Addis Ababa Institute of Technology

School of Graduate

Energy Center

Experimental Analysis of Solar Thermal Tea Dryer

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Declaration

I, Miskir Teffera Eshetie declare that this thesis is the result of my own work and that all source or material used for this thesis has been truly acknowledged. This thesis is submitted in partial fulfillment of the requirement for Master's Degree in Energy Technology at Addis Ababa University and to be made available at the university's Library under the role of the Library. I confidently declare that this thesis has not been submitted to any other institutions anywhere for the award of any academic degree, diploma, or certificate.

Signature: ________________________

Date: ________________________

Acknowledgement

Before all I am very grateful to the **Almighty God**, for his blessing and graces through the entire work of this study. I would like to express my deep feeling of happiness to all my families especially my mom, who encourages me to finish this study with full of commitment.

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Abstract

The tea drying is a heat transfer between the product and the surrounding to dry the leaf and make ready for market. Conventional tea dryer consumes too much energy since the water will be heated using the electric boiler. The main objectives of this research are to design, manufacture and test the performance of solar thermal tea dryer. The solar dryer was mathematically designed using the data gathered from the National Metrological Agency. The solar dryer was sketched on the solid work before it goes to the workshop for construction. The construction of the dyer was done in Addis Ababa Institute of Technology, Mechanical Engineering workshop. The designed dryer has a collector area of $1.3m^2$ and a ventilation area of $0.1m^2$. The assessment has been done with scientific experiment using different measuring methods and tools at Addis Ababa Institute of Technology, Addis Ababa University, and Addis Ababa, Ethiopia. The solar radiation on the collector, the ambient temperature, the temperature on the solar collector, and inside the dryer chamber, including the wind speed were measured and analyzed. The sample products used to measure the performance of the dryer are *Moringa* (drumstick tree) and *Ginger*. Due to a problem countered in bringing tea leaves without losing moisture. The initial moisture content of the *Moringa* (drumstick tree) leaf was 50% and the final moisture content was 5.1%, and for *Ginger* the initial moisture content was 68% and the final moisture content was 13.1%. The total moisture removed from the sample products was 44.9 % and 43.9 % for *Moringa* and *Ginger* respectively. The drying rate for *Moringa* and *Ginger* is 0.27 ${}^{kg}/_{hr}$ and 0.25 ${}^{kg}/_{hr}$, respectively. The average collector efficiency is 36.3% and 22.1% with no load and with load, respectively. The total time taken to dry the products is 6 h. Finally, the overall efficiency of the dryer for drying *Moringa* and *Ginger* is 23.8% and 21.5%, respectively. The solar dryer could be used for drying other agricultural products after testing at different seasons especially when there is a high and low solar radiation and temperature to see the maximum and minimum performance of the dryer.

Keywords: Solar Dryer, *Moringa* Leaf, *Ginger*, Solar energy, Solar collector, Drying chamber, Drying efficiency, Design and Manufacture

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Nomenclature

Symbols	**Meaning**
A_c	Area of the collector
A_v	Area of ventilation
C_p	Specific heat capacity of air
F_R	Heat removal factor
hr	Hour
L_v	Latent heat of water
L	Length of the collector
kJ	Kilo joule
kg	Kilogram
Km	Kilometer
K	Kelvin
m	Meter
M_i	Initial moisture content
M_f	Final moisture content
M_{dr}	Average drying rate
M_r	Moisture to be removed
M_p	Sample mass of the drying product
Q_u	Useful energy
Q_{load}	Drying heat load
S_r	Solar radiation

s	Second
T_a	Ambient temperature
T_c	Collector temperature
T_f	Output temperature from the drying bed
t_d	Drying time
v_w	Wind speed
UV	Ultra-violate
W	Width of the collector
τ	Transmittance
α	Absorbance
ρ_{Air}	Density of air
V_a	Volumetric air flow
$\dot{m}_a$	Mass flow rate
η_D	Efficiency of the dryer

Chapter One

Introduction

1.1. Background

Worldwide Solar thermal energies are mostly applicable on the electrical energy usage in companies. In Ethiopia the usage of the renewable energy other than hydropower energy is rarely applied. Some industries use electrical energy that comes from Ethiopian electric power. Recently it is very difficult to get the electric power, so as a solution some industries use their own energy like small wind turbine system and some of them use solar energy system [1].

In Ethiopia industries use solar energy system to support the energy supply. Some of the energy technologies used in the companies is solar air heating and cooling system, solar water heating system and some of them are used for home supply [2]. From all of the renewable energies other than the hydro-power the solar energy is more applicable on individual area in Ethiopia [2].

One of the applications of solar energy is drying. In ancient time solar energy of drying is used to dry clothes, some agricultural foods like chili, and to make the water hot by using the open air sunning. But now a days the thermal use changes from open sunning to indirect solar drying system. Drying is the removal of moisture from a product in order to make the product to stop the chemical reaction and change so that it will have a better life time on the market. A tea leaf is one of those agricultural products that needs to be dried [3].

Tea leaf has to go on a lot of processes in order to be called tea; one of the main processes is drying. Since tea has a lot of capability of making a chemical reaction and has to have a good quality. It cannot be dried in open air drying system. Tea plantation industries use direct electric power from the main grid for drying purpose. Therefore to minimize the energy consumption it is better to use a solar thermal tea drying system.

Solar thermal drying system can be classified in to three sections. Those are called open sun drying, direct drying and indirect drying system. The one which is more applicable for tea drying is indirect solar thermal drying system [4].

The indirect solar thermal drying system is a way of drying a product without direct contact with the solar energy source, sun. It has three main parts the solar collector, the drying chamber and the hot air removing gap. So the air that comes from the ambient will pass through the air gaps on the collector to the solar drying chamber to remove the moisture of the product. This will take different times depending on the solar absorber material, the quantity of glazing material and the moisture content in the product. Since the tea plant has a high chemical change property it is better to dry it as fast as possible [4].

The main objective of this research is to design the indirect solar thermal tea dryer and test the performance of the designed and manufactured dryer in Addis Ababa Institute of Technology, Addis Ababa University, and Addis Ababa, Ethiopia.

1.2. Statement of the problem

A tea leaf needs to be dried in order to be on market for longer time without losing its quality. The drying process needs medium temperature and lower drying time. However, in industries the tea leaf is dried by using a high temperature and faster time energy converter electric water heating dryer.

Fastest drying time is needed but drying the tea with a high temperature will affect the quality of the tea, and there will be a high consumption of electric power from the grid for heating up the water at higher temperature using water heating system. So to minimize consumption of electrical energy the solar thermal drying system needs to be installed. The other main reason is that there is no solar thermal tea dryer that has been installed in Ethiopia. This paper tries to have the minimum drying time compared with other researches. This research tries to manufacture a tea dryer that works thermally by using solar energy, which will keep the quality in desirable form.

1.3. Objectives

The main objective of this research is to design, manufacture and test the performance of solar thermal tea dryer in Addis Ababa.

The specific objective of this research includes:

- To design the solar thermal tea dryer mathematically.
- To design the solar dryer on 3D Solid-work.
- To construct the designed solar dryer.
- To test the performance of the dryer.

1.4. Delimitation

In this research, the drying mechanism of tea by using the solar thermal was analyzed. But it can only be operated in the sunny season. So during the summer time, the dryer cannot be used since the sun will not be available as needed. That means if there is solar radiation available during summer, the sun radiation will not be strong enough to operate the drying machine. There should be a backup mechanism during the summer time or other times when there is no sufficient sun radiation in order to operate the given drying machine. The backup mechanism is not included in this research.

1.5. Organization of thesis

The first chapter describes the introduction of the research while chapter Two is the literature review that describes about the type and classifications of solar dryers are briefly described. Then the basic principle of solar radiation and thermal insulation mechanisms are described. Then finally the pervious works on solar thermal dryer is listed.

Chapter Three is a material and method section. That describes and compares the materials used for the construction of the dryer. And select the best one for the model manufacturing. The other part also describes the methods used for preparing this research.

Chapter Four is about a design of solar tea dryer. It contains the data gathering and analyzing part and it describes the main designing parameters. Beside that the 3D model of the dryer is shown.

Chapter Five is manufacturing of the solar tea dryer. It describes the dimension of each material used for the construction of the dryer. Then show the ways and methods of assembling the dryer.

Chapter Six is the experimental setup and procedures section. It shows what parameters to be tested and how is the performance of the dryer with different situations.
Chapter Seven is the result and discussion section. It describes the final achievement of the experiment.

Chapter Eight is conclusion and recommendation section. This part describes the conclusion of the overall research and what are not specifically done on this paper. Finally it recommend for other researchers to do what is not done on this research.

Chapter Two

Literature Review

Mostly in ancient time solar energy is used for different applications like drying of closes, foods, fruits and vegetables for domestic use in order to be preserved for later use. Now a day's solar energy technology is used for drying of products to increase the life time of the products. The most dominant way of drying technology is the open drying technology. It is simple and most usable one. It has its own draw backs related with quality and nutritional value of the product. To minimize this problems there are different type of solar dryer technologies to dry up products. The main purpose of designing solar dryer is to extract the solar radiation that comes from the sun to useful heat energy. In the following section the types and methods of solar drying are discussed.

2.1. Classifications of dryers

Dryer system can be classified primarily according to their temperature range in to high temperature dryer and low temperature dryer [5]. High temperature dryers are where the drying process will be faster. They are mostly applicable for products that require a short drying time. They are fossil fuel powered dryers.

In the case of low temperature dryers, the moisture content of the product is usually brought in equilibrium with the drying air by constant ventilation. It enables the products to dry in bulk and used for long term storage system. Most practically realized designs of solar energy are of low temperature dryers.

Dryers are also classified by the source and circulation of the drying air [5]. Active dryers are dryers that use unnatural mechanism to process the drying. It might be using the fans (or other artificial method) to make the hot air flow from the absorber to the chamber. That means, it need an external source of power to operate the fan, and it might be electrical or solar.

Passive dryers are using natural way to dry the products. That means they do no need external source of energy. The hotter air will flow to the chamber by wind pressure or naturally. Figure 2.1 shows types and classification of solar dryers[6].

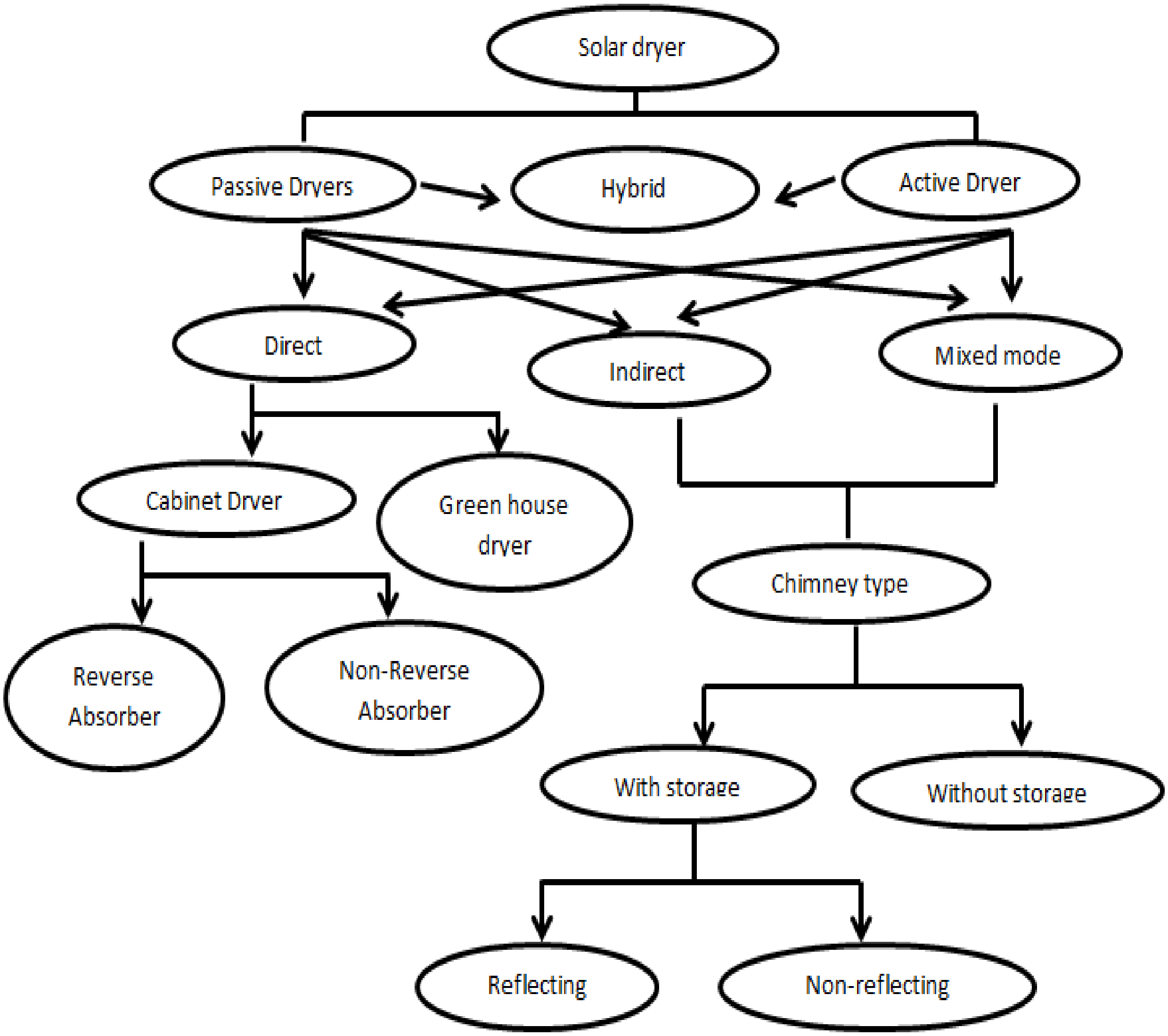


Figure 2.1- Types and classification of dryers [6]

Accordingly to the working principles, dryers are also classified as open sun or indirect drying [5]. Open sun drying or sunning is a way of exposing the products directly to the sun by spreading in to the ground. The radiations might be reflected back to the air and others will be absorbed by the ground and from the ground to the drying product heat will be transferred. Figure 2.2 shows the working principal of open sun drying.

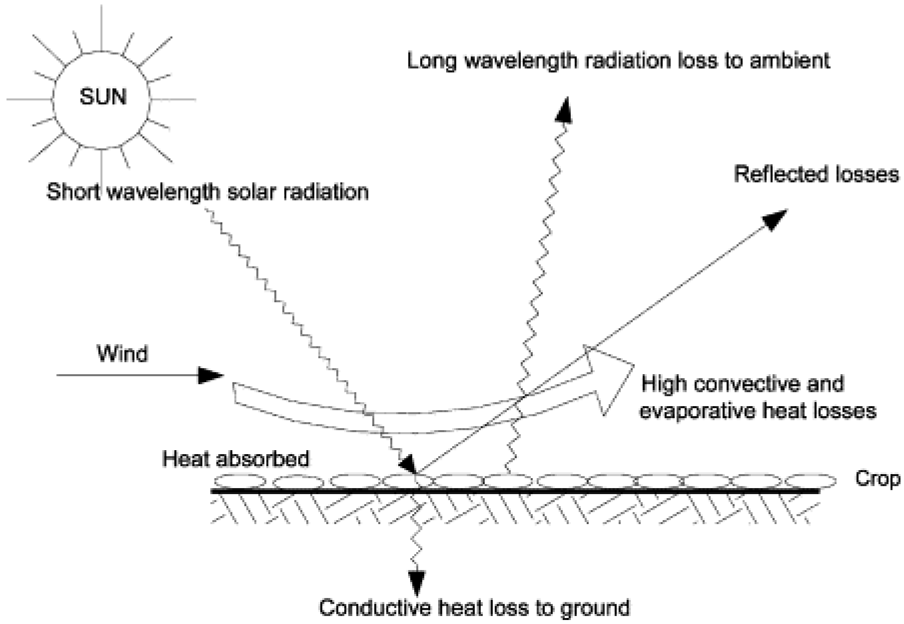


Figure 2.2- Open sun drying [5]

Direct solar drying system use solar radiation directly to dry up the product. It usually has a drying cabinet constructed by insulating box and on top of that there is a glass or plastic cover with an air ventilation holes on it. The top cover of the dryer which is glass/ plastic covers the product from the dusts, insects, and animal interference. The ventilation holes are available at the top and bottom of the dryer to maintain the circulation of air throughout the dryer. The solar radiation will be interrupted by the glass cover, some of them will be reflected back to the atmosphere and the other will be transmitted inside the cabinet. It is simple and cheaper but it has the following limitations; it has small capacity and used for only small scale applications, direct exposure of the sun will create chemical reaction on the product, the moisture that comes from the product will affect the transmittance property of the glass and to make the dryer effective, the temperature of the air needs to be high [5]. Figure 2.3 shows direct solar dryer.

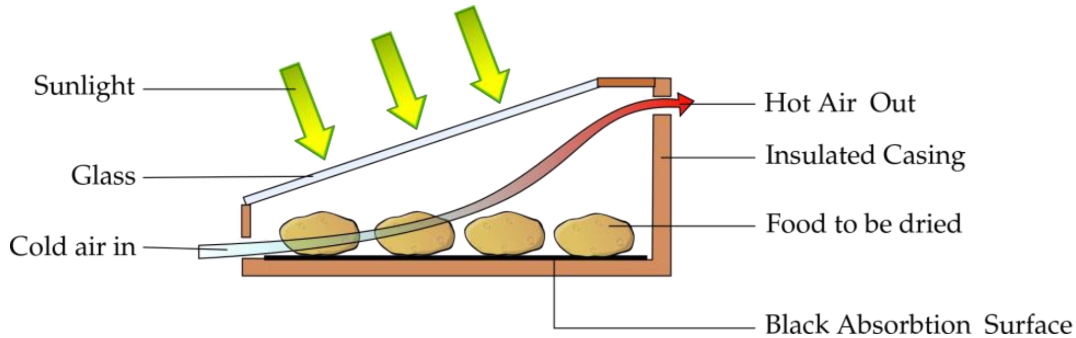


Figure 2.3- Direct solar dryer [7]

Indirect solar drying are dryers that use the solar energy not directly but by transferring the solar radiation in to heat energy. It has the solar collector that collects the sun radiation from the sun. The main collector material for the conversion process is the absorber plate, the collector also have the ventilation hole that uses for the flow of air from outside to the drying chamber. The drying chamber is a place where the drying product is placed. After the air goes through the drying chamber it has to go out of the chamber through the chimney by having the moisture removed from the product. The positive effect and the draw backs are listed below [5]. Figure 2.4 shows a type of indirect solar dryer.

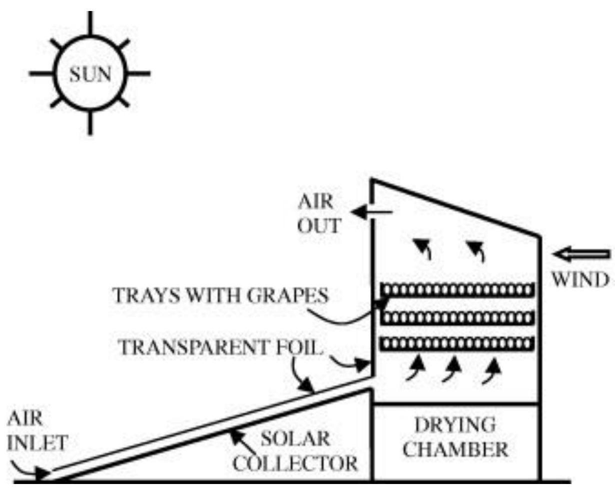


Figure 2.4- Indirect solar dryer [5]

The positive effect of the indirect solar energy is higher air temperature inside the dryer, since the product is not exposed to direct sun light it doesn't loss its color and nutritional value, it is used to dry multi products, has a longer durability, and simple constriction and easy to handle. The draw backs are over drying of products on the lower tray, uncomfortable to handle it on the mid-day, it has a high heat loss through the body of drying cabinet, has a lower capacity, poor moist removal, and invisible for detection of product dryness.

There are also dryers that have effective drying process or for the purpose of drying multiple food products. These are greenhouse dryers, tunnel dryers, flat plate collectors, evacuated tube collectors, and concentrated collectors. Green house dryers are used for mass drying purpose. It is applicable n large areas and its body is constructed built from transparent material and it has an air circulation system using ventilation holes [8]. Tunnel dryers, the air flows in at one end and exists in other end. The design develops at university of Hohenheim, Germany. It uses PV-solar panel to heat the inlet air.

Due to their collector type the indirect dryers are classified in to three [9]. Flat plate collectors are not optical concentration of sunlight and they are generally stationary. The outlet temperature is not exceeding 100℃. Evacuated tube collectors are Vacuum to reduce heat lost and to protect the absorber coating from detrition. They collect both direct and diffuse solar radiation and it have a temperature up to 140℃. Focusing collector follows the sun to get the direct radiation. It cannot utilize diffuse radiation and have a capability of producing high temperature. Focusing collector can be classified in to cylindrical trough, parabolic trough, parabolic dish, power tower and Fresnel lens [9].

Cylindrical trough has a circular shape with a focal plane that will track the sun. Parabolic trough is troughs concentrate sunlight onto a receiver tube that is positioned along the focal line of the trough. It can receive 400℃ and produce steam for generating electricity. Parabolic dish system is also called Parabolic and point focus, it is similar in appearance to a large satellite dish, but has mirror like reflectors and absorber at the focal point. It can receive 1000℃. Power tower system is an array of sun tracking flat mirror called heliostats concentrate irradiation from the sun on to a receiver, a top central tower, and it can produce or receive a temperature from 550℃ to 1500℃. Fresnel lens for solar concentration is developed for concentrating photovoltaic application. The lenses are designed its Plano side to face the sun (parallel light source), and the Fresnel surface to face photovoltaic cells (focus).

2.2. Solar radiation

Solar radiation is called the solar resource which is a general term for the electromagnetic radiation emitted by the sun. Solar radiation can be captured and turned into useful forms of energy, such as heat and electricity, using a variety of technologies [10].

2.2.1. Basic Principles

Every location on Earth receives sunlight at least part of the year. The amount of solar radiation that reaches any one spot on the Earth's surface varies according to geographic location, time of the day, season, local landscape, and local weather [10].

Because the Earth is round, the sun strikes the surface at different angles, ranging from 0° (just above the horizon) to 90° (directly overhead). When the sun's rays are vertical, the Earth's surface gets all the energy possible. The more slanted the sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffuse. Because the Earth is round, the frigid Polar Regions never get a high sun, and because of the tilted axis of rotation, these areas receive no sun at all during part of the year. The Earth revolves around the sun in an elliptical orbit and is closer to the sun during part of the year. When the sun is nearer the Earth, the Earth's surface receives a little more solar energy. The Earth is nearer the sun when it is summer in the southern hemisphere and winter in the northern hemisphere. However, the presence of vast oceans moderates the hotter summers and colder winters one would expect to see in the southern hemisphere as a result of this difference.

The 23.5° tilt in the Earth's axis of rotation is a more significant factor in determining the amount of sunlight striking the Earth at a particular location. While tilting results in longer days in the northern hemisphere from the spring (vernal) equinox to the fall (autumnal) equinox and longer days in the southern hemisphere during the other 6 months. Days and nights are both exactly 12 hours long on the equinoxes, which occur each year on or around March 23 and September 22.

The rotation of the Earth is also responsible for hourly variations in sunlight. In the early morning and late afternoon, the sun is low in the sky. Its rays travel further through the atmosphere than at noon, when the sun is at its highest point. On a clear day, the greatest amount of solar energy reaches a solar collector around solar noon.

2.2.2. Diffuse and Direct Solar Radiation

As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by air molecules, water vapor, clouds, dust, pollutants and forest fires [10]. This is called diffuse solar radiation. The solar radiation that reaches the Earth's surface without being diffused is called direct beam solar radiation. The sum of the diffuse and direct solar radiation is called global solar radiation. Atmospheric conditions can reduce direct beam radiation by 10% on clear, dry days and by 100% during thick, cloudy days.

2.2.3. Heat transfer modes

Heat flows from higher temperature to lower temperature. Though it looks simple, heat transfer is quite complex phenomenon. There are three basic modes of heat transfer, conduction, convection, and radiation [11]. Conduction takes place at a microscopic level. Atoms or molecules at higher temperature have high levels of energy. Through vibration, this energy is passed on to neighboring atoms and molecules. In other words, in conductive mode of heat transfer, vibrating atoms and molecules are parts of their energy [11]. This kind of heat transfer can take place between two or more substances or through the substance. Conduction can also take place when electrons move from one atom to another. Transient conduction takes place when temperature within an object changes as a function of time.

Convection is a mode of heat transfer which takes place through the movement of collective masses of heated atoms and molecules. Convection requires actual flow of material particles whereas in conduction, the heat is transferred through vibration without the atoms or molecules leaving their original position. In convection, heat transfer takes place through both diffusion and advection [11]. As convection requires the actual movement of the heated atoms/ molecules, it requires presence of a fluid for heat transfer.

Radiation is a mode of heat transfer which takes place through vacuum and hence, does not need a physical medium. Radiation takes place either through vacuum or through a transparent medium. In radiation mode, heat transfer takes place through photons present in the electromagnetic waves. The random movement of atoms and molecules in heated substances results in emission of electromagnetic waves which carry the heat to be transferred [11]. The radiation heat transfer is governed by Stephen- Boltzman law. A body radiates heat at all temperatures above the absolute zero, irrespective of the ambient temperature.

2.2.4. Thermal insulation

Thermal insulation is the reduction of heat transfer (i.e. the transfer of thermal energy between objects of differing temperature) between objects in thermal contact or in range of radiative influence. Thermal insulation can be achieved with specially engineered methods or processes, as well as with suitable object shapes and materials [12]. The main advantages of thermal insulation are reducing energy cost, prevent moisture condensation, and also reduce the capacity and size of new mechanical equipment. It also reduces emission of pollutants and enhances the process performance.

2.3. Previous works on dryers

Almost literatures reviewed are based on indirect flat plate collectors. Others are on direct flat collectors. So some literature reviews are discussed that are more related to this research considering their time of publication chronologically. The earliest ones are discussed at the first and more recent are in the last section of this chapter.

Bolaji and Olalusi [13] Constructed and evaluated the performance of an indirect solar active dryer for food preservation (Figure 2.5). The temperature rise inside the drying cabinet was up to 74% for 3 hours immediately after noon time. At that moment the drying rate and the efficiency was 0.62 $^{kg}/_{h}$ and 57.5% respectively. The rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level. And the final observation was that the temperature inside the dryer and collector was much higher than the ambient temperature.

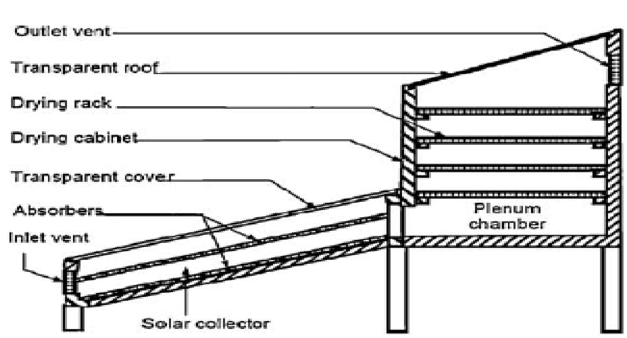


Figure 2.5- Indirect solar active dryer for food preservation [9]

Madhlopa et.al [14] developed a dryer that consists of flat plate collector, wire mesh absorber, glass cover chimney and drying chamber (Figure 2.6). Both the drying chamber frame and the collector were constructed from wooden sheets painted pink. Both the collector was integrated to a drying chamber for food dehydration. During the noon hours the temperature will be raised to 40°C and the thermal efficiency of flat plat collector and wired mesh absorber was approximately 21% and 17% respectively at a flow rate of 29.88 ${}^{kg}/_{h}$.

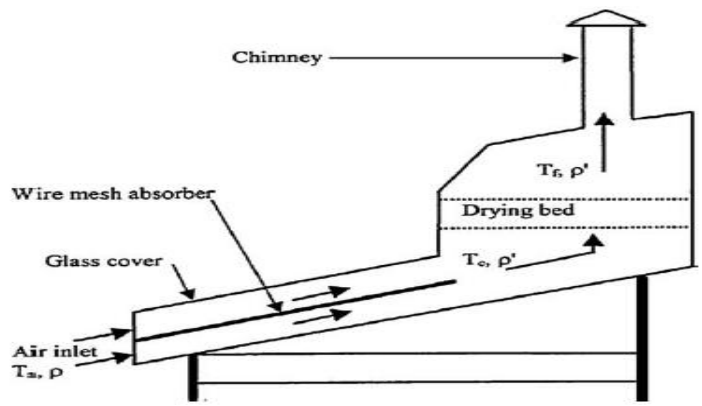


Figure 2.6- Madhalopa's dryer with flat plate collector [10]

An active mode with wind ventilated natural convection solar dryer has been reported by Ekechukwu and Norton [15]. The drying system consists essentially of a solar air heater integrated to the drying chamber at the base, and a rotary wind ventilator at the top of the dryer chimney. To reduce the heat losses, the northern facing wall and bottom horizontal panel are blackened. The rotary wind ventilator was built from moving corrugated vane rotor.

Smitabhindu et.al [16] has done the performance, simulation, and optimization of solar assisted drying system of banana. Also in the article the simulation results was compared with the experimental result. The optimum value of the collector area and recycling factor was found as 26 m^2 and 90% respectively. Schirmer et.al [17] has developed a multi-purpose solar dryer for banana in Thailand. So this paper shows that the dryer can dry up to 300 kg of banana in each drying batch. It also can minimize the time duration used to take for drying from 5-7 days to 3-5 days and the temperature will vary between 40 and 65°C.

El-Sebaii et.al [18] reported that moisture content of tomato decrease from 95% to 85% and then 7% within 36 hours and 28 hours for full size tomato and sliced one under the same condition.

Hossain and Bala [19] developed a multi-purpose solar dryer that can dry up to 80 kg of chilies. Chilies have higher moisture content to be removed and it need high temperature to dry. The dried chili has a better quality than the chili dried by direct sunning. The average temperature rise in the dryer was about 22℃ above the ambient temperature and almost constant throughout the dryer. The system that is constructed has its own protecting system from rain, dust, birds and dirt. It also can dry up both the red and green chili.

Essalhi et.al [20] designed and develop a multipurpose natural indirect solar dryer consisting of a solar heater and drying chamber. The solar heater also consists of a finned absorber (painted matte black), glass cover, insulation and frame. This system can be used for drying various agricultural products like fruits and vegetables. One of the successful dried products was Grape.

The research that has done on design and development of chili dryer, by Hossain et.al [21] was identifying the moisture content of the chili. The moisture content was determined by the oven drying method. Before drying it was weighted and after drying it also weighted. Then, the moisture content to be removed from the chili was calculated. The pressure throughout the dryer and the energy requires for drying was calculated. After calculating the moisture to be removed from the product it also showed the collector area for the dryer, vent area, and drying area. And finally he describes the physical features of the drier. The final result was decreasing the moisture content from 73% to 14%. The mass flow rate was 468 ${}^{kg}/_{h}$, the drying area was 7.5m^2, and the number of trays was 4.

The research that has been done on effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa beans by Dina et.al [22].The moisture content of the cocoa beans was 59.15% to 60.37% with different batch. He calculated and finds the following parameters like drying effectiveness was 38.4%, specific energy consumption was 18.94 ${}^{MJ}/_{kg}$ and effective diffusivity was 8.94×10^{-11} ${}^{m^2}/_{s}$.

The average temperature with in the drying chamber varies from 9℃ to 12℃ above the ambient temperature. The maximum temperature with in the drying chamber varies from 40℃ to 54℃. This temperature was suitable for drying cocoa beans. The solar dryer integrated with desiccant type thermal energy storage make drying more effective. The experiment showed the traditional direct sun drying spent 55h and this drying time minimized to 41h by using adsorbent type desiccant and it was 30h by using absorbent type desiccant. The main finding of this research was the solar energy was more effective when it is integrated with desiccant thermal energy storage.

The research that has done on thermal performance of indirect forced convection solar dryer and kinetics analysis of mango by Wang et.al [23] the analysis of drying mechanisms of Mango experimentally and theoretically. Some of the theoretical analyses described are, the total required heat for drying process, the drying rate, the thermal efficiency, the specific moisture extraction rate and effective moisture diffusivity are calculated for the Mango slice. The drying characteristics at four different temperatures (40, 44, 48, and 52℃) has been compared and analyzed. The variation of moisture content and drying rate has been shown. It was observed that the drying time at the drying temperature of 52℃ was lower than the drying time compared to others. Due to the increase of drying temperature in drying chamber the convective mass transfer between mango slices and the drying air reduces the drying time. Furthermore, it was also found that the drying rate was higher in the initial periods because of the rate of moisture removal decreases gradually along with the evaporation of moisture from surfaces. Subsequently, part of the energy can be consumed to move the moisture from the interior parts of mango slices to the surfaces.

The research that has done on design, development and performance of indirect type solar dryer for banana drying by Lingayat et.al [24]. During the analysis, first the initial moisture content of the banana has been identified to be 78%. Then the solar radiation, air temperature and relative humidity of the area were analyzed during the research. The maximum solar radiation was found to be $1219 W/m^2$ at 12:40 PM and the average solar radiation was obtained as $897.04 W/m^2$. The temperature of air at the outlet of the collector and the chamber was 81℃ and 78℃ respectively. After that the collector efficiency was calculated and the thermal efficiency was 31.50%. Finally the overall dryer efficiency was found to be 22.38% in the dryer chamber.

A research has been done on tomato slices drying in a liquid desiccant-assisted solar dryer coupled with a photovoltaic-thermal generation system by Dorouzi et.al [25]. This research paper has been done on solar dryer coupled with PV regeneration system. The parameters that was analyzed was the drying rate, solar fraction, solar heat fraction, solar electric supply to electricity consumption because of the PV, specific moisture extraction rate and finally the color analysis of the drying product which is tomato. Then the following output was achieved. The drying time was 27% shorter when applying the activation of RH 18% instead of 28%. Due to the temperature rise from 60 to 70℃ leads to the reduction of drying time around 10%. The solar electricity to electricity consumption was ranged between 0.45 and 1.7. The average value of solar electricity ratio was approximately 2.2 times higher if tomato slice dried at temperature of 60℃ instead of 70℃. The color was also shifted towards darker surface color.

The main research gaps are the dryers that are designed and constructed before has a higher drying time and some of the research have a lower collector efficiency and overall efficiency. The aim of this research is to experimentally analyze solar tea dryer. This research will use solar collector that will absorb the solar collector and convert it in to a high temperature in to the drying chamber and to dry the tea leaf with the minimum duration of time.

Chapter Three
Materials and Methods

This chapter contains the materials and methods used to construct the dryer for each section of the dryer, and the design of the dryer is explained. The comparison and the selection of materials are shown and explained in each sub sections and the design specification and the data gathered from the metrology and the *Wush Wush* tea plantation are also explained.

3.1. Materials

3.1.1. Selection of Dryer Type and Materials for the Dryer Parts

The possible alternatives of the solar dryer are listed in literature review of Chapter 2. From the listed dryer types the indirect solar dryer is chosen. The first reason to choose the indirect dryer type is that the tea leaf cannot be dried by direct sun due to its chemical content and has a capability of making chemical reaction. The indirect solar dryer has higher air temperature, has a longer durability and easy to handle.

Indirect solar dryer has three main parts, which includes the solar collector, dryer cabinet, and ventilation area or chimney. This type of dryer is also classified in to two, the first one is the table type and the second is the L-shaped Dryer. The comparison between the two types of dryer is listed in the Table 3.1 [8].

Table 3.1- Comparison between indirect solar dryer types [4]

L-shaped Dryer	Table type Dryer
Has high temperature	Has high temperature
The drying product will have a good quality because it is not directly exposed to the sun	The drying product will have a good quality because it is not directly exposed to the sun
Used to dry multiple products	It is not feasible for multiple drying
Easy to handle	Heavier to handle
Flexible for further improvements	It is very challenging for further improvements

The type of the dryer selected to be the indirect L-shaped dryer, due to its higher temperature, good quality of a drying product and easy to handle compared with table type dryer.

3.1.2. Selection of Materials for the Dryer Parts

The indirect solar dryer has three parts; a solar collector, a solar cabinet dryer and chimney (ventilation area). Solar collector is a part where the solar radiation will be absorbed and collected. It has a glass which is the outer cover of the collector, absorber material which absorbs the sun radiation and a frame and insulator.

Glazing material is the pouter cover of the solar collector which will also use to increase the absorption of the solar collector. The important parameters of the solar glazing material are the reflection, absorption and transmission. In order to get high efficiency we need to choose the glazing material with a low value of reflection and absorption but higher value of transmission. The main parameters to choose the glazing materials from the market is, the material should have higher strength which cannot be damaged easily due to different conditions, high durability, higher life span and finally it has to be non-degradable during the exposing of UV light.

There are two materials mostly used as a glazing material which are available in the market and used in most research papers are listed in the Table 3.2 with their thermal property [26].

Table 3.2- Comparison between glass and plastic [26]

Glass	Plastics
The volume change due to high temperature is very low.	It can change the volume due to high temperature
It Can absorb, reflect, and refract light.	It has a resistance to breakage light weight.
90% of transmitting as much as the incoming short wave.	It passes high short wave and long transmittance hence it have high performance.
It has higher life span.	It has a lower life span.

The material for glazing purpose is selected to be glass. Glass is selected due to its advantage in terms of absorbance, reflectivity and transmittance compared with plastic.

During the construction, the absorber is coated with a dull black paint which will be a better absorber, and the paint is matt black. The best materials that are available in the market as an absorbing materials are Copper and Aluminum. The comparisons of thermal property between the two materials are listed in Table 3.3 [26].

Table 3.3- The comparison between Copper and Aluminum [26]

Materials	Copper	Aluminum
Thermal conductivity Value	401W/m℃	250W/m℃
Specific heat capacity Value	0.39 KJ/KgK	0.91 KJ/KgK
Cost	6.00 US $/Kg	1.90 US $/Kg

The best and selected absorbing material for this research is aluminum. The cost of Aluminum is lower than the copper.

Insulation is used to reduce heat loss to the outside air. There are materials used as insulation for the solar collector material. From those mostly used in researches as insulation material is polyurethane foam and mineral wood and their properties are listed in Table 3.4 [26].

Table 3.4- Comparison between polyurethane foam and mineral wool [26]

Polyurethane foam	Mineral wool
It has a density of 36kgm^{-3}.	It has a density of 24kgm^{-3}.
It has thermal conductivity 0.018w/mK at 10℃.	It has thermal conductivity 0.045w/mK at 10℃.
Relative moisture absorption rate is low	Relative moisture absorption rate is high.
It’s not mostly available in the market and expensive	It is available in the market and cheap.

The selected material for insulation purpose is mineral wood, because it is available in the market and cheap.

Solar cabinet dryer is a large wooden or metal box where the product is located in trays or shelves inside it. In most cases, the air is warmed during its flow through a low pressure drop solar collector and passes through air ducts in to the drying chamber and over drying trays containing the product. And it can be constructed from sheet woody material or a metal. Most preferable one is metal sheet box to prevent water or moisture content. Chimney is where the moist air is discharged through air vent that is found at the top of the chamber. It can be also constructed from the metal sheet, with circular shape.

3.2. Methods

The overall methods used in this research are shown in the below Figure 3.1.

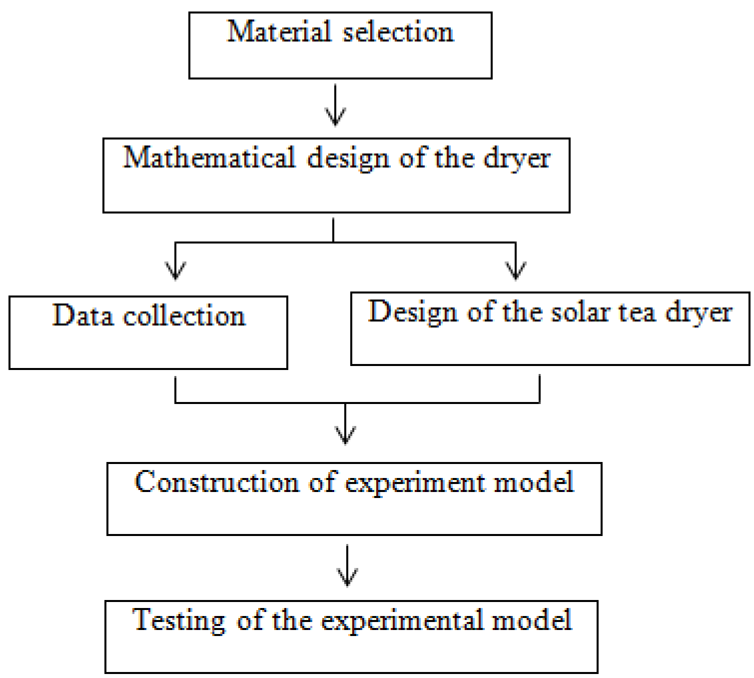


Figure 3.1- Method

3.2.1. Material selection

Since this research has a prototype model, there are materials required for the construction of each part of the dryer. So that the material are listed, described and compared based on their thermal properties, availability and cost. They are selected based on most availability on the market, with low cost, and good thermal property.

3.2.2. Design of the solar tea dryer

The data used for the design of the dryer will be collected from National Metrological Data Agency and the *Wush Wush* tea plantation. The yearly average solar radiation, yearly average temperature and yearly average wind speed of *Bonga* was gathered from the National Metrological Data Agency. The initial and final moisture content and the temperature used to dry the tea data was gathered from the *Wush Wush* by having a questioner and interview the company staffs.

The main design specifications for the dryer includes the moisture to be removed from the product, the drying heat load, the mass flow rate and volumetric air flow, the output temperature of the dryer, and the collector area and ventilation area. Then, after mathematical y7design the dryer will be sketched on 3D design on solid work software.

3.2.3. Construction of experimental model

The designed model will be implemented practically. It shows the construction of solar collector, the cabinet which assembles the supporters the trays and the doors of the cabinet, the supporting legs and the ventilation tube by referring the 3D sketch from the solid work design.

3.2.4. Testing of the experimental model

The designed and manufactured model will be tested using standard procedure. Testing of the model was conducted in two ways, No load and with load. In case of no load-the dryer was tested without the product to be dried. The performance of the model was tested with tea leaf inside the cabinet.

Testing of the model includes the output temperature of the collector (includes the temperature on the top and bottom of the collector), the temperature inside the drying cabinet, the temperature of the air that leaves the ventilation area, the mass of the dried product and finally the over efficiency of the dryer.

3.2.5. Preparation of samples

The sample assumed to be dried was tea. But due to unavailability of the tea leaf the sample is changed to other product. The main reason for tea not available is the road trip from *Bonga* to Addis Ababa is almost two days so during the traveling the leaf will be damaged and chemical property of the leaf will be changed.

The best solution is to substitute the product with other agricultural product which has the same chemical property and approximate moisture content value. The selected products are *Moringa* and *Ginger.* The similarity of the products with tea is shown in the below Table 3.5.

Table 3.5- Comparison between the sample products

Drying product	Tea	*Moringa*	*Ginger*
Product type	Agricultural product	Agricultural product	Agricultural product
Used for	Drinking purpose, medical treatment purpose.	Drinking purpose, medical treatment purpose.	Drinking purpose, medical treatment purpose.
Initial moisture content of the product.	81%	79%	82%
The moisture content after processing the products	53%	50%	57%
Final moisture content	3%	5.1%	13.1%

Chapter Four

Design and Manufacturing of the Solar Tea Dryer

It is a section where the overall design of the dryer is discussed. Before going to the design directly the data that are gathered from the National Metrological Data Agency are analyzed and then the basic designs of the dryer parts are listed.

4.1. Data analysis

The data used for this research was gathered from the metrology for the location where the tea plantation industry is located, and the general process of the tea drying and manufacturing process from the *Wush Wush* tea plantation industry.

4.1.1. Specifications

The specifications are the physical and environmental factors that related from the design of the dryer. The environmental factors are analyzed base on the location where the tea plantation is located. It includes the solar radiation, wind speed and the temperature of the area.

Wush Wush tea plantation industry is located in *Bonga*, Southern of Ethiopia. *Bonga* is located at latitude of 7.28° and longitude of 36.23° in the Northern hemisphere. It is 1714 m above sea level. The solar radiation for the specific place *Bonga* is logged every 15 minute by the National Metrological Agency. The logged data is in the form of $^{w}/_{m^2}$ so in some parameters $^{w}/_{m^2}$ is used but at some point it will be used as$^{KJ}/_{m^2}$. So it is analyzed and the average monthly and yearly values of 4 years data (2014 -2018) are shown in Table 4.1and Figure 4.1.

Table 4.1- Monthly and Yearly Average Solar Radiation of *Bonga*

Months	Maximum of solar radiation($^{kJ}/_{m^2}$)	Minimum of Solar radiation($^{kJ}/_{m^2}$)	Monthly Average of solar radiation($^{kJ}/_{m^2}$)	Yearly Average Solar radiation ($^{kJ}/_{m^2}$)
January	103.75430	66.76500	85.25965	
February	104.64844	68.29406	86.47125	
March	107.67938	39.70078	73.69008	
April	109.78969	63.27563	86.53266	
May	99.783280	39.01641	69.39984	
June	95.158130	41.17359	68.16586	
July	92.719220	42.57797	67.64859	78.37
August	101.51063	34.69172	68.10117	
September	109.90453	63.78797	86.84625	
October	106.40672	76.07250	91.23961	
November	106.04578	26.26734	66.15656	
December	111.52781	70.20656	90.86718	

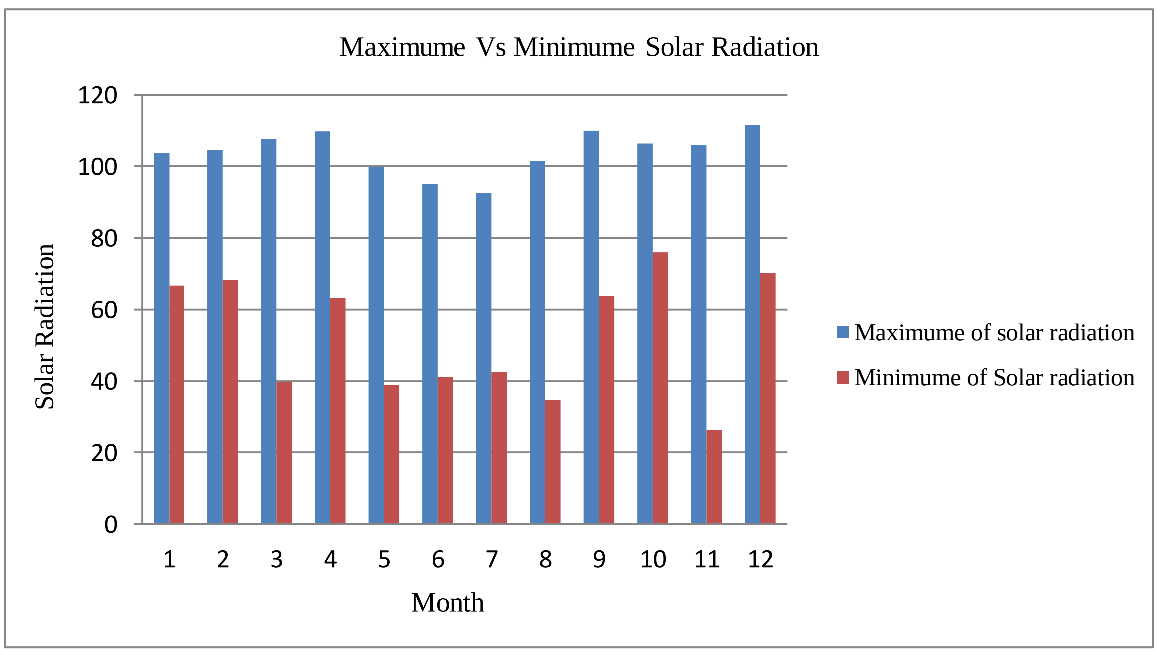


Figure 4.1- Maximum and minimum solar radiation of *Bonga*

The temperature for the location of *Bonga* was also logged as temperature minimum and temperature maximum for every day of the month at a specific time of 3:00LT morning and 12:00LT afternoon respectively. The analyzed data is shown in Table 4.2 and Figure 4.2.

Table 4.2- Monthly and yearly average value of temperature minimum and maximum

Month	Average T_{Max} ^0C	Average T_{Min} ^0C	Monthly average ^0C	Yearly average ^0C
January	30.44	10.42	20.43	
February	30.02	10.84	20.43	
March	30.78	12.14	21.46	
April	30.71	13.67	22.19	
May	23.45	14.45	18.95	
June	29.44	12.91	21.17	21
July	29.62	12.42	21.02	
August	26.33	12.88	19.60	
September	27.67	12.92	20.29	
October	32.69	12.40	22.55	
November	29.78	11.15	20.47	
December	29.58	9.88	19.73	

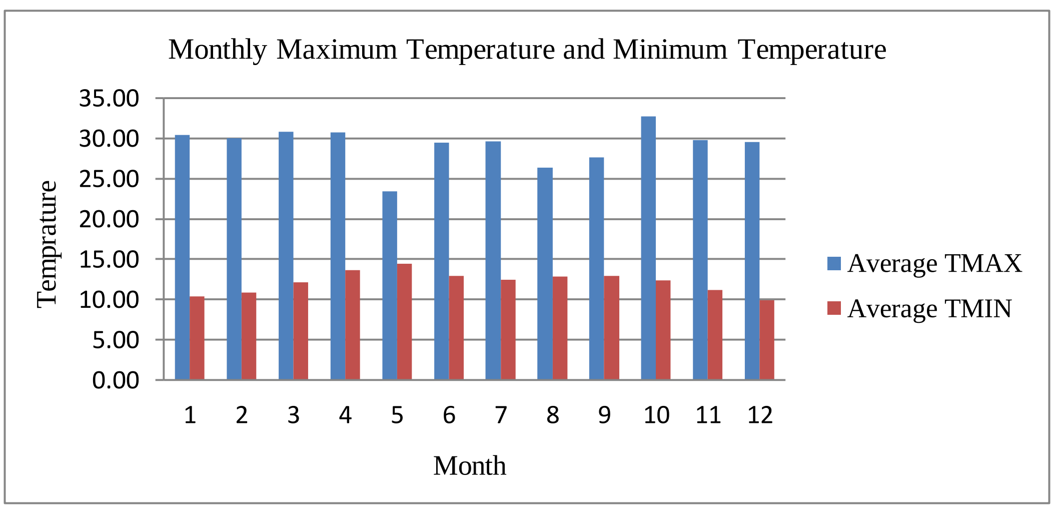


Figure 4.2- Monthly temperature maximum and temperature minimum of *Bonga*

The wind speed data for the location of *Bonga* has been logged every day of the month for a year. The logged data was in terms of $^{km}/_{h}$ but the standard value or unit was in terms of $^{m}/_{s}$. Then the data converted to its standard unit value and each average monthly and yearly value has shown in the Table 4.3 and the graph on Figure 4.3.

Table 4.3- Maximum and minimum monthly and yearly average value of wind speed

Month	Maximum WS($^{m}/_{s}$)	Minimum WS($^{m}/_{s}$)	Average WS($^{m}/_{s}$)	Yearly WS $^{m}/_{s}$
January	0.58573	0.55688	0.57130	0.59
February	0.62472	0.57628	0.60050	
March	0.56598	0.52949	0.54774	
April	0.56881	0.54787	0.55834	
May	0.59284	0.53057	0.56171	
June	0.58721	0.55577	0.57149	
July	0.58153	0.56475	0.57314	
August	0.61714	0.56665	0.59189	
September	0.65689	0.61609	0.63649	
October	0.64555	0.61769	0.63162	
November	0.64549	0.61909	0.63229	
December	0.61069	0.50689	0.55879	

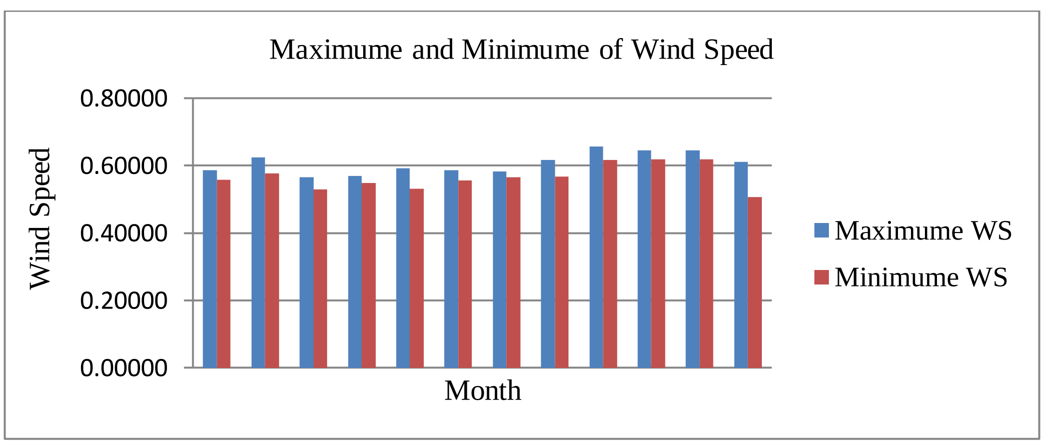


Figure 4.3- Maximum and minimum average wind speed of *Bonga*

4.1.2. Data from *Wush Wush* tea industry

The data gathered from the tea plantation Agro-industry is based on a questioner. The main question asked to the agro-industry manager:

1. How does the process of the drying and manufacturing of the tea plant?

As per the gathered information the tea has the following processes in order to be called tea and to be on the market. It has the following nine processes.

Process 1- Tea Planting – the tea leaf has been planted over the area where the place is in good condition.

Process 2- Tea leaf harvesting – the tea leaf will be plucked from the area where it is planted by the tea pickers. They have their own method of plucking.

Process 3- Withering – the tea leaf will spread in the weathering area for troughs for conditioning physically and chemically. It has to be in the weathering area for 12 up to 16 hours.

Process 4- Crushing, Tearing and Rolling - by the CTC (crush, tear, and curl) machine the leaf will be crushed and rolled in to smaller pieces.

Process 5- Fermentation/ Oxidization - it is the process where the green tea will be changed to tan color. Humidified cold air is blown through the leaf so the chemicals in the raptured call react with oxygen in the air.

Process 6- Drying – it is the process of drying the rolled and crushed tea leafs. The drying temperature is 110^0C. The rolled tea leaf will stay 25 up to 30 min in the dryer. After the drying the tea leaf with Tan color will be changed to blackish brown.

Process 7- Grading – it is a process of categorizing the rolled leafs with their size.

Process 8- Cleaning – it is the process of cleaning and removing the unwanted wastes from the drying tea.

Process 9- Packing – it is the process of packing the tea leafs with their perspective size in order to be on market.

2. How to dry the tea leaf?

The process of drying is classified in to two sections. The first is the moisture minimization of the leaf through the weathering process. When the leaf is on the weathering stage and exposed to the air the moisture content will be minimized by 1/3 of the initial moisture content.

The other drying process is when the rolled leaf goes through the dryer and the moisture will be minimize until it becomes in to standard.

3. The initial and final content of the dryer?

The initial moisture content of the tea leaf will be classified in two stages. The initial moisture content of the plucked tea is 83%. Then after the leaf goes through weathering process the initial content will become 53%. Then the final moisture content will be 3%.

4. How much temperature of the dryer is needed to dry the tea leaf after it has to go through the dryer?

The total temperature needed to dry up the rolled tea leaf is 110^0C. The tea leaf needs 25 up to 30 minutes to be dried in the standard form. So from the above gathered information the general specifications for the geometrical design of the dryer will be listed on Table 3.

4.2. Components of the design of the dryer

Before calculating and designing the solar dryer component values there are other parameters to be calculated and analyzed. Each parameter is listed below.

4.2.1. Initial parameters

The specification is important for overall design of the dryer. The initial parameters are listed below with their detailed assumption:

Table 4.4- Specifications for the design of the dryer

Specification	**Values**	**Reference**
Initial moisture content	53%	[*Wush Wush* Head Office]
Final moisture content	3%	[*Wush Wush* Head Office]
Yearly average solar radiation	201.9 $^{W}/_{m^2}$ or 78.4 $^{KJ}/_{m^2}$	National Metrological Agency
Yearly average ambient temperature	21^0C	National Metrological Agency
Yearly average wind speed	0.59 $^{m}/_{s}$	National Metrological Agency
Sample weight	7 kg	-
Drying time	3 Hours	Eltawila et.al [27]
Collector output temperature	50^0C	Kalogirou [28]

4.2.2. Determining the moisture to be removed

The moisture to be removed from the product is the value of the moisture in the given product that will be removed during the drying process. It is shown in terms of kg, and it can be calculated as Equation 4.1. [21]

$$M_r = \frac{M_p(M_i - M_f)}{(100 - M_f)} \text{ --- } \mathbf{4\text{-}1}$$

Where M_r is the moisture removed from the product, M_p is the weight of the sample product, M_i is the intial moisture content of the product, and M_f is the final moisture content of the product. The moisture content of the processed tea is 53% before it goes through the dryer, and the final moisture content will be 3%. From the Equation 4.1 the moisture to be removed 7 kg of tea leaf will be:

$$M_r = 3.61 \text{ kg}$$

Then the average drying rate will be calculated by using Equation 4.2, the drying time can be estimated to be 3 hours based on other researches [21].

$$M_{dr} = \frac{M_r}{t_d} \text{ --- } \mathbf{4\text{-}2}$$

Where M_{dr} is the drying rate of the drying product and t_d is the time required to dry the product. The drying rate will become:

$$M_{dr} = 1.203 \ {}^{\text{kg}}/_{\text{h}}$$

4.2.3. Determining drying heat load

It is the energy used to remove moisture from the drying product. It can be determined by the initial and final moisture content of the drying product. It can be calculated as shown in the Equation 4.3 [21].

$$Q_{load} = M_r L_v \text{ --- } \mathbf{4\text{-}3}$$

Where Q_{load} is the energy used to remove the moisture from the product, L_v is the latent heat of water. The moisture to be removed from the leaf is 3.61 kg and the latent heat of water is to be *2258* ${}^{KJ}/_{Kg}$ the drying heat load is:

$$Q_{load} = 116.4 \text{ MJ}$$

4.2.4. Determining mass flow rate and volumetric air flow

It is the air needed to effect the drying. It depends on the output temperature of the collector and the ambient temperature. It can be calculated by using Equation 4.4 as follow [29].

$$\dot{m}_a = \frac{M_w L_v}{C_p(T_d - T_a) * t_d} \quad \text{-----} \mathbf{4\text{-}4}$$

The mass flow rate for 7 kg of sample weight of tea with ambient temperature of 21^{0}C and drying time of 3 hours will be:

$$\dot{m}_a = 0.038 \ {}^{kg}/_{s}$$

The volumetric air flow is the total air needed to remove the moisture in the product and it depends on the density of the air around the location where the dryer has been tasted and also the mass flow rate. It can be calculated by using Equation 4.5 [29].

$$V_a = \frac{\dot{m}_a}{\rho_{Air}} \quad \text{-----} \mathbf{4\text{-}5}$$

The volumetric air flow for density of air 1.02 ${}^{kg}/_{m^3}$ for *Bonga* will be:

$$V_a = 0.0377 \ {}^{m^3}/_{s}$$

4.2.5. Determining output temperature of the dryer

It is the output temperature that comes out of the drying cabinet after it dry up the product. It can be estimated by using Equation 4.6 [29].

$$T_f = T_a + 0.25(T_o - T_a) \quad \text{-----} \mathbf{4\text{-}6}$$

The final temperature that comes from the drying cabinet for the ambient temperature of 21 ^{0}C and collector output temperature of 50 ^{0}C will be:

$$T_f = 28 \ ^oC$$

4.2.6. Determining area of the collector

It is the area where the solar radiation will be converted to heat energy. When the area of the collector is larger the more solar energy will be absorbed and the more heat will be produced. The collector area can be calculated from Equation 4.7 as follow [30].

$$A_c = \frac{M_r \ (m_i - m_f) L_v}{F_R(\tau\alpha) S_r} \quad \text{-----} \mathbf{4\text{-}7}$$

The transmittance value of the pure glass 81.412 and absorbance value of black painted aluminum is 0.3 then the value of the collector area is 1.26 m^2.

Then either the length or the width of the collector will be assumed and calculated.

$$\boldsymbol{w} = \frac{A_c}{L} \text{ --- } \mathbf{4\text{-}8}$$

Where the length of the collector will be 1 m and the width will be:

w =1.26 m

4.2.7. Determining area of Ventilation

The hot air from the collector will be flowing to the drying cabinet to remove the moisture from the drying product, and then the hot air will be saturated and removed through the ventilation area. It can be calculated as shown in Equation 4.9 [31].

$$A_v = \frac{v_a}{v_w} \text{ --- } \mathbf{4\text{-}9}$$

The ventilation area of the dryer for wind speed of 0.59 $m/_{S}$ will be:

A_v = 0.06 m^2

Then the diameter of the hole can be calculated by using Equation 4.10:

$$\boldsymbol{D} = \sqrt{\frac{4*A_v}{\Pi}} \text{ --- } \mathbf{4\text{-}10}$$

Where the diameter of the dryer ventilation area will be:

D = 0.25 m

4.2.8. Determining useful energy

It is an energy that comes from the dryer collector and it will be calculated as shown in the Equation 4.11 as follow [29].

$$Q_{ua} = m_a C_{pa} (T_{ab} - T_{am}) \text{ --- } \mathbf{4\text{-}11}$$

4.2.9. Determining dryer efficiency

The overall dryer efficiency will be depending on the collector area and the energy that comes from the collector which is the useful energy. It can be calculated as shown in the Equation 4.12 [29].

$$\eta_D = \frac{Q_u}{S_r A_c} \text{ --- } \mathbf{4\text{-}12}$$

4.3. Mechanical design of the dryer

After sizing and analyzing the design of the dryer, the overall design is determined. The material type and specification for selection are listed in chapter 3 of this research. The experimental setup of the research has been constructed based on the conceptual design. The conceptual design of the dryer is shown in the below figure.

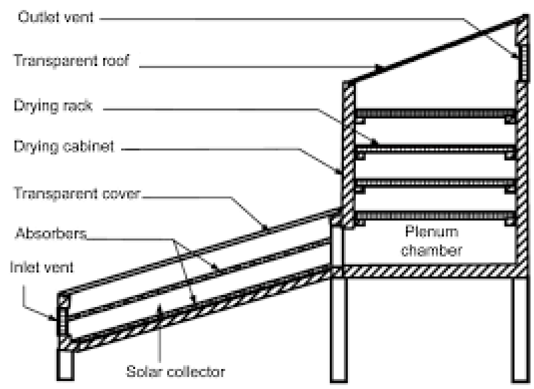


Figure 4.4- The schematic diagram for Flat Plate Collector drier type [32]

The sketch design of the dryer is designed using Solid work software tool. Each parts of the dryer are designed and sketched in detail and assembled based on the schematic diagram, it is shown below as follow.

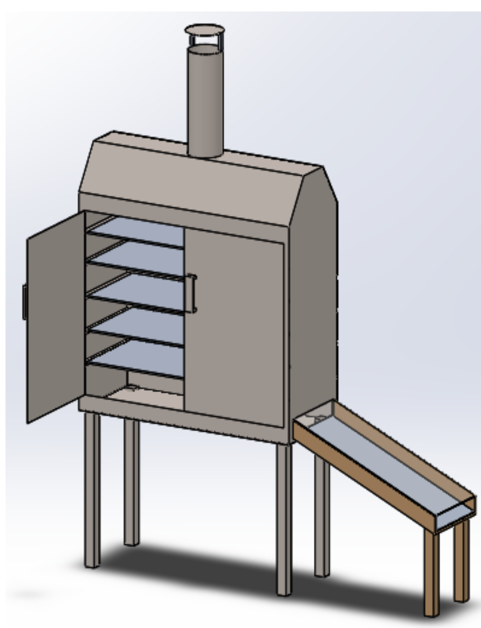


Figure 4.5- Solid work 3D design of the tea solar dyer

4.4. Manufacturing

Assembly of the dryer has different sections. Each section is assembled in Addis Ababa Institute of Technology, Mechanical Engineering workshop. Each steps used to construct the dryer is shown, described, and discussed as follow.

4.4.1. Construction of the solar collector

The collector is the main part of the dryer that collect the useful energy (solar energy) that comes from the sun and transfer the heat to the air that comes from the ambient air that passes through it. The outer cover of the collector is constructed by using sheet metal which has a thickness of 1 mm. But the sheet metal will lose the heat easily so there is a need of insulation using fiber glass that is placed between the outer cover body and the absorber plate. The total dimension of the solar collector is 1500 mm*1000 mm. Figure 5.1 shows the front and side covers of the solar collector.

Figure 4.6- Front and sides cover of the solar collector

After the fiber glass placed on the top of the cover body there is also a need of wood as insulation for the side sections. The wood dimension is 1500 mm*140 mm*50 mm supported the collector in both left and right side. Then after the fiber glass has been placed, the cover body and the absorber plate which is the aluminum is placed. The aluminum is polished with black paint in order to increase heat absorbance. It has a thickness of 1mm and dimension of 1500 mm*1000 mm. Finally the glazing material will be placed on the upper part of the cover frame with a space of 100 mm from the absorber plate. The glazing material is glass that has a thickness of 4mm and dimension of 1500 mm*1000 mm. The space between the absorber plate and the glazing material was covered with wired mesh to prevent bigger sized dusts interring to the solar dryer. Figure 4.7 shows assembly of solar collector without glazing and assembly of the solar collector respectively.

Figure 4.7- Assembly of solar collector for the tea dryer

4.4.2. Construction of the dryer chamber

The drying chamber is where the drying product (Tea) will be placed and heated by the hot air that comes from the collector. The drying chamber body (Figure 4.9) is constructed with sheet metal only which has a thickness of 1 mm. The main reason to use a 1 mm thickness sheet metal is due to not easily affected by the ambient temperature than other type of sheet metals. The total area of the drying chamber is 800 mm*1000 mm and has a height of 1000 mm excluding exhaust tube. As discussed in the previous chapter this dryer has four trays used to place the drying product. The trays are made of wired mashed (Figure 4.8) with very tiny holes used to transfer heat throughout the dryer. They have a dimension of 700 mm*900 mm. The gap between the trays is 200 mm from the last tray till the upper tray.

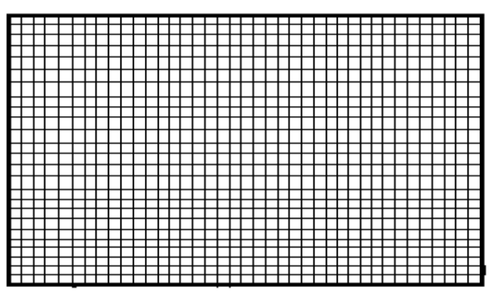


Figure 4.8 Wire meshed Try

Figure 4.9- Drying chamber of the solar tea dryer

The chamber also have holes in the upper part to transfer the hot air that have the moisture on it and comes from the chamber to the outside environment. It has a circular shape with the radius of 75 mm and a height of 600 mm (Figure 4.10).

Figure 4.10- Exhaust tube of the solar tea dryer

The chamber has one door which is constructed using flat plastic sheet with a sliding mechanism. The door is made of flat plastic sheet to make the drying product visible for the outside environment.

4.4.3. Construction of supporter leg

The dryer has six supporting legs with the frame on it. The back four legs support and carry the dryer chamber, and have a height of 900 mm and dimension of 2 mm*40 mm*400 mm. The front two legs are a supporter for the collector and it has a dimension of 40 mm*40 mm*500 mm. All supporting legs are made of metals (Figure 4.11).

Figure 4.11- Back and front leg of the solar tea dryer

4.4.4. Tilt angle of the collector

The tilt angle of the collector is designed to be 22.3^0 to the north facing. The main reason behind the tilt angle to be 22.3^0 is discussed in chapter four. But the design is done for the location of *Bonga* and since the experiment was conducted in Addis Ababa the tilt angle will be changed into 23.9 °.

- Latitude of $8.9^{0} + 15^{0} = 23.9^{0}$ approximately 24^{0}.

Figure 4.12- Tilt angle of the solar collector

Chapter Five

Experimental Setup and Instrumentation

The solar dryer has a solar collector, drying chamber and the Air ventilation. Each parts of the dryer listed and discussed in previous chapter. In this section the dryer setup, the test location, the sensor setup on the dryer and the instruments used while measuring the data are discussed.

5.1. Dryer Setup and Test Location

The solar dryer with a solar collector and dryer chamber is shown in Figure 5.1.

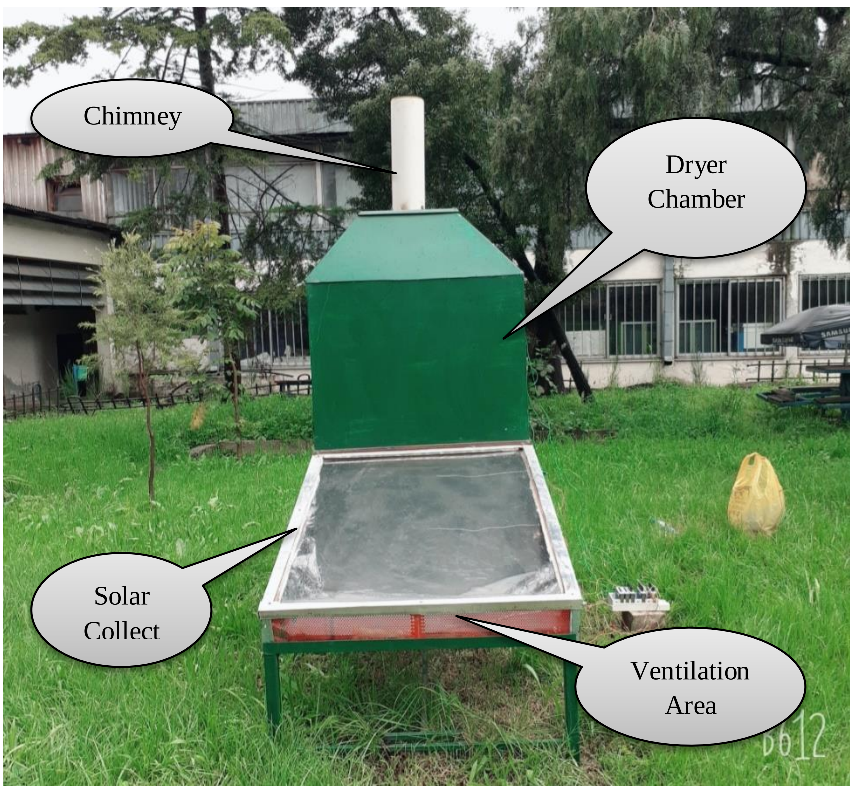


Figure 5.1- Setup of the solar dryer

The dryer location is Addis Ababa with geographical location of latitude, 9.04N and Longitude, 38.7E (Figure 5.2). The solar collector has faced south with east-west orientation and has tilted at 23^0. But while the month of May and June the dryer chamber has a shadow on the solar collector, so it is placed towards the North direction [33].

5.2.Sensor Positioning

The main objective of this research is to evaluate the performance of the solar tea dryer. So the measuring system was installed in and around the dryer. Figure 5.2 shows the location of the sensors used while measuring the temperature performance. While the blue dotes are the instrument used to measure the temperature which is called National Instrument NI DAQ-9211.

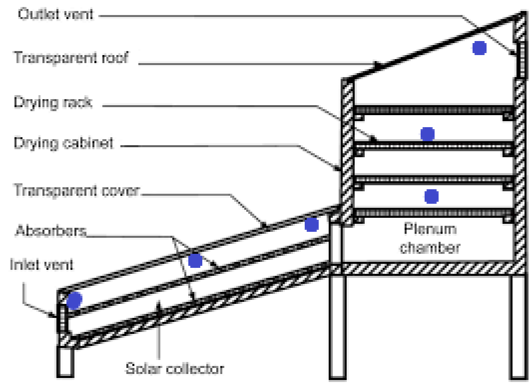


Figure 5.2- Schematic diagram of sensor positioning on a dryer

5.3. Instruments

5.3.1. Data Logger

The data logger used for this performance evaluation is National Instrument NI DAQ-9211. It captures data from the sensors and converted to useful data form. Figure 5.3 shows the data logger.

Figure 5.3- National Instrument NI DAQ-9211

The NI DAQ-9211 logger is a device which can take a data and stored for further analysis. The use of this device in this research is reading of the temperature by using the sensors and store in the form of excel format. It has its own software used for converting the data in to usable format. The software is called LABVIEW 2017 [Appendix D].

5.3.2. Environmental Meter

It is a testing device used to measure the temperature, the humidity, and the wind speed. The main purpose of this instrument is to measure the wind speed. The wind speed is measured every 30 minutes difference. The instrument is shown in Figure 5.6 (a).

5.3.3. Infrared Meter

It is a device used to measure the surface or external temperature of a material. The device generates the value without any contact with the product. The infrared meter will be shown in Figure 5.6 (b)

5.3.4. General Moisture Meter

It is a device used to measure the moisture content of the product from wet base. It has two sensors so the product has to contact both sensors to detect the wet content of the product. The moisture meter is shown in Figure 5.6 (c)

(a) (b) (c)

Figure 5.4- Measuring Device a) Infrared Meter, b) Environmental Meter, and c) General Moisture Meter

5.4. Preparing the sample product

The dryer is designed for the black tea leaf but due to the sample leaf is not available in Addis Ababa, and also to move it from the place where the farm land, it needs 2 days. Because of the transportation problem, the leaf will be damaged. So the best way to evaluate the dryer is substituting it with a similar product.

The samples used in this research evaluation are *Moringa* (drumstick tree) leaf and *Ginger*. Each product is processed as follows. First the *Moringa* is exposed to open air after cultivation without exposing to the ambient air (withering) (Figure 5.8). Then the leaves were crushed in to pieces for ease of processing. Finally the moisture content will be reduced to 50%.

Figure 5.5- Withered and crushed *Moringa*

In case of *Ginger* the first step is washing and removing the soil. After partly removing dirt, it will be crushed into pieces. While crushing the ginger it has water. Finally, the ginger is crushed and the water is removed to reduce the moisture content from 80% to 57%.

5.5. Measuring performance of a dryer

5.5.1. Dryer performance with-out load

This evaluation is performed without the load or the sample. The measured parameters during evaluating the dryer without the load are the ambient temperature that goes through the inlet of the collector, and the temperature that come the outlet of the collector, the ambient air velocity that will go through the collector and finally the solar radiation of the sun on the area where the experiment is applied.

5.5.2. Dryer performance with load

This measurement is performed while the product is inside the drying chamber. The parameters measured during the loaded condition were the temperature that comes from the collector and flows in to the drying chamber, the temperature on the 1st tray of the dryer, the temperature on the 3rd tray of the dryer and finally the temperature that will leave the drying chamber, and finally the moisture content of the drying product.

Chapter Six
Result and Discussion

This section describes the result of the overall research. It describes the output of the evaluation and discusses each other. It specifically describes the solar radiation, temperature variation and the wind speed (the air flow) variation in the area where the experiment was conducted. Then the moisture removed from the sample will be discussed and also the useful energy of the solar collector and the drying chamber and finally the efficiency of the overall dryer will be discussed.

The experiment was evaluated for six days, the first three days with no load and the other three days with load. The measured values was the temperature on the absorber plate, at the outlet of the collector and at the outlet of the drying chamber, and the drying air velocity (wind speed). Three tests were conducted with load to evaluate the performance of the solar dryer using the *Moringa* (drumstick tree) leaf and *Ginger* as a sample. Then after measuring the inlet and outlet temperature of the collector, the collector efficiency, dryer chamber efficiency and the overall efficiency of the dryer is calculated.

Each sample has a weight of 3kg. While measuring the performance of the dryer the test was conducted for four hours per day because of the rain on the afternoon.

6.1. Solar radiation of the test location

The average solar radiation around the area where test was conducted, AAiT is 384.7 $^{w}/_{m^2}$ and 561.1 $^{w}/_{m^2}$ from May 31 – June 2 and June 15 – June 17, 2020 respectively. The solar radiation collected by the solar collector was calculated to be 538.5 W and 785.5 W for no load and with load respectively. The solar radiation variation with time is shown in Figure 6.1 and Figure 6.2 and the raw data is shown in Appendix A.

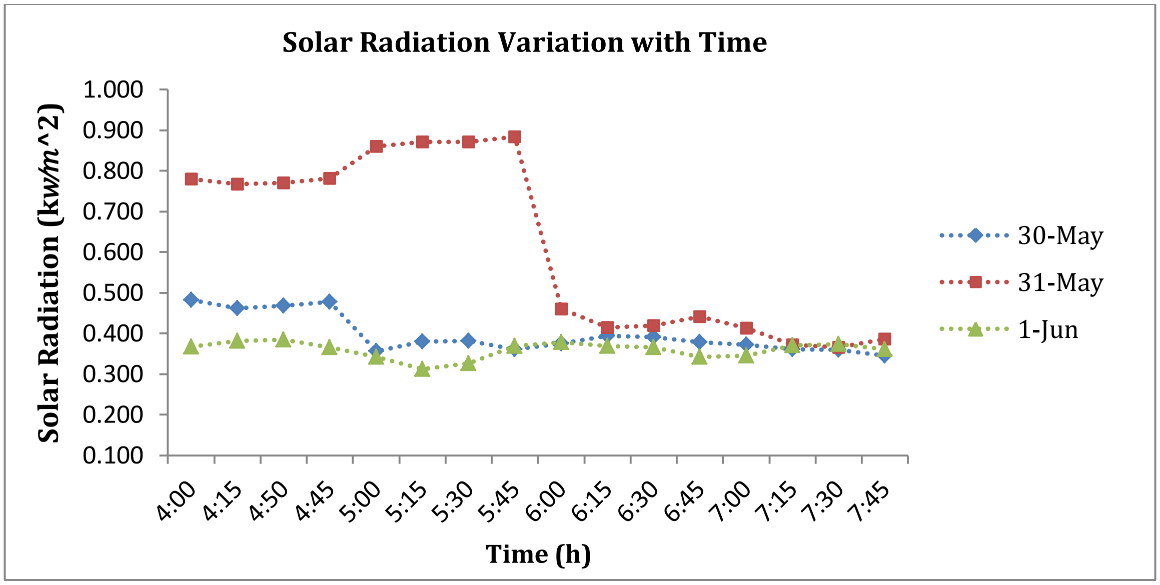


Figure 6.1- Solar Radiation Variation with Time for No-Load

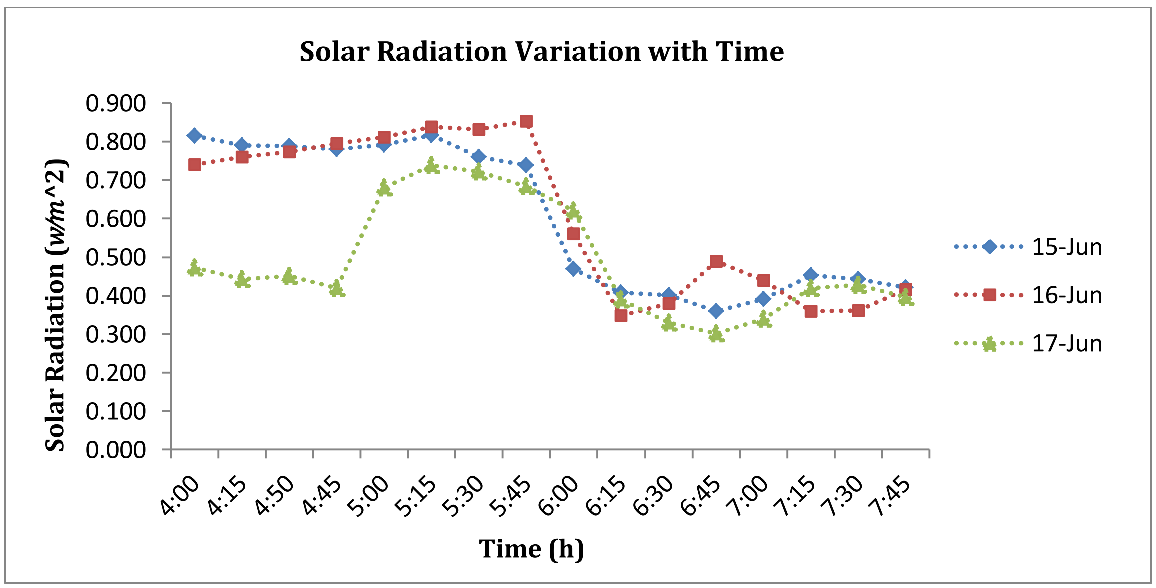
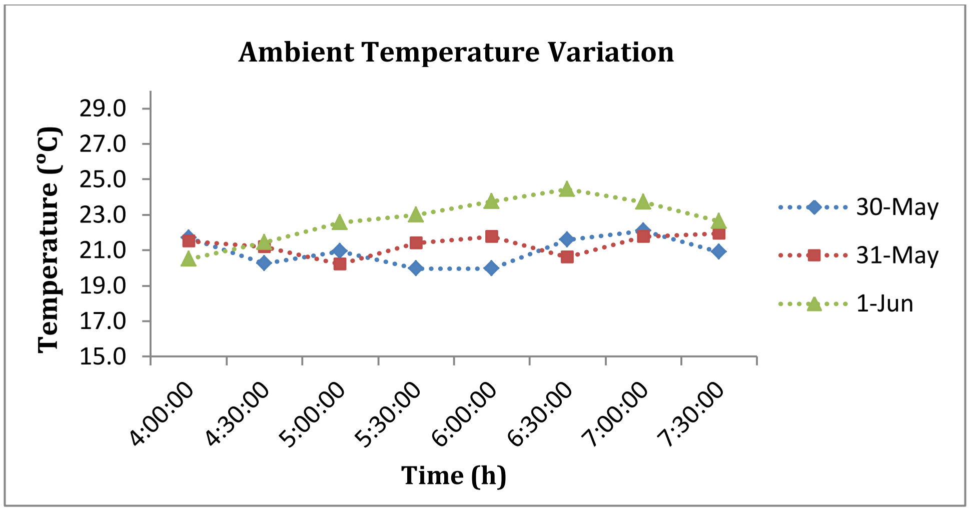


Figure 6.2- Solar Radiation Variation with Time with Load

The research for experimental analysis of performance evaluation of solar dryer for potato, the average solar radiation at the same location was 954.26 $^{w}/_{m^2}$ [34]. Similarly, the research of comparative experimental investigation between parabolic dish and flat plate collector based solar drier for saw dust briquette, the average solar radiation was 468.6 $^{w}/_{m^2}$ [35].

6.2. Temperature Variations Measurement result

The temperature variation is measured with load (June 15 – June 17) and without load (May 30 – June 1). The average inlet and outlet temperature of the solar collector is measured and has a result of 21.9 °C and 36 °C, respectively. For each of the three days the graph is shown in Figure 6.3 and the raw data is shown in Appendix A. Similarly, the average inlet temperature that comes from the solar collector, the temperature on tray 1, temperature on tray 3 and the outlet temperature from the drying chamber were 28.6 °C, 27.3 °C, 23.7 °C and 22.8 °C respectively.



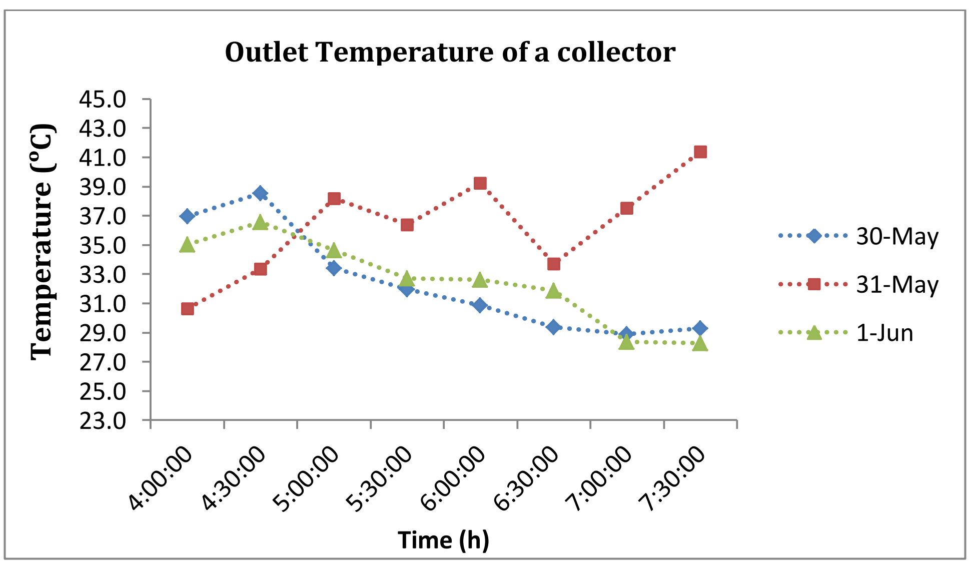


Figure 6.3 The Temperature Variation without the Load

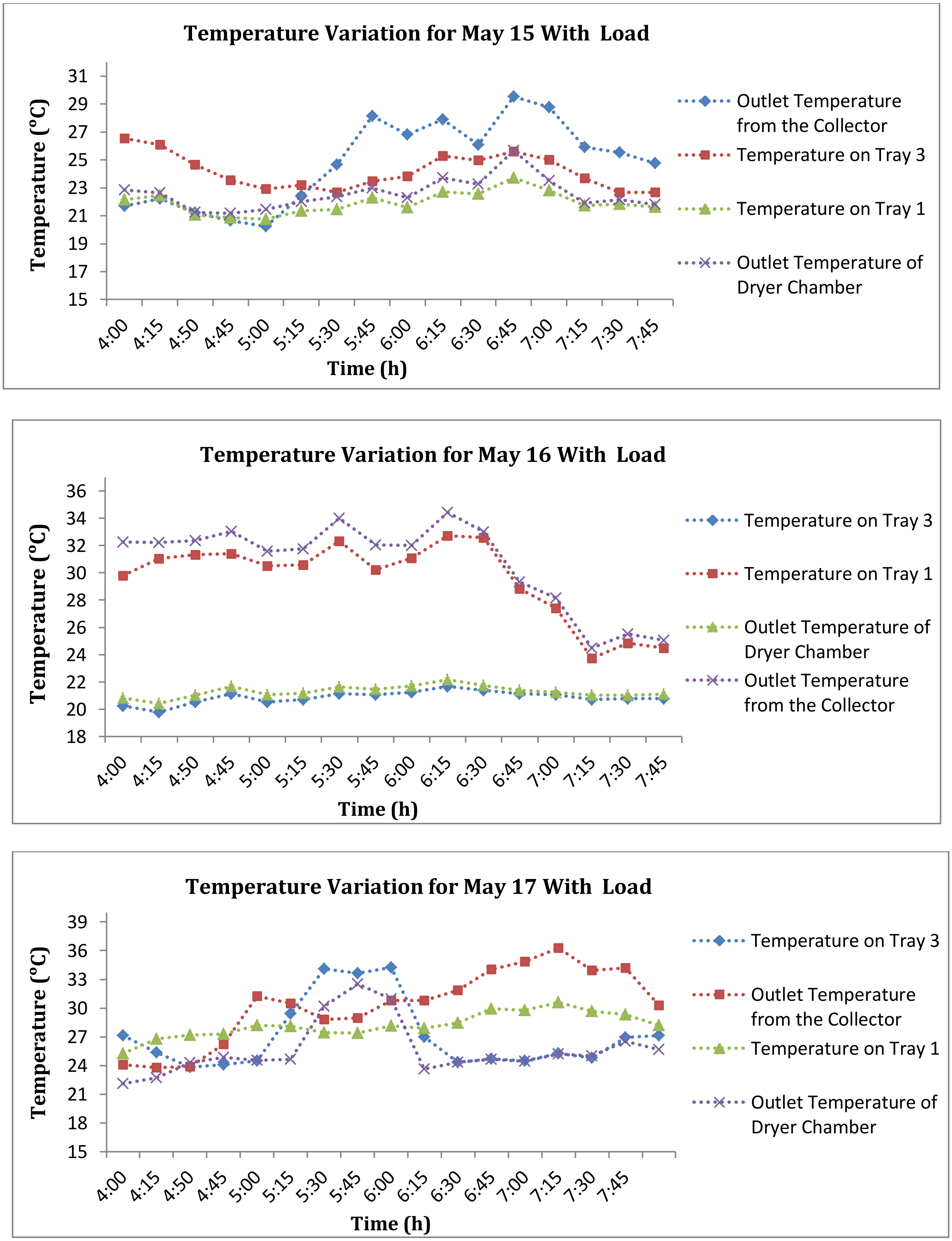


Figure 6.4- Temperature Variation with load

On the research of experimental analysis for performance evaluation of solar dryer for potato, the average inlet and outlet temperature of the solar collector was 21.36°C and 48.01°C respectively [34]. In the research for comparative experimental investigation between parabolic dish and flat plate collector based solar drier for saw dust briquette, the average inlet and outlet temperature of the solar collector was 25°C and 42.3°C respectively [35].

6.3. Measured Air flow Speed Variation

The wind speed is measured by using the instrument called environmental meter which has anemometer. The reading was done every 30 minutes because of the absence of air flow on the area. Then the average wind speed value during the evaluation of the dryer with load and no load case were 0.13 m/s and 0.14 m/s respectively. The average four hours data for wind speed evaluation without the load (May 30 – June 1) and with load (June 15 – June 17) is shown in the Figure 6.5 and the raw data for it is shown on Appendix A.

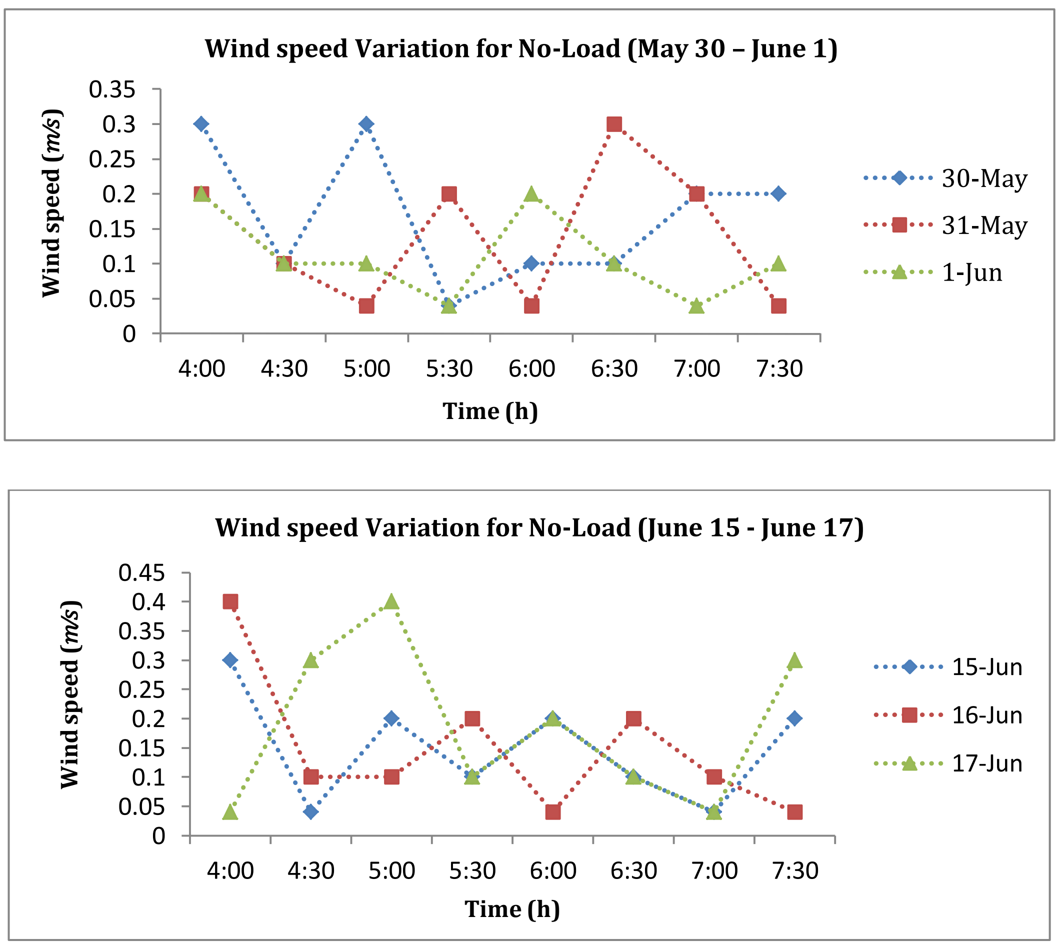


Figure 6.5- Air Flow Variation with No-Load and with Load

The average air flow for experimental analysis of performance evaluation of solar dryer for potato was 0.2 $^{m}/_{s}$ [34]. In the case of comparative experimental investigation between parabolic dish and flat plate collector based solar drier for saw dust briquette, the average air flow was 0.6 $^{m}/_{s}$ and 0.7 $^{m}/_{s}$ while measuring without load and with load respectively [35]. The wind speed in this case is higher than this and the previous research [34]. So, due to the high wind speed, the overall efficiency could move down to 23% [35].

6.4. Moisture removed from the sample

The moisture removed from the sample is measured in two ways, by using the measurement device called moisture meter and the second is by using the mass difference. While designing the dryer the input product was black tea leaf but due to the unavailability of the leaf the sample product is changed to *Moringa* (drumstick tree) leaf and *Ginger*. After processing the samples has a weight of 3 kg.

The moisture removed from the sample of *Moringa* was from 50% (3kg) to 5.1% (1.4kg), and for the sample of *Ginger* the moisture was reduced from 57% (3kg) to 13.1% (1.5kg). By using the mass balance the moisture removed from the samples were:

m_i(3kg) and the m_f(1.4kg), the M_w= 3 kg (50%) – 1.4 kg (5.1%) = 1.6 kg (44.9%) of water removed from *Moringa* and m_i(3kg) and the m_f(1.5kg), the M_w= 3 kg (57%) – 1.5 kg (13.1%) = 1.5 kg (43.9%) of water removed from *Ginger*. The drying rate of the *Moringa* (Drumstick tree) is 0.267 $^{kg}/_{h}$ and the drying rate of *Ginger* is 0.25 $^{kg}/_{h}$ from Equation 4.2.

Figure 6.6- *Moringa* Leaf Before and After Drying

The performance evaluation of a mixed mode solar dryer the drying rate was 0.62 $^{kg}/_{h}$ [13].

6.5. Result analysis based on the heat transfer concept

While using a solar drying system heat is transferred from the collector to the drying chamber through conduction, convection and radiation heat transfer modes. The heat transfer flow are related mathematically and described as follow.

6.5.1. Useful energy at the collector

The heat will flow from the black painted aluminum plate to the drying chamber through air and this process is called convection. So the useful energy of the collector is using Equation 4.11 and it is 0.188 kW.

6.5.2. Useful energy utilized in the drying chamber

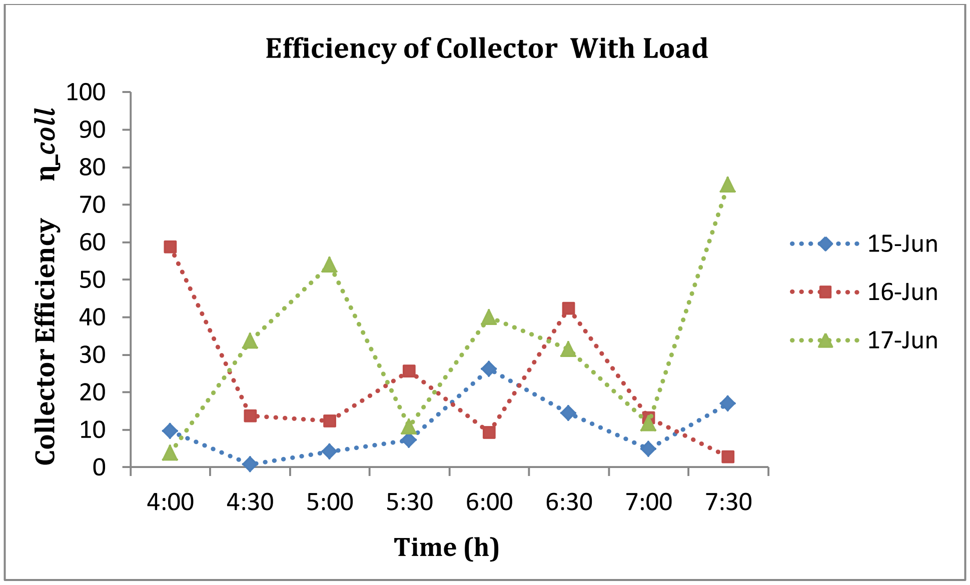
To calculate the amount of heat required for drying *Moringa* and *Ginger* were calculated using Equation 4.3. The useful energy utilized in the drying chamber for *Moringa* and *Ginger* was 3616 kJ and 3390 kJ, respectively.

6.5.3. Determination of efficiency of the drying system

The energy that is gained by the ambient air and the sample drier product with respect to the input energy is analyzed using energy calculation methods. The overall drying efficiency is determined by the output product heat utilization to the input energy to the solar collector.

The thermal efficiency can be calculated by dividing the output heat energy gain by the air to the input solar radiation to the absorber. The collector thermal efficiency varies with respect to time, the wind speed, temperature and solar radiation. So it can be calculated using Equation 4.12.

For No-Load case the collector efficiency is calculated to be 36.3%. Similarly, with load the collector efficiency becomes 22.1%.The plot of the thermal collector efficiency will vary with the mass flow rate, temperature and the solar radiation. So the variation of the efficiency with time for No-Load and with Load is shown in Figure 6.8 and the raw data is shown on Appendix A.



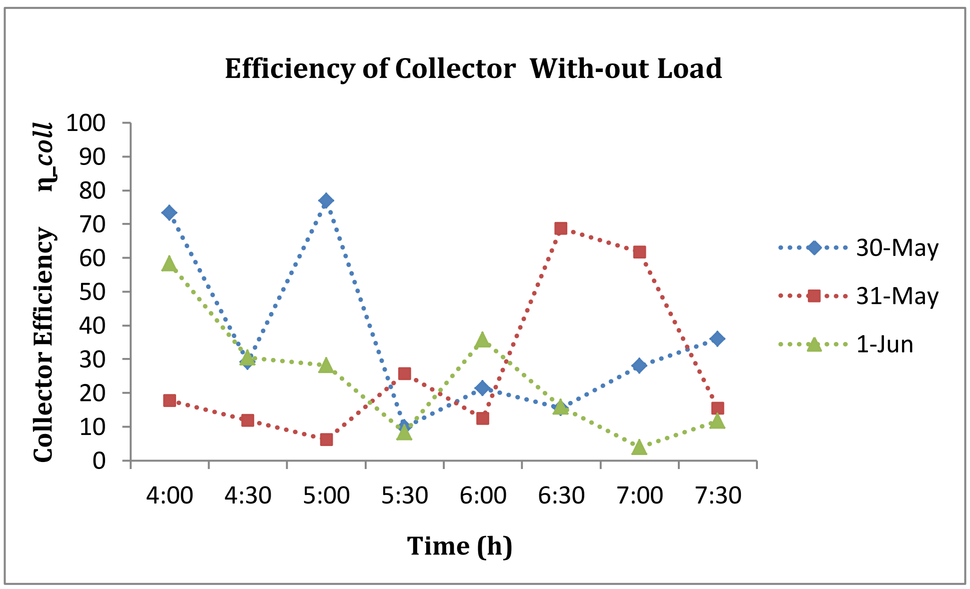


Figure 6.7- Efficiency of the Collector With and without load and Time

The average thermal collector efficiency for the experimental analysis of performance evaluation of solar dryer for potato was 28.68% [34]. And on the research of comparative experimental investigation between parabolic dish and flat plate collector based solar drier for saw dust briquette, the average thermal collector efficiency was 9.6% and 8.3% while measuring it without load and with load respectively [35]. The efficiency of the solar collector for the design, development and performance of indirect type solar dryer for banana drying research was 31.5% [24].

The drying chamber efficiency is a ratio of the outlet temperature to inlet temperature. It is evaluated while the Load is on. It can be calculated:

η_{ch} = 76%

The efficiency will vary with the ambient temperature; the temperature outlet of absorber varies. So the variation of the efficiency with respect to time is shown below in Figure 6.9 and the raw data is shown in Appendix B.

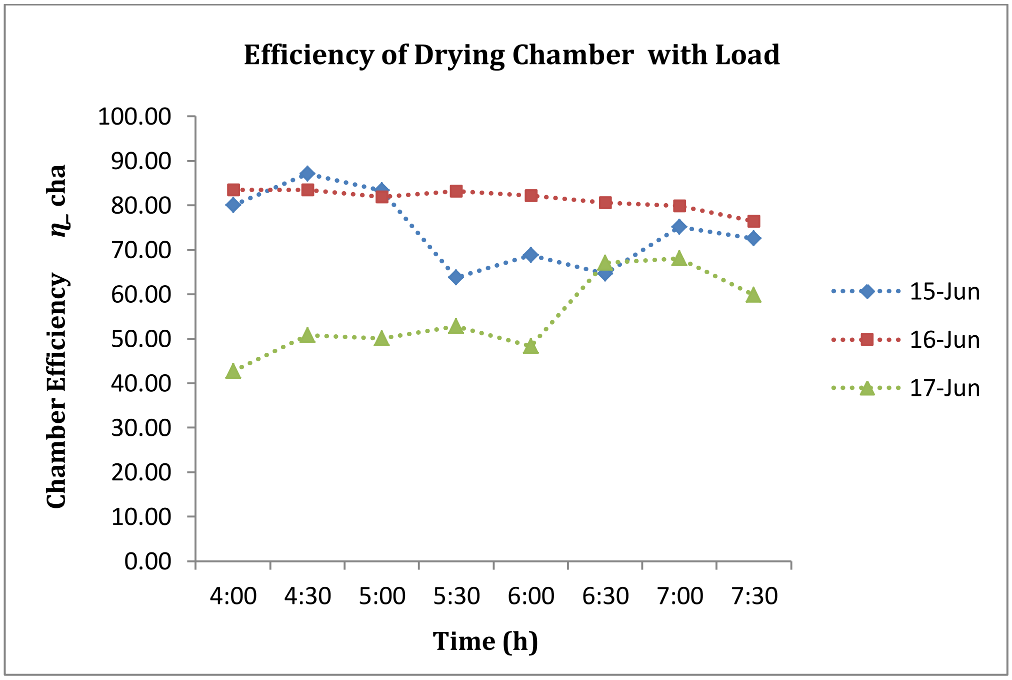


Figure 6.8- The Overall Efficiency of Drying Chamber VS Time

The average dryer chamber efficiency on the research of experimental analysis for performance evaluation of solar dryer for potato was 65% [34] which is comparable with the solar Dryer chamber efficiency for Ginger. In case of comparative experimental investigation between parabolic dish and flat plate collector based solar drier for saw dust briquette, the average dryer chamber efficiency was 25.6% while measuring with load [35]. The value was very low due to the loss on the drying chamber.

The overall drying efficiency is depends on the latent heat of water, the moisture removed from the product and the time taken to dry up the product. It is different for each of the products, because of the mass of the moisture removed from each product. The overall efficiency for drying *Moringa* and *Ginger* were 23.8% and 21.5% respectively. Where these overall efficiency for the drying efficiencies are compared with the research of experimental analysis of performance evaluation of solar dryer for potato was 16%, it is better placed for drying product. The overall drying efficiency of performance of the rack type greenhouse effect solar dryer for wild Ginger was 8.2%, which is less than the drying efficiency of both *Moringa* and *Ginger* by more than half. It is because of there is a high energy loss through the transparent wall, the chimney and the energy will be absorbed by the metal components of the dryer [36]. The overall drying efficiency for the design, development and performance of indirect type solar dryer for banana drying was 22.38% [24].

Chapter Seven

Conclusions and Recommendations for Future Work

7.1. Conclusions

It is a section where the outcomes of the overall research will be concluded. The conclusion is listed in two ways, the conclusion on the theoretical work and conclusion on the experimental work.

The theoretical achievements of the research are gathered from the mathematical design of the dryer. The designed collector area of the dryer is 1.26 $m^2$and approximately it is 1.3 m^2 with 1000 mm width and 1300 mm length, and it also has a height of 140 mm. The drying chamber has an area of 800 mm*1000 mm, and a height of 1000 mm. The dryer has four trays with a dimension of 700 mm* 900 mm. The ventilation area of 0.06 m^2, so the air inlet space on the collector is 100 mm*1000 mm and the diameter of the air outlet on the drying chamber is 25 mm. The expected output temperature that comes out of the solar collector is 50°C. and mathematically the mass flow rate of the designed dryer is 0.038$^{kg}/_{s}$, and the useful energy of the dryer is 0.89kW. And finally the designed dryer chamber efficiency is to be 88.9%.

The experimental work output is not the same as the exact value of the expected designed outputs. The prototype model of the dryer has almost exact dimensions as the designed one. The collector and the ventilation area is 1.3 m^2 and 0.1 m^2 respectively. The dryer has also three trays with a space of 250 mm. The average output temperature that comes from the solar collector is 36°C and 30°C in case of the No-Load and without the Load respectively. The output average mass flow rate is become 0.0133 $^{kg}/_{s}$ and 0.0153 $^{kg}/_{s}$ with No-Load and with Load respectively.

The useful energy based on the value of the mass flow rate is become 0.188 kW and 0.167 kW for No-Load and with Load respectively. The output collector efficiency for No-Load is 36.3% and while for load is 22.1%.

Base on the data collected from the data logger the output temperature that comes out of the drying chamber on average become 22.8°C and based on that efficiency of the drying chamber become 67.9%.The time taken to dry up both products was 6 hours, based on this drying time, the overall system efficiency for both products is different. The difference is due to the variation of the temperature and the properties of the products. So for *Moringa* (Drumstick tree) leaf the efficiency become 23.8% and for *Ginger* the efficiency became 21.5%.

7.2. Recommendation for future works

For this experimental result the performance of the solar dryer is evaluated. But some of the values are lower than the design values. The following points are important suggestions for future works:

- This experiment is designed for drying of tea leaf but it is possible for future works and studies for purpose of drying other agricultural products by modifying the collector area, by replacing the materials of the absorber plate and the glazing material.
- The efficiency of the dryer can be improved and tested on different seasons especially when there is a high solar radiation and temperature, since the dryer directly depends on the solar radiation.
- Since solar radiation is not availability throughout the whole year, it is better to find other renewable energy mechanisms to support the drying system, such as biofuel.
- While in some areas there is no air velocity flow (wind speed) so it is better to provide the dryer with an extra fan system that uses a photovoltaic source. This will also improve the efficiency of the dryer.
- Since the hot air flows from the collector to the drying chamber from only the bottom, the drying capacity of each tray is different, so it is better to have equally distributed the hot air for each tray throughout the pipe.

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Appendix

Appendix A: Raw data of without load and with load measurements

May 30, 2020

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	$^{w}/_{m^2}$	^{0}C	^{0}C	$^{m}/_{s}$	$^{kJ}/_{kg°C}$	m^2	$^{kg}/_{s}$	kw	%
4:00:00	0.471	21.7	37.0	0.30	1.012	1.35	0.031	0.472	73.24
4:30:00	0.472	20.3	38.5	0.10	1.012	1.35	0.010	0.189	29.19
5:00:00	0.367	21.0	33.4	0.30	1.012	1.35	0.031	0.386	76.83
5:30:00	0.370	20.0	32.0	0.01	1.012	1.35	0.004	0.050	9.81
6:00:00	0.384	20.0	30.9	0.10	1.012	1.35	0.010	0.113	21.43
6:30:00	0.381	21.6	29.4	0.10	1.012	1.35	0.010	0.080	15.43
7:00:00	0.366	22.1	28.9	0.20	1.012	1.35	0.020	0.141	28.09
7:30:00	0.352	20.9	29.3	0.20	1.012	1.35	0.020	0.174	35.98
Average	0.4	20.9	32.4	0.2	1.0	1.4	0.0	0.2	36.2

May 31, 2020

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	$^{w}/_{m^2}w$	^{0}C	^{0}C	$^{m}/_{s}$	$^{kJ}/_{kg°C}$	m^2	$^{kg}/_{s}$	kw	%
4:00:00	0.774	21.5	30.7	0.20	1.012	1.35	0.020	0.189	17.84
4:30:00	0.776	21.2	33.4	0.10	1.012	1.35	0.010	0.126	11.81
5:00:00	0.865	20.2	38.2	0.04	1.012	1.35	0.004	0.074	6.27
5:30:00	0.877	21.4	36.4	0.20	1.012	1.35	0.020	0.310	25.79
6:00:00	0.421	21.8	39.2	0.04	1.012	1.35	0.004	0.072	12.53
6:30:00	0.430	20.6	33.7	0.30	1.012	1.35	0.031	0.406	68.83
7:00:00	0.385	21.8	37.5	0.20	1.012	1.35	0.020	0.326	61.67
7:30:00	0.377	22.0	41.4	0.04	1.012	1.35	0.004	0.080	15.51
Average	0.6	21.3	36.3	0.1	1.0	1.4	0.0	0.2	27.5

1

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	$w/_{m^2}$	^{0}C	^{0}C	$m/_s$	$kJ/_{kg°C}$	m^2	$kg/_s$	kw	%
4:00:00	0.375	20.5	35.0	0.20	1.012	1.35	0.020	0.300	58.40
4:30:00	0.374	21.5	36.6	0.10	1.012	1.35	0.010	0.156	30.50
5:00:00	0.323	22.6	34.6	0.10	1.012	1.35	0.010	0.125	28.26
5:30:00	0.355	23.0	32.7	0.04	1.012	1.35	0.004	0.040	8.23
6:00:00	0.373	23.8	32.6	0.20	1.012	1.35	0.020	0.183	35.83
6:30:00	0.352	24.5	31.9	0.10	1.012	1.35	0.010	0.077	15.88
7:00:00	0.366	23.7	28.4	0.04	1.012	1.35	0.004	0.019	3.85
7:30:00	0.366	22.7	28.3	0.10	1.012	1.35	0.010	0.058	11.63
Average	0.4	22.8	32.5	0.1	1.0	1.4	0.0	0.1	24.1

Raw data of the measurment with load

June 15, 2020

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	$w/_{m^2}$	^{0}C	^{0}C	$m/_s$	$kJ/_{kg°C}$	m^2	$kg/_s$	kw	%
4:00:00	0.805	18.6	22.0	0.30	1.012	1.35	0.031	0.106	9.60
4:30:00	0.784	18.9	20.9	0.04	1.012	1.35	0.004	0.008	0.78
5:00:00	0.808	19.1	21.3	0.20	1.012	1.35	0.020	0.046	4.18
5:30:00	0.739	19.3	26.4	0.10	1.012	1.35	0.010	0.073	7.26
6:00:00	0.436	19.8	27.4	0.20	1.012	1.35	0.020	0.156	26.19
6:30:00	0.375	20.6	27.8	0.10	1.012	1.35	0.010	0.074	14.49
7:00:00	0.423	20.6	27.3	0.04	1.012	1.35	0.004	0.028	4.79
7:30:00	0.419	20.4	25.2	0.20	1.012	1.35	0.020	0.098	17.03
Average	0.6	19.7	24.8	0.1	1.0	1.4	0.02	0.1	10.5

June 16, 2020

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	W/m^2	^{0}C	^{0}C	m/s	kJ/kg^oC	m^2	kg/s	kw	%
4:00:00	0.750	17.6	32.2	0.4	1.012	1.35	0.041	0.604	58.82
4:30:00	0.782	18.5	32.7	0.1	1.012	1.35	0.010	0.147	13.69
5:00:00	0.826	18.2	31.7	0.1	1.012	1.35	0.010	0.139	12.28
5:30:00	0.840	18.7	33.0	0.2	1.012	1.35	0.020	0.295	25.68
6:00:00	0.461	18.9	33.2	0.04	1.012	1.35	0.004	0.059	9.36
6:30:00	0.437	18.9	31.2	0.2	1.012	1.35	0.020	0.254	42.39
7:00:00	0.386	19.5	26.3	0.1	1.012	1.35	0.010	0.070	13.30
7:30:00	0.395	21.6	25.3	0.04	1.012	1.35	0.004	0.015	2.81
Average	0.6	19.0	30.7	0.1	1.0	1.4	0.02	0.2	22.3

June 17, 2020

Time interval	I_s	T_{amb}	T_{abs}	V_{air}	C_P	A_C	m_a	Q_U	η_c
Units	W/m^2	^{0}C	^{0}C	m/s	kJ/kg^oC	m^2	kg/s	kw	%
4:00:00	0.457	18.1	23.9	0.04	1.012	1.35	0.004	0.024	3.84
4:30:00	0.430	18.6	25.0	0.30	1.012	1.35	0.031	0.199	33.74
5:00:00	0.702	18.3	30.9	0.40	1.012	1.35	0.041	0.519	53.99
5:30:00	0.708	18.8	28.9	0.10	1.012	1.35	0.010	0.105	10.80
6:00:00	0.428	19.4	30.8	0.20	1.012	1.35	0.020	0.234	39.97
6:30:00	0.303	20.3	33.0	0.10	1.012	1.35	0.010	0.130	31.46
7:00:00	0.406	19.8	35.6	0.04	1.012	1.35	0.004	0.065	11.70
7:30:00	0.416	20.2	34.1	0.30	1.012	1.35	0.031	0.430	75.33
Average	0.5	19.2	30.3	0.2	1.0	1.4	0.02	0.2	32.6

Appendix B: Raw data of the dryer chamber efficiency

June 15, 2020

Time interval	T_{amb}	T_{abs}	$T_{Tray\ 1}$	$T_{Tray\ 3}$	T_{outlet}	η_{DC}
Units	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	%
4:00:00	18.6	22.0	26.3	22.8	20.1	80.1
4:30:00	18.9	20.9	24.1	21.2	19.8	87.1
5:00:00	19.1	21.3	23.1	21.7	20.3	83.3
5:30:00	19.3	26.4	23.1	22.7	21.9	63.8
6:00:00	19.8	27.4	24.6	23.0	22.2	68.8
6:30:00	20.6	27.8	25.3	24.5	23.2	64.6
7:00:00	20.6	27.3	24.4	22.7	22.3	75.1
7:30:00	20.4	25.2	22.7	22.0	21.7	72.5
Average	19.7	24.8	24.2	22.6	21.4	74.4

June 16, 2020

Time interval	T_{amb}	T_{abs}	$T_{Tray\ 1}$	$T_{Tray\ 3}$	T_{outlet}	η_{DC}
Units	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	%
4:00:00	17.6	32.2	30.4	20.6	20.0	42.76
4:30:00	18.5	32.7	31.4	21.3	20.8	50.81
5:00:00	18.2	31.7	30.5	21.1	20.6	50.03
5:30:00	18.7	33.0	31.3	21.6	21.1	52.87
6:00:00	18.9	33.2	31.9	21.9	21.5	48.31
6:30:00	18.9	31.2	30.7	21.6	21.3	67.03
7:00:00	19.5	26.3	25.6	21.1	20.9	68.09
7:30:00	21.6	25.3	24.7	21.1	20.8	59.94
Average	19.0	30.7	29.6	21.3	20.9	55.0

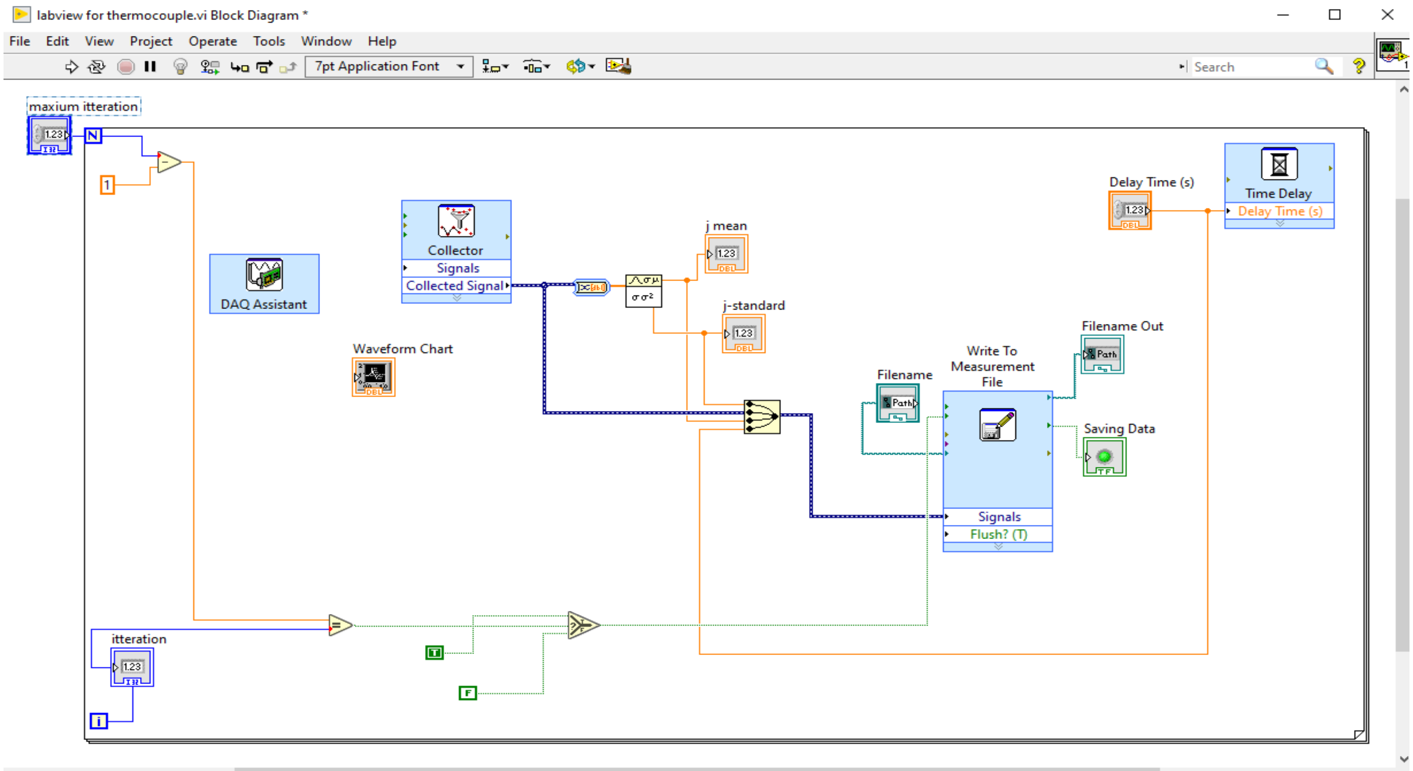
June 17, 2020

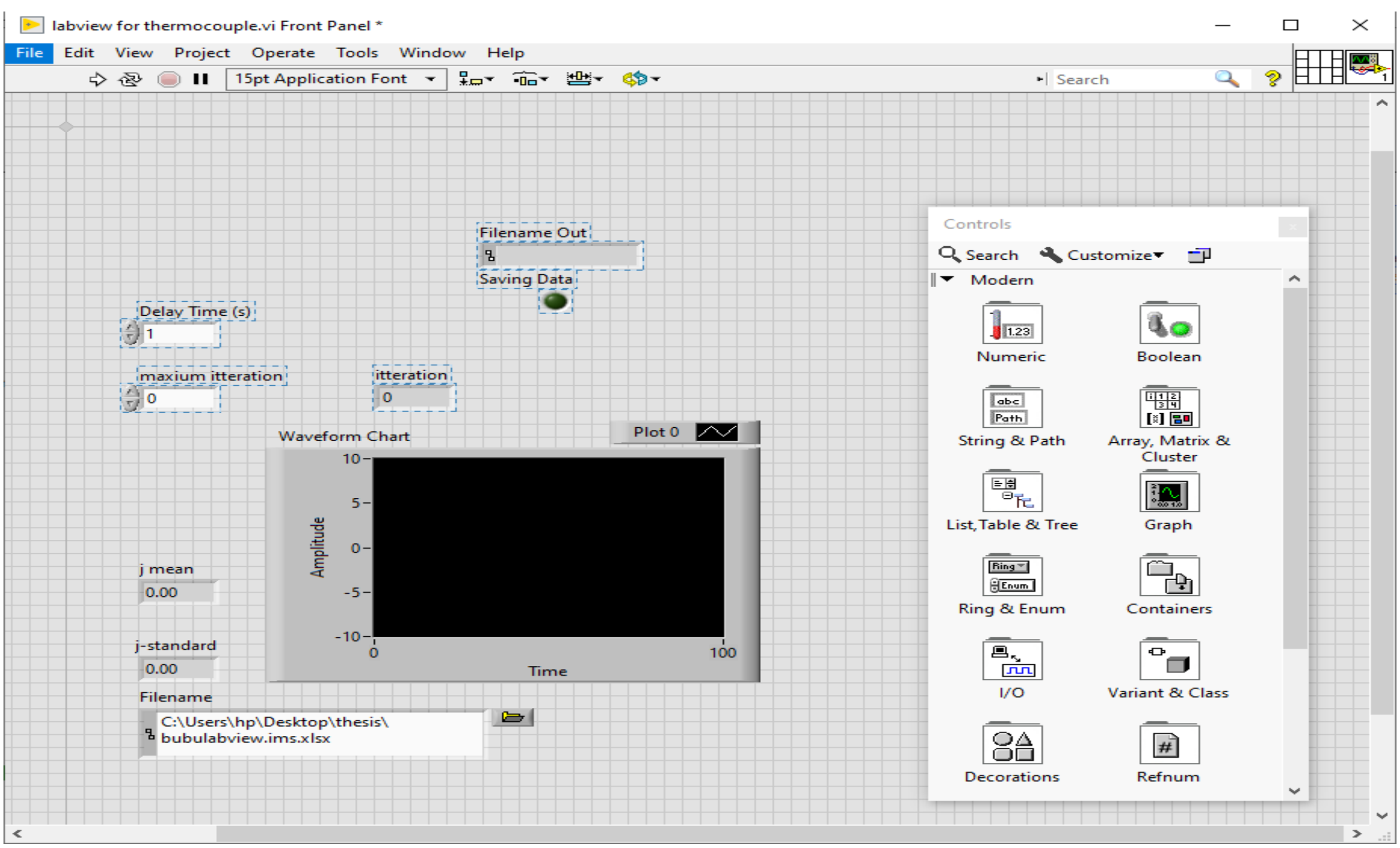
Time interval	T_{amb}	T_{abs}	$T_{Tray\ 1}$	$T_{Tray\ 3}$	T_{outlet}	η_{DC}
Units	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	%
4:00:00	18.1	23.9	26.0	26.2	22.4	83.49
4:30:00	18.6	25.0	27.2	24.0	22.6	83.47
5:00:00	18.3	30.9	28.2	27.0	24.6	81.98
5:30:00	18.8	28.9	27.4	33.9	24.7	83.18
6:00:00	19.4	30.8	28.0	30.6	25.3	82.18
6:30:00	20.3	33.0	29.2	24.5	24.5	80.65
7:00:00	19.8	35.6	30.2	24.9	24.8	79.84
7:30:00	20.2	34.1	29.5	25.9	25.8	76.45
Average	19.2	30.3	28.2	27.1	24.3	81.4

Appendix C: Questioner used for *Wush Wush*

1. How does the process of the drying and manufacturing of the tea plant?
2. How to dry the tea leaf?
3. The initial and final content of the dryer?
4. How much temperature of the dryer is needed to dry the tea leaf after it has to go through the dryer?

Appendix D: LABVIEW Block diagram and Front Panel





Appendix E: Manufacturing drawing for tea drying solar dryer