05)^{40}} \]

Therefore, Future Value, \( P_f = \text{Ksh. 1,140,584} \)
The solar dryer designed in this project will cost roughly **Ksh. 162,015** (Present value) and **Ksh. 1,140,584** (Future value, 40 years), after accounting for the various costs involved. According to (Swain, 2014), a fuel-fired Mechanized dryer of the same capacity will require **Ksh. 732,870** (Present value) and **Ksh. 5,159,397** (Future value, 40 years). This clearly shows that a solar dryer system is a better replacement for the biomass fired dryer.

Revenues saved by using Solar dryer in place of Biomass fired dryers= 732,870- 162,015= Ksh. 570,855.

\[
\text{CBR} = \frac{570,855}{162,015} = 3.52
\]

The Cost Benefit Ratio (CBR) is 3.52 which is greater than 1. This means the project is viable.

The conventional way of drying coffee, that is, sun drying has been reported to incur Ksh. 4,000 per kg of coffee dried, on the bear minimum, after factoring in the space, labor, and drying period involved (Mwangi, 2007). Taking the capicity of this dryer system i.e. 86 kg, then;

Cost of sun drying= 86 × 4,000= Ksh. 344,000

Revenues saved by using solar dryer system in place of sun drying:

= 344,000- 162,015= Ksh. 181,985

Therefore, \[
\text{CBR} = \frac{181,985}{162,015} = 1.12
\]

This implies that, there will be higher benefits of utilizing this design compared to natural sun-drying, since the CBR is greater than 1.
CHAPTER 6

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The overall objective of this design project was to design an affordable solar dryer system for drying parchment coffee to replace or reduce dependence on fuel-fired mechanical driers. In order to achieve this broad objective, several specific objectives were set as captured in the introduction section of this report. The output of the design therefore, was a solar dryer system that addressed these design objectives.

The solar dryer has a collector efficiency of 32.5 %, a pick-up efficiency of 25 %, and a system efficiency of 24 %. The system efficiency is within the range of efficiency for forced convection dryers, that is, 20-30 %. The collector efficiency is within the range of 30-40 % for the given collector area. The Cost-Benefit ratio is 3.52 compared with a biomass fired dryer of the same capacity and 1.12 compared to natural sun drying. This implies that the project is economically feasible and a desirable option.

The solar dryer, so designed, minimizes both space and labour requirements in the coffee drying while accomplishing successful drying. The capacity of this model dryer system is 86 kg of wet parchment coffee per m². However, for commercial purposes, this design can be scaled upwards to achieve desired coffee handling capacity.

The solar dryer reduces moisture content of parchment from 55 % to 10.5 % wet basis within a span of 4 days upon which the crop is stable for storage. The products being dried in this system are completely protected from rains, insects and other foreign matter that would compromise the quality of the final product. Consequently, the product achieved is of high quality and meets the market requirements.

It can be concluded that the solar collector at defined rates and operational times increases drying efficiencies of parchment coffee about 20 to 40 %, that is, 3.4 times compared to natural sun drying. However, the solar collector needs to be cleaned from time to time to eliminate the deposits of dust which would ultimately lower the amount of solar irradiation into the collector.

A regulating device is mounted onto the hot-air duct. It is designed to be operated manually. When the drying temperatures go beyond the required values, the devise is adjusted thus letting in cold air from the atmosphere to lower the dryer temperature.

A chimney is fitted on top of the drying chamber and its main role is to allow moisture ridden-air to escape from the dryer. This is important in two main ways. First, it minimizes the build-up of
moisture above the drying bin which is very undesirable in a drying system. Secondly, it offers the suction effect due to the space created by exhausted air, thus more hot air is forced into the drying chamber. The result is faster drying rates.

It is important to expose the coffee to natural sunlight at the soft black stage so that the moisture can be reduced gradually from about 33% to 22%. This is a good practice in the drying of coffee since it helps to improve the cup-quality. It is also mandatory to do so in Kenya.

### 6.2 Recommendations

- Controlling air temperature manually is ineffective and can lead to overheating of the coffee. An automatic temperature regulating device is therefore very necessary and should be incorporated into the design for better results.
- An auxiliary energy source such as electricity should be incorporated into the system to provide energy when the weather conditions are unfavorable. It would also give harmony and uniformity of temperatures during drying.
- An alternative energy for driving the fan, most probably solar energy, should be tapped to reduce the cost of energy and hence the overall drying cost.
- There is need to carry-out further work in this design by producing the prototype and testing the system to see whether the theoretical results given here are consistent with the real system in operation.
CHAPTER 7

7.0 REFERENCES


8. Werner Weiss, Josef Buchinger, Solar drying, (establishment of a production, sales and consulting infrastructure for solar thermal plants in Zimbabwe).


## CHAPTER 8

### 8.0 APPENDICES

Appendix A1: Tables

**Table A1-1: Typical checklist for preliminary evaluation and selection of solar dryers.**

<table>
<thead>
<tr>
<th>SR. NO.</th>
<th>PARAMETER</th>
<th>FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Physical features of dryer</td>
<td>• Type, size and shape</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Loading capacity (kg/ unit tray area)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Loading/unloading convenience</td>
</tr>
<tr>
<td>2</td>
<td>Thermal performance</td>
<td>• Drying period/time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Drying efficiency</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Airflow rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Solar insolation</td>
</tr>
<tr>
<td>3</td>
<td>Properties of the material being handled</td>
<td>• Physical characteristics (wet/dry)</td>
</tr>
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<td></td>
<td></td>
<td>• Particle size</td>
</tr>
<tr>
<td>4</td>
<td>Drying characteristics of the material</td>
<td>• Type of moisture (bound, unbound or both)</td>
</tr>
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<td></td>
<td></td>
<td>• Initial moisture content</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Final moisture content</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Permissible drying temperature</td>
</tr>
<tr>
<td>5</td>
<td>Flow of material to and from the dryer</td>
<td>• Quantity to be handled per hour</td>
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<tr>
<td></td>
<td></td>
<td>• Continuous or batch operation</td>
</tr>
<tr>
<td>6</td>
<td>Product qualities</td>
<td>• Contamination</td>
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<td></td>
<td></td>
<td>• Uniformity of final moisture content</td>
</tr>
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<td></td>
<td>• Appearance</td>
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<td></td>
<td>• Flavor</td>
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<td>Recovery problems</td>
<td>• Dust recovery</td>
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<td>• Solvent recovery</td>
</tr>
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<td>8</td>
<td>Facilities available at site of possible</td>
<td>• Space</td>
</tr>
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<td></td>
<td>installation</td>
<td>• Temperature, humidity, and cleanliness of air</td>
</tr>
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<td>• Available fuels</td>
</tr>
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<td></td>
<td>• Source of wet feed</td>
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<td>9</td>
<td>Economics</td>
<td>• Cost of dryer</td>
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<td>Other parameters</td>
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<td>• Safety and reliability</td>
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<td>• Maintenance</td>
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Table A1-2: Meteorological Data (For month of May, 2014)

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<th>D.b Temperature (°C)</th>
<th>W.b Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Sun duration (Hrs)</th>
<th>Solar radiation (mj)</th>
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Table A1-3: Meteorological data (For month of November, 2014)

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<th>W.b Temperature (°C)</th>
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<th>Sun duration (Hrs)</th>
<th>Solar radiation (mj)</th>
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Appendix A2: Figures

Figure A2-1: Flowchart showing steps involved in wet-processing of coffee.

- Picking of Ripe cherries
- Sorting by hand to remove unripe & overripe
- Pulping of the coffee
- Washing of pulped beans
- Drying of wet beans
- Storing of dried beans in gunny
- Coffee beans dispatched to coffee curing works
- Pulping machine & washer system
- Coffee effluent
- Coffee spread on drying beds or fed to the dryer
Figure A2-2: Psychrometric Chart
Appendix A3 Design drawings

U.O.N.
F21/3557 /2010

CROSS SECTION VIEW

DESIGNED BY: MWANGI JEREMIAH

CHECKED BY: ENG. DR. GICHUKI MUCHIRI

ALL DIM. IN M
### SIDE VIEW A

**DESIGNED BY:** MWANGI JEREMIAH  
**CHECKED BY:** ENG. DR. MUCHIRI  
**ALL DIM. IN M**