Addis Ababa University
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School of Mechanical & Industrial Engineering
Thermal Engineering

Mathematical Modeling and Simulation of Mixed Mode Natural Convection Solar Dryer for Green Banana Flour Production

A Thesis Submitted to the school of Mechanical & Industrial Engineering Addis Ababa Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

BY

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DECLARATION

First, I hereby declare that this M.Sc. thesis entitled "**Mathematical Modeling and Simulation of Mixed Mode Natural Convection Solar Dryer for Green Banana Flour Production**" is my original work and that all sources and materials used for this thesis have been appropriately acknowledged. This thesis has been submitted in partial fulfillment of the requirements for M.Sc. degree in Thermal Engineering at Addis Ababa institute of Technology, School of Mechanical, and Industrial Engineering. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate. Quotation from this thesis is allowable without special permission if an accurate acknowledgement of source is made.

Betelihem Zemedkun Lodamo _______________ ___________

Name Signature Date

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief. This has been submitted for examination with my approval.

Kamil Dino Adem (PhD) ____________ ____________

Advisor Signature Date

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First and above all, I bow my nee to praise the almighty God for his grace in the completion of this work, for the wisdom he gave me, for the blessings and protection in every direction of my life.

Next, I would like to express my deepest gratitude to my advisor Dr. Kamil Dino Adem for his valuable guidance, encouragement, patience and constructive comments from the beginning until the completion of this thesis. This thesis would not have come to completion without his unreserved support. I give thanks to my friend Mr.Getnet, who was also helping me.

My heartfelt gratitude goes to all of my family who was always on my side persistently throughout my entire academic life. Last but not least, I would like to thank my husband Fiseha Kedir for his tireless support.

ABSTRACT

Fruit drying is one of fruit preservation technique so as to increase shelf life of the produces and reduce food losses. Open air is an old and usual way of drying systems, it consumes a lot of time and also other problems related with contamination. It also consumes bigger space. Solar dryer uses direct solar energy in a better way to produce great amount of heat by using different means, such as, solar air heater and drying chamber with many compartments to handle more products in a good air circulation, only consuming small space. The main objective of this thesis work is to design, model and simulate a natural convection mixed mode solar greenhouse dryer integrated with solar air collector (SAC) for drying of green banana. The dryer consists of an arc roof structure covered with polyethylene plastic on a concrete floor. Solar air collector tilted at an angle of 21º is connected with the greenhouse. To investigate the drying performances of the mixed mode natural convection solar greenhouse dryer, dynamic model of heat and mass transfer was developed and thin layer drying model was selected and this system of non-linear partial differential equations was solved numerically using MATLAB/Simulink software. Comparative study on the performance of the green house dryer with and without SAC was conducted with software simulation. The result showed that the maximum air temperature, maximum product temperature, and maximum cover temperature, without and with solar air collector are found to be 33℃, 46℃, and 78℃ and, 34℃, 54℃, and 79℃ respectively. The moisture ratio of green banana reduced from 1.58 % (db) to 0.2 % (db) within 3 days. Effect of wind speed on the drying performance was also simulated and as a result wind speed has inverse effect on the drying temperature. Therefore, the designed greenhouse solar dryer with solar air heater has a good performance for drying of fruits within a reduced time span and better quality.

Key words: Mixed mode, Natural convection, MATLAB/Simulink, Dynamic model, Solar air collector.

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NOMENCLATURE

L_v	Latent heat of vaporization of water from the GB slices surfaces (kJ/kg).
M_w	Mass of water evaporated from the GB (kg)
T_d	Temperature of outgoing air from the drying chamber (°C)
T_a	Ambient air temperature (°C)
M_{we}	Mass of the wet GB slices (kg)
M_i	Initial moisture content on wet basis (% wb).
M_f	Final moisture content on wet basis (% wb)
R_a	Gas constant (kJ/kg*K)
T_o	Temperature of air at the collector outlet (°C)
P_a	Partial pressure of dry air in the atmosphere, (N/m2)
C_p	Specific heat capacity of air, (kJ/kg*K)
$\dot{V}_a$	Volume flow rate of the drying air (m3/s)
t_d	Drying time per day (hrs.)
v_a	Total volume of air required for removing the moisture m^3
M_1	Initial mass of the GB slices, (kg)
M_2	Final mass of the GB slices (kg)
GB_l	Thickness of the GB slices in the drying chamber
W_T	Width of the tray
L_T	Length of tray, which is equal to length of the chamber

t_d	Drying time, (hrs.)
I_T	The total solar radiation incident on the collector surface (W/m²).
H	Horizontal radiation (W/m²)
R	Ratio of solar energy on tilted surface to that on the horizontal
H	Efficiency of the collector
Q_s	Energy stored which is negligible, (kJ/kg)
Q_l	Heat loss from the collector, (kJ/kg)
Q_u	Useful energy gained by the air, (kJ/kg)
Q_{uc}	Useful heat gain by the collector, (KJ/kg)
Q_{solar}	Solar energy input on the dryer, J
A_{dryer}	Dryer area, mm²
t_s	Drying time, s
Q_{dryer}	Energy required for vaporization, J
m_r	Moisture removed, kg
I_{sc}	Solar constant (W/m²)
n	Day of the year
C	Diffuse radiation factor
$(MC)_e$	Equivalent heat capacity of the collector in J/ K,
T_o	Outlet temperature of the collector,
T_i	Inlet temperature of the collector,

F_r	Heat transfer factor of the collector
U_l	Heat loss coefficient of the heat collector in W/(m2K)
Q_c	Heat energy within drying air and cover due to convection
$Q_{c,am}$	Energy transfer between cover and ambient air
$Q_{s,c}$	Energy transport among atmosphere and cover owing to radiation
Q_{solar}	Heat absorbed by cover from solar insolation
$Q_{p,c}$	Energy exchange between drying product and cover by radiation
m_c	Mass of cover
Ac	Area of cover
C_{pc}	Specific heat capacity of collector
T_a	Drying air temperature
T_c	Cover temperature
T_s	Sky temperature
T_p	Product temperature
$h_{c,c-a}$	Convective heat transfer coefficient
$h_{r,c-s}$	Radiative heat transfer from cover to sky
$h_{r,p-s}$	Radiative heat transfer coefficient between product and cover.
h_w	Convection heat transfer coefficient between cover and atmosphere
α_c	Absorptivity of cover material, and It is solar insolation
δ_c	Thickness of cover of greenhouse

Kc	Thermal conductivity of insulation used
V_W	Wind speed
v_a	Kinematic viscosity of air
k_a	Thermal conductivity of air
P_r	Prandtl number
U_c	Overall heat loss coefficient

GREEK SYMBOL

φ	Latitude (degrees),
β	Angle of inclination of surface from horizontal (degrees),
δ	Angle of declination (degrees)
ω	Hour angle (degrees).

CHAPTER 1:
INTRODUCTION

1.1 Background

The use of solar energy in recent years had reached a remarkable edge. Along with other forms of renewable energy sources, such as biomass, geothermal, wind, fuel cell and ocean energy, it has a great potential for a wide variety of applications because it is abundant and available. Among those applications of solar energy, preservation of fruits and vegetables by drying technique is one of the common applications of solar power. The importance of solar energy using for drying applications has been increased due to the changes of traditional energy sources price according to environmental concerns and expectations of conventional sources depletion (Al-Neama et al. 2018).

Drying is a technique which involves dehydrating fruits to remove excess water either by natural process of sun drying or with the help of dehydrators. In other word, drying is a simple process of moisture removal from a product in order to reach the desired moisture. The prime objective of drying apart from extended storage life can also be quality enhancement, ease of handling, further processing and sanitation and is probably the oldest method of food preservation practiced by human kind (Mujumdar et al. 2012).

Bananas are a very nutritious fruits which nature provides for earth. Banana has 8 stage of ripeness (Figure 1.1); the stage this research will use is usually called the 2nd or the 3rd stage. Green bananas are hard to peel with bare hands and essentially taste like potato and it is perfect for those who need to monitor sugar levels because it is lower on the glycemic index. The other great thing about unripe bananas is they give a jolt of prebiotics to the gut. They contain resistant starch, a type of fiber that ferments in intestines, feeding the good bacteria (Falcomer et al. 2019).

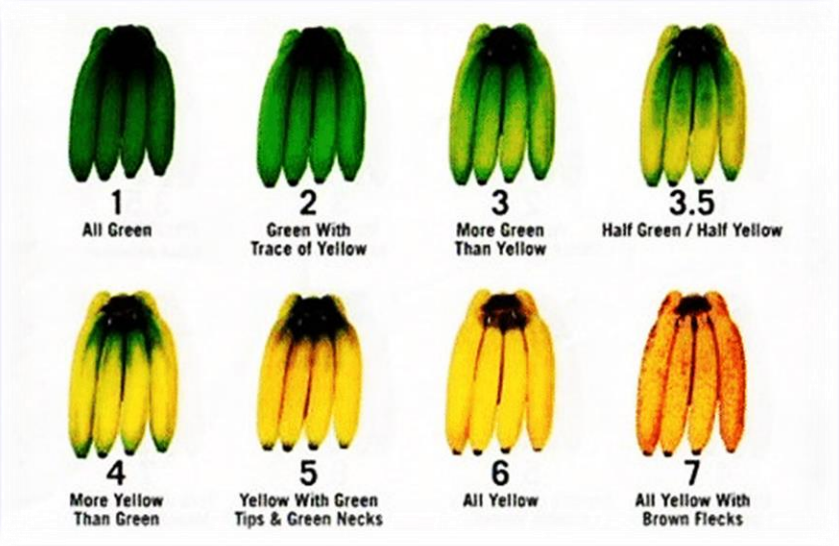


Figure 1.1: Stages of banana ripeness(Veroustraete 2016)

Unripen banana also have a very essential benefits for health. So, by drying and milling unripen banana we can get another variety of healthy food. Unripen banana cannot be eaten without converted as a powder, so to make powder the banana should be peeled, sliced, dried and milled. Drying takes much of the time. In a country with insufficient food and shortage of energy supply is a common crisis, banana powder can be a supplementary food items in a different way to use it at home and drying it only using solar power with additional air heater will ease a big problem in the country (Hassanain et al. 2009). The following plate (Figure 1.2) shows how the flour would look like after it is dried and milled.

Figure 1.2: Green banana flour(Macri August 6, 2018)

Ethiopia has a comparative advantage in a number of horticultural commodities due to its favorable climate, proximity to European and Middle Eastern markets and cheap labor. However, the production process for fruits is much less developed than the production of crops in the country. On average more than 2,399,566 tons of vegetables and fruits are produced by public and private commercial farms, this is estimated to be less than 2 percent of the total crop production (EIA 2012).

The fruit drying system is not known at the market level, by drying fruits we can distribute the fruit easily to the whole part of Ethiopia, especially for those places which are not bearing fruits and also for export market. The Southern Nations and Nationalities Peoples' Regional State of the country is the leading banana producer region which accounts for 68.72% (37,076.85 hectares) area of land coverage by banana production, 77.53% (370,784.17 tones) of the fresh banana produce and 22.38% (1,504,207) of the banana producers. This has favored the region to benefit from increased food security, income generation, employment opportunities and from the enhancement of local and regional economic developments (Alemu 2016). Arbaminch is Located in the Gamo Gofa Zone of the Southern Nations, Nationalities, and Peoples Region about 500 kilometers south of Addis Ababa, at an elevation of 1285 meters above sea level. It is a well-known banana producing country in Ethiopia. 65% of bananas are distributed to the whole country from this place. This has a great value for the country's fruit market including fruit export for better economy. Countries which are greatly involved in this market are North America, Europe and Asia Pacific (Marketwatch 2019)

Drying is the basic and most time taking process in the banana powder production process. In order to make the fruit sell fast, dryers role take the major part. Of course, there are different types of dryers, electric driven dryer, open air dryer and fuel consuming dryer and solar dryer. Open sun drying is the most common and the oldest method to preserve agricultural produce. However, being unprotected from rain, wind-borne dirt and dust, infestation by insects, rodents and other animal, products may be seriously degraded to the extent that sometimes become inedible and the resulted loss of food quality in the dried products may have adverse economic effects on domestics and international markets (Akoy et al. 2006, Belessiotis et al. 2011).

Therefore, solar dryers have been developed to overcome these problems of open sun drying. The most important advantage of the solar dryers is that they work on renewable energy and are pollution free. Also, solar dryers can be easily constructed from local materials. Therefore, to increase the income of the country and to improve the food-processing industries, it is worthy to use solar dryers for preservation of the products (Lingayat et al. 2017, Tarigan 2018). To improve the thermal performance of the indirect solar dryers, the thermal performance of the solar air heater connected to the drying chamber should be improved (El-Sebaii et al. 2012). Mixed mode solar dryer uses direct sun radiation to heat the product inside the dome shape plastic and additional air heater for better air circulation inside the drying chamber.

MATLAB is a very useful tool to develop mathematical models for prediction of the product temperature, air temperature, and the moisture evaporated (Janjai et al. 2009).

This research is concerned on modeling and simulating a solar dryer of mixed type for drying sliced unripen banana for green banana powder production in Arbaminch, Ethiopia.

1.2 Statement of problem

Ethiopia is situated in the tropical zone, its wide range of altitude, from below sea level to over 3000m above sea level, gives it a wide range of climate from humid tropics to alpine climates, where most types of horticultural crops could be successfully grown (Alemu et al. 2008). Banana is one type of fruit produced in the country. According to Baini et al. (2007) and many other authors,(Hassanain et al. 2009, Falcomer et al. 2019), the high moisture content of bananas makes them susceptible to mold growth. India, the world's largest banana producer, reported post-harvest losses as high as 35 – 45%, whereas Brazil reported a product loss of approximately 40%. As cooling is not a viable technique to prolong the shelf life of bananas, an alternative to this end is drying. Therefore, the post-harvest loss is about 40% of the production. To reduce the losses, an alternative is to dry the product and using it in another form like flour (Pereira et al. 2014).

Processed fruit market is a very well-known market all over the world but drying and packing fruits for market is not developed in Ethiopia, though there are plenty of fruits around different parts of the country. By packing and selling dried fruits, it can be one means of income. This can be achieved by using a well-modeled solar fruit dryer.

Open air is an old and usual way of drying systems, it consumes a lot of time (5 to 6 days) and also other problems related with contamination. It also consumes bigger space. Conversely, Solar dryer uses direct solar energy in a better way to produce great amount of heat by using different means, such as, solar air heater and drying chamber with many compartments to handle more products in a good air circulation, only consuming small space.

Mathematical modeling and Simulation of mixed mode natural convection solar dryer, specifically for green banana in Arbaminch, Ethiopia has not been done before. This research will have a contribution to the knowledge for modeling better dryer for green banana slices.

1.3 Objectives

The main objective of the research is to investigate the drying performance of mixed mode natural convection solar drier by applying MATLAB simulation and developing mathematical model for green banana drying process.

The specific objectives of the research include:

- To design a greenhouse direct solar dryer and solar air heater for drying a sliced green banana.
- To model the mathematical equation of the dryer
- To simulate the drying characteristics using MATLAB Simulink and
- To prepare manufacturing drawing for the final dryer

1.4 Scope of the Present Work

This study focused on the design and simulation of a natural convection greenhouse solar dryer with air heater, suitable for large-scale production for weather condition of Arbaminch, Ethiopia. The study tries to find appropriate type of solar drier, proper design of the dryer, proper design of the Solar Air Collector (SAC), to select and model the best drying model equation for banana, and Simulation of the Greenhouse Solar Dryer (GHSD) temperatures.

1.5 Delimitations

In this research project, prototype will not be manufactured. However, this can be done by other scholars. But there will be a manufacturing drawing to be used by other researchers.

The design also has no other backup systems other than solar power, which means at the time where sun light is not available the dryer cannot perform drying.

1.6 Organization of the Thesis

This thesis composed of seven chapters. The first chapter introduce the concept of fruit drying, solar drying applications and system components, literature survey was presented in chapter two with its summary. The third chapter presents the material and method section of the paper followed by chapter four which presents the detailed design of the work. The fifth chapter shows the mathematical models of the theoretical design and numerical simulation of system components for the performance investigation. The sixth chapter presents the major finding and results of numerical formulations. The last chapter includes the conclusion of the whole work and recommendation for further study.

CHAPTER 2:
LITERATURE REVIEW

2.1 Fruit Drying

Vegetables and fruits are the main source of vitamins A and C, which are essential nutrients. However, post- harvest loss is high (30 - 40%) resulting into economic and nutritional loss. Open sun drying is a traditional method practiced widely in tropical climates for drying agricultural products. Considerable savings can be made with this type of drying since the source of energy is free and sustainable. However, this method of drying is extremely weather dependent and has the problems of contamination, infestation, microbial attacks, etc., thus affecting the product quality. Additionally, the drying time required for a given commodity can be quite long and result in post-harvest losses. Therefore, appropriate methods of fruit and vegetable processing and preservation to bridge seasonal gaps in nutrient supply are required. Current market research indicates the need for an economical solution to efficiently dehydrate fruit and vegetables in equatorial climates (Ndawula et al. 2004).

"Inter-American Institute for Cooperation on Agriculture, United States Peace Corps "on their solar dryer manual of "Solar Drying of Fruits & Vegetables", explains that, dried vegetables are usually reconstituted in soups, sauces, and other items. Dried products cannot be marketed the same as fresh produce, but there are many advantages; less weight for transport and packaging, well-enough taste, long shelf-life, and year-round availability. Likewise,(Janjai et al. 2009) also observed that banana is dried not only for preservation purposes, but also for modification of the taste, flavor and texture to meet consumer preferences and to increase the market value of the product.

Solar drying is a very familiar practice of humankind in preservation of organic food items.(Chouicha et al. 2013), on their "experimental investigation of solar drying of sliced potatoes" they mentioned that solar energy is one of the non-polluting and economical energy sources which are more requested worldwide. Many scholars have done many researches to improve the traditional way of drying in to modern technology. And they strongly suggest, using solar dryer with additional air heater to make the drying time much better than the open-air sun drying. Thereby the mixed type of solar dryer is much better than the open-air direct sun drying and other electric/fuel consuming dryers for developing countries in economic sense.

Scholars proved that improvement of solar collector performance will enhance the performance of drying process. And the main fields of development in drying process are experimental research, modeling and simulation, long term performance measurements, design, construction, testing and control(Al-Neama et al. 2016).

2.2 Drying rate parameters

Drying is a combination of heat and mass transfer operation. The main aim of drying is to remove moisture as fast as possible at a temperature that does not seriously affect the flavor, texture and color of the food. Among the factors that influence the rate of drying are the moisture content of solids, sorption isotherms and the drying temperature (Sharma et al. 2012). These can be further explained as follows.

Moisture Content of Solids: Moisture content can be expressed as the weight of water as a proportion of total weight either of the wet material or dry matter. The drying process takes place until there is no net transfer between the food and air. In this situation, it is called as equilibrium moisture content. It is varying depending on the types of material or product (Mujumdar et al. 2012)

Sorption Isotherms: The relationships between the equilibrium relative humidity of the air (ERH) and the equilibrium moisture content within solids (Me) is important in order to determine the end point of drying and for product stability evaluation during drying. This relationship at various temperatures is called moisture sorption isotherms(Hii et al. 2012).

Drying Temperature: Drying under controlled conditions of temperature and humidity helps the crop to dry reasonably rapidly to a safe moisture content level and to ensure a superior quality of the product (Mujumdar 2003) . If the temperature is too low in the beginning, microorganisms may grow before the food is adequately dried. If the temperature is too high and the humidity is too low, the food may harden on the surface. In addition, the rate at which drying air is moved through the chamber should ensure that a sufficient volume of fresh air is maintained to prevent saturation process (Al-Neama et al. 2016).

2.3 Solar drying

In the article "Solar drying of agricultural products: A review" (El-Sebaii et al. 2012) states that the postharvest losses of agricultural products in the rural areas of the developing countries can be reduced drastically by using well-designed solar drying systems. Among the different types of solar dryers, the indirect mode forced convection solar dryer has been demonstrate to be superior in the speed and quality of drying. They also mention that the solar air heater is the most important component of the indirect solar drying system and improvement of the solar air heater would lead to better performance of the drying system. This paper is only a review and further computer simulation and experimental investigation is needed to quantify the use of the mixed mode solar dryer benefits.

As (Sharma et al. 2012) argued on their article called" Construction and Performance Analysis of an Indirect Solar Dryer Integrated with Solar Air Heater", they mentioned that the conventional sources of energy for drying of agricultural product is an expensive process for developing countries. They developed an indirect type natural convection solar dryer and found that the hot air reaches average drying temperature of 45ºc in natural convection than that of forced convection with no air heater, which is, 40ºc. However, this experiment does not utilize the direct sun efficiently because of the wood material they use as a drying chamber. The size of the dryer they constructed also not enough for mass production.

According to (Sobowale et al. 2017), "design, construction and evaluation of a small scale solar dryer" tries to construct a solar dryer with air heater to dry agricultural crops (maize and plantain) and concluded that the dryer can rapidly dry food items to a safe moisture compared to open sun drying. In this experiment, it was able to get 50.50ºc of temperature in the dryer with a corresponding ambient temperature of 34.50ºC. The moisture content removal 40.6% to 43.2% using the solar dryer was achieved as against 27.89% to 28.2% using the sun-dried method and indicated 12.71% to 15.0% difference, respectively.

2.4 Type of dryer's review

The solar dryers can broadly be classified into four broad types. Open drying, direct solar dryer, indirect solar dryer, mixed mode solar dryer, Hybrid solar dryer.

2.4.1 Open sun drying

Depends on environmental conditions, such as solar radiation, wind, and other ambient conditions, it usually leads to the deterioration of the products because of many detriments, such as reduced quantity due to the wind, wastage, rainfall, and animal and anthropological impedance (Figure 2.1). The open drying process is not suitable for large amounts of products processed by large firms. Apart from the disadvantages of higher cost of labor, larger area requirement, and decreased quality of products, it also involves a labor-intensive process before the products can be ready for storage(El-Sebaii et al. 2012). Open sun drying depends on environmental conditions, such as solar radiation, wind, and other ambient conditions. It usually leads to the deterioration of the products because of many detriments, such as reduced quantity due to the wind, wastage, rainfall, and animal and anthropological impedance. Storing the crop during the night and being subjected to rain under a shelter can led to remoistening. As the drying process is relatively slow, considerable losses occur, including insect infection, enzymatic reactions, growth of micro-organisms, and augmentation of mycotoxin, which causes an ascertainable reduction in product quality. Non-uniform drying also leads to the degeneration of the agricultural products during storage. Serious drying problems arise, particularly in humid tropics and subtropical areas, where agricultural food products have to be dried during the rainy season (Eswara et al. 2013).

Figure 2.1: Open sun drying system (Werdinger 2013)

2.4.2 Direct solar dryers

These dryers use transparent covers to reduce heat losses while simultaneously giving the product protection from rain and dust (Figure 2.1). The product inside the dryer requires less attentions, like attack of the product by rain or pest (both human and animals), compared with those in the open sun drying.(Gbaha P et al. 2007), designed a direct type natural convection solar dryer and then tested experimentally by drying cassava, bananas and mango slices. This drying is a simple design and can be manufactured by farmers from local materials. It has a relatively moderate cost and is easy to use. They reported that the thermal performance of the newly developed dryer in terms of heat and mass transfers influenced by solar incident radiation were found to be higher compared to open sub drying for the selected food materials. This type of process is liable to contamination by infestation (Sobowale et al. 2017).

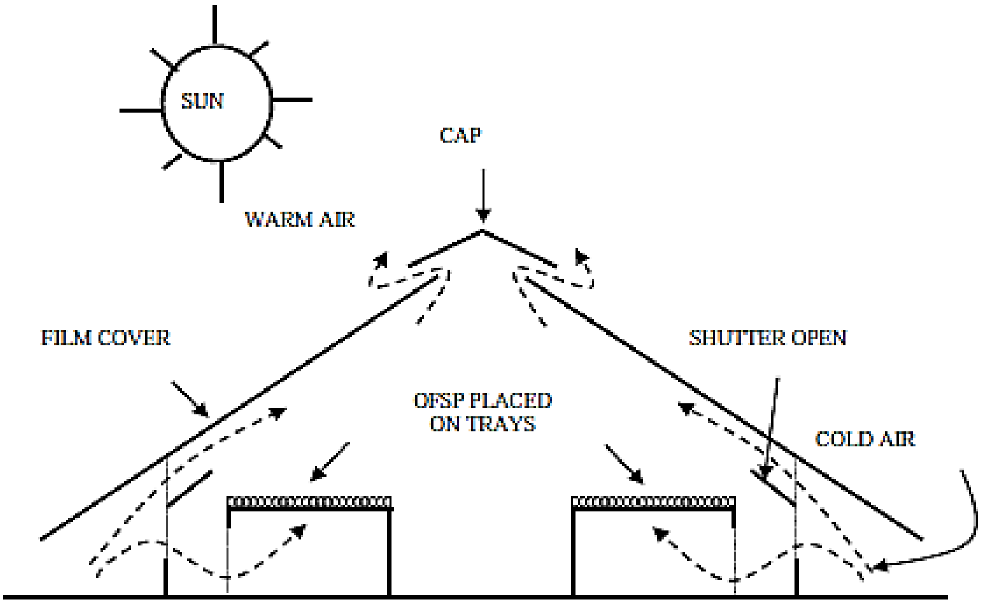


Figure 2.2: Direct solar dryer (Sobowale et al. 2017)

2.4.3 Indirect solar dryer

The sun's heat is first collected by the solar collectors and is then passed onto the dryer cabinet, where the drying occurs (Figure 2.3). The dryer is capable of giving good output and is ideal for small scale farmers because of its low-cost requirements. However, it cannot be applied for commercial drying purposes due to its low throughput. An experiment done by (Vijayan et al. 2016) on bitter gourd drying using indirect dryer, the initial moisture content of bitter gourd on wet basis was reduced from 92% to 9% in 7 h for the mass flow rate of 0.0636 kg/s, on the other hand open sun drying takes 10 h. Hence considerable drying time is reduced in indirect solar drying. However this drying technique doesn’t use the direct sun irradiation(Vijayan et al. 2016).

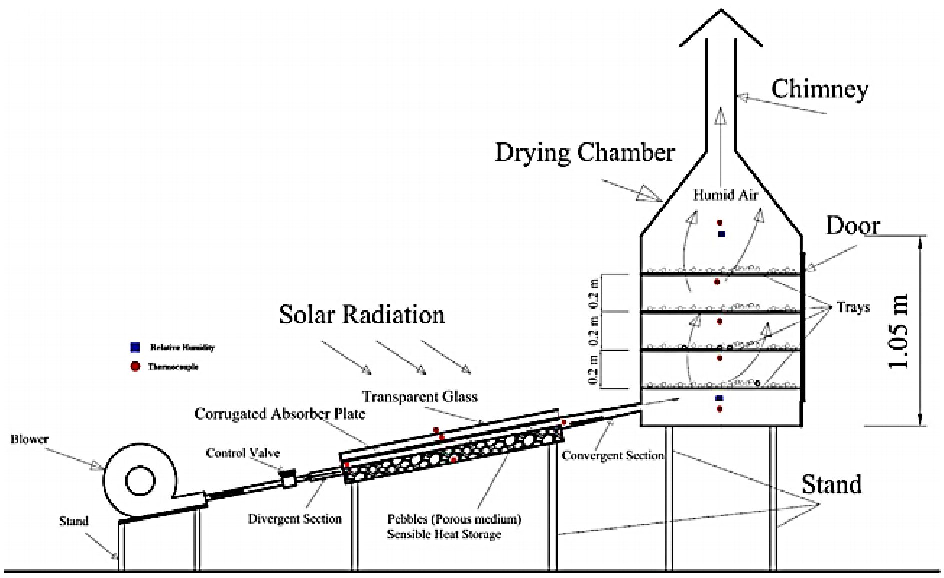


Figure 2.3: Indirect solar dryer (Vijayan et al. 2016)

2.4.4 Mixed mode solar dryer

This is also known as a multi-purpose dryer; the produce is dried by both direct sun radiation and the indirectly heated air. Drying temperature and moisture constant are the most important variables for controlling the drying rate in this type of dryer. Compared with sun drying, direct and indirect solar dryers, the mixed-mode dryer is the best of the three because it has the highest drying rate (Figure 2.4). A previous study that examined the design and performance of this kind of solar dryer verified the accelerated drying process and its ability to dry agricultural products by quickly reaching better conditional moisture level, thus making it ideal for food preservation (Bolaji et al. 2008) (Simate 2003)., discussed the basic concepts by involving computer modeling for mixed mode solar dryers. The system gives satisfactory drying efficiencies of 21 to 24 % and consumes 6-8% energy with the capacity to dry the products to a moisture content of 13% at ambient temperature (25°C).

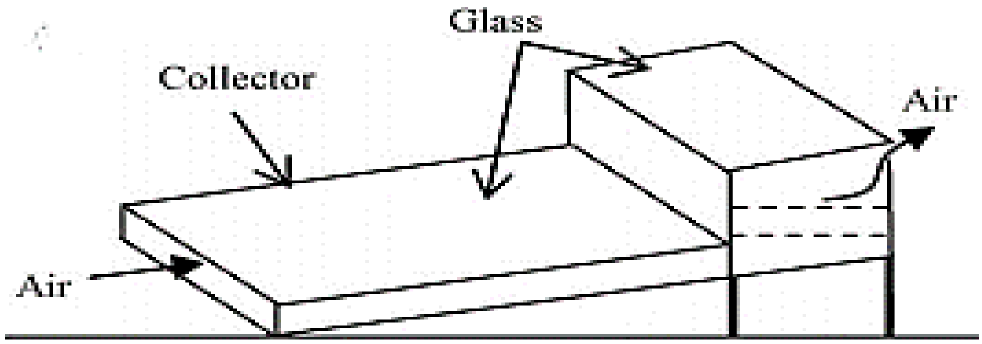


Figure 2.4: Mixed mode solar dryer(Simate 2003)

2.4.5 Hybrid solar dryer

In these dryers, although the sun is used to dry products, other technologies are also used to cause air movement in the dryers. Hence the drying process is not dependable on solar radiation. Blower is used for proper air movement in hybrid solar dryer which can be powered by solar photovoltaic system Hybrid solar dyer can control drying of any agricultural produce by efficient way and also helps to maintain product qualities for example, fans powered by solar PV can be used in these types of dryers (Figure 2.5). However, the design and optimization of hybrid dryers often involve construction of expensive prototype systems and time-consuming studies(GN et al. 2009).

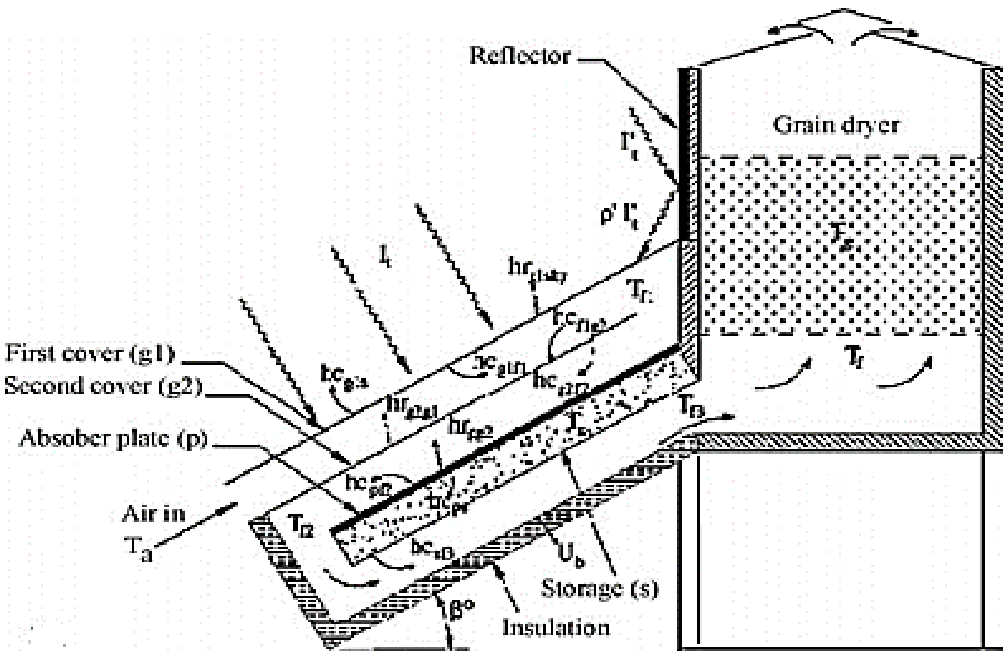


Figure 2.5: Hybrid solar dryer with air heater and thermal storage(Fudholi et al. 2010)

In addition to those major classifications we discussed, solar dryers further can be classified as natural convection solar dryer and forced convection solar dryer depending on the mode of air circulation inside the drying chamber. Natural circulation dryer (passive mode) is when the air inside the chamber moves due to natural circulation only (Figure 2.6). This means the products get heated due to direct absorption of heat or due to high temperature in the enclosure and then moisture evaporated from the products escapes out of the chamber by natural circulation of air. This type of dryer however has low capacity and a limited drying rate. Its performance is highly dependent on weather conditions limiting its wide scale application. The other one is a forced convection solar dryer (active mode dryer), in these types of solar dryers, air is forced into or out of the drying chamber using a blower or fan which is electrically or mechanically operated or hydraulically activated (Figure 2.7).

Many scholars suggested that mixed type of solar dryer is much better than the open-air direct sun drying. Mixed mode solar dryer uses direct sun radiation to heat the product inside the dome shape plastic and additional air heater for better air circulation inside the drying chamber. A properly designed mixed mode solar dryer for green banana drying has not been done yet. Thereby, simulation and modeling will be performed in this research.

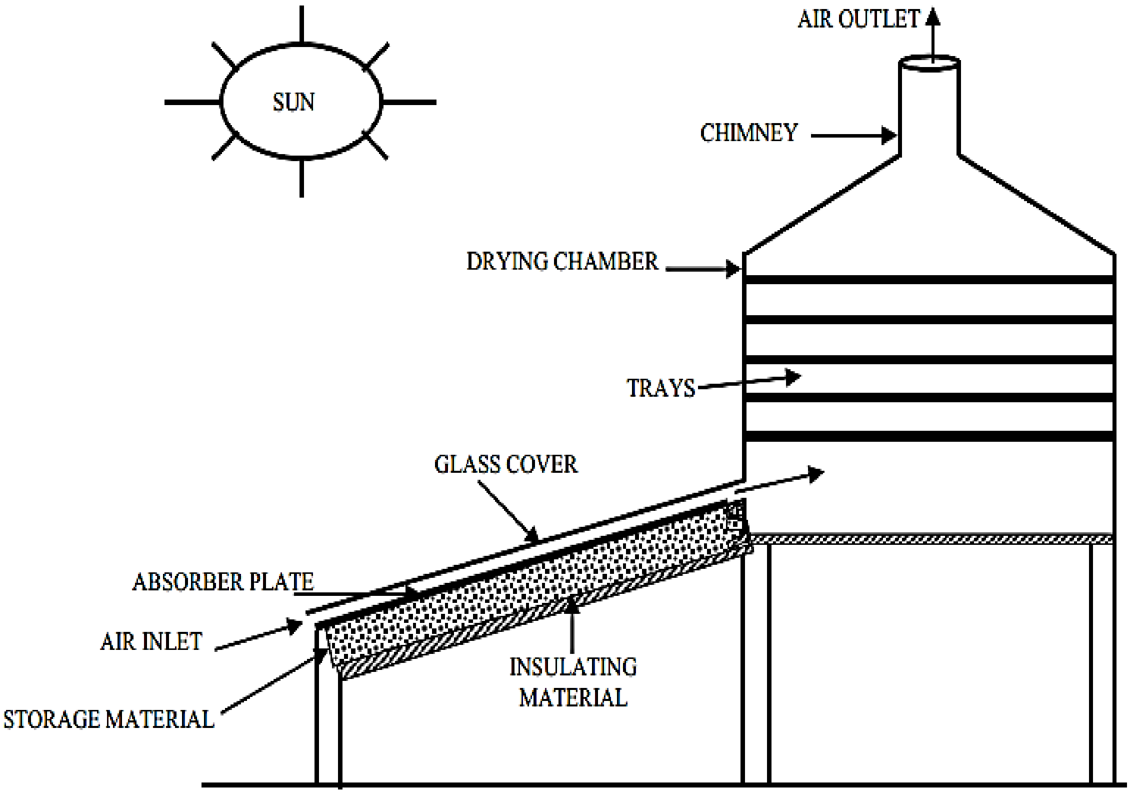


Figure 2.6: Natural convection solar dryer(Gbaha P et al. 2007)

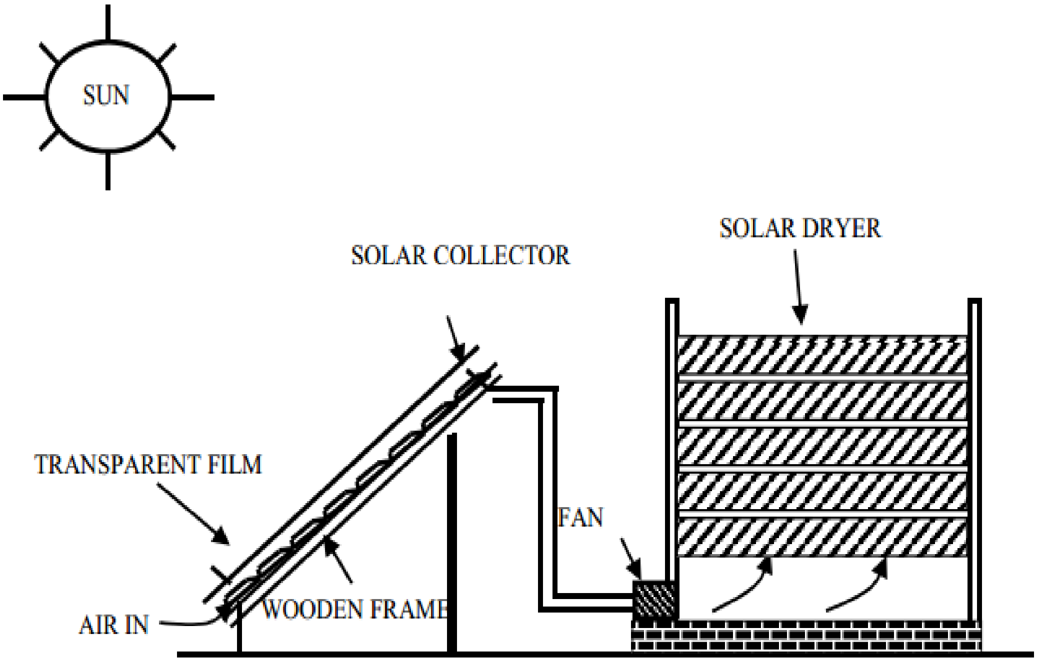
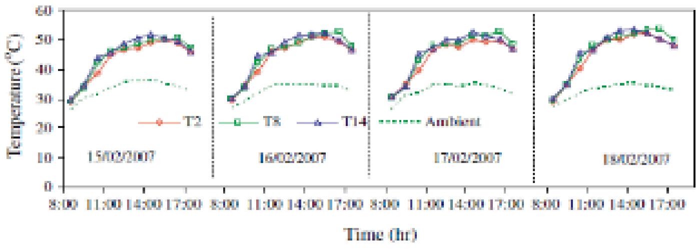
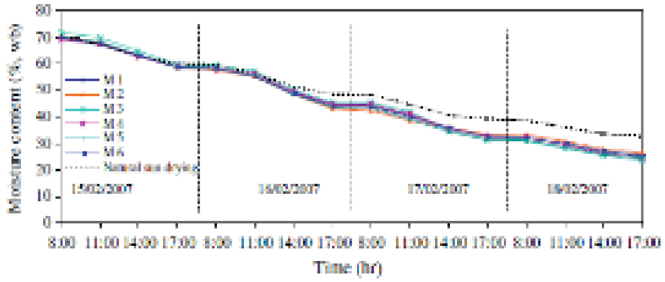
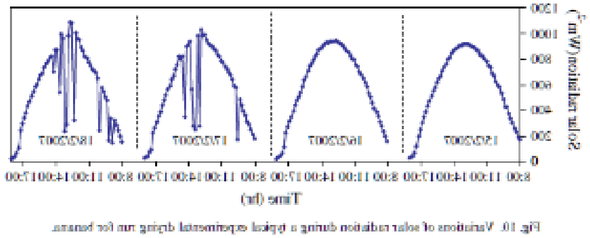


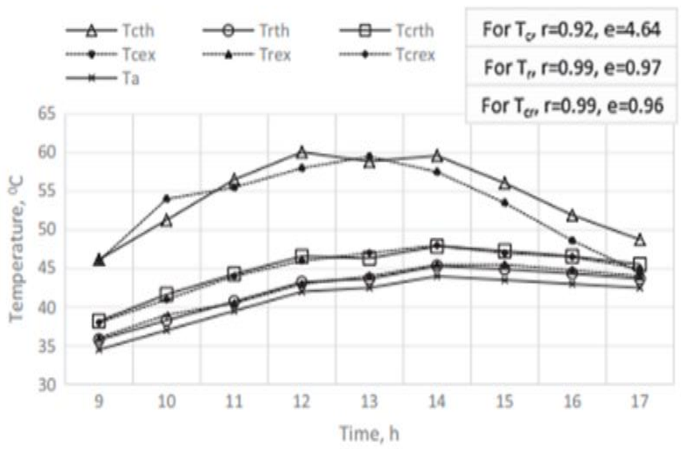
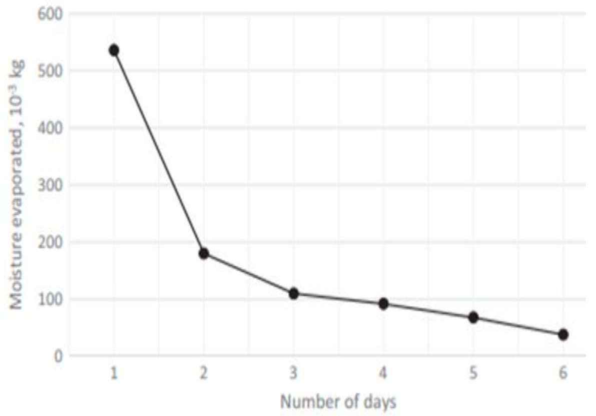
Figure 2.7: Forced Convection solar dryer(Bolaji et al. 2008)

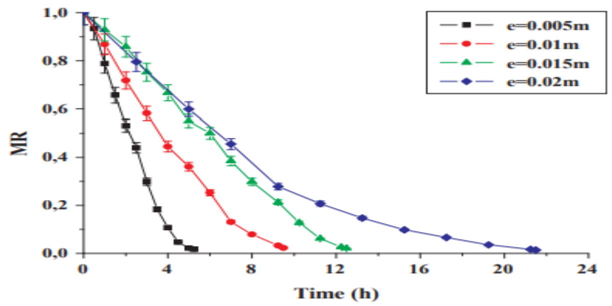
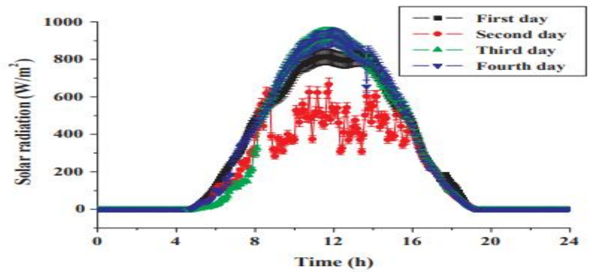
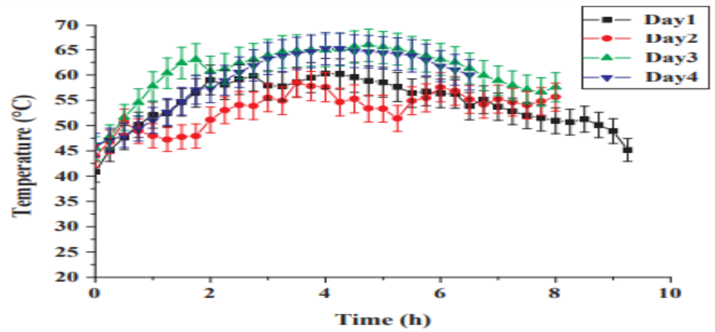
2.5 Some simulation result reviews on solar drying

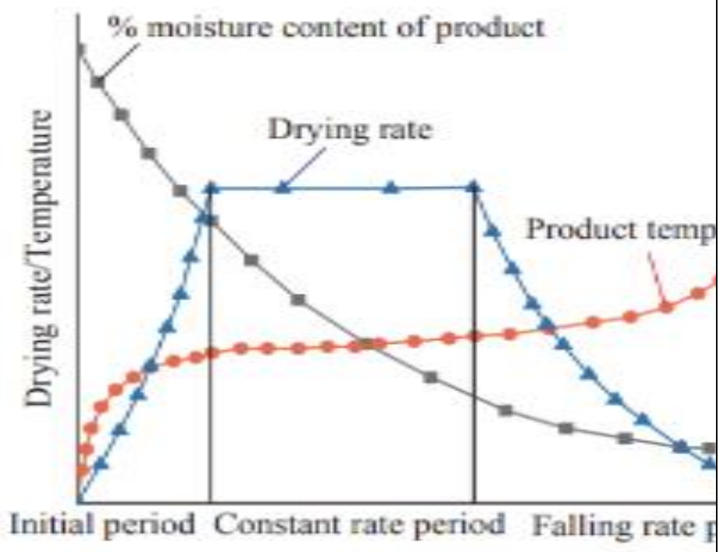
Reviews of literatures indicated that considerable efforts have been invested in research and development of different solar dryers. However, limited research works were reported on mixed mode greenhouse solar fruit dryer with solar air heater for mass production. Thus, the present work aims to improve the performance greenhouse solar dryer by adding solar air flat plate collector. Table 2.1 shows, articles reviewed on simulation results of previous works on solar dryers.

Table 2.1 Summary of simulation results reviewed

No	Name of researcher	Name of the journal and date	Title of the research	This paper presents	Result
1	(Janjai et al. 2009)	**Science direct, Solar Energy** 2009	Experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana	experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. The numerical solution was programmed in Compaq Visual FORTRAN version 6.5.	  

2	(Tiwari et al. 2016)	Science direct, Solar Energy 2016	Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer	This paper presents A hybrid photovoltaic–thermal (PVT) greenhouse solar dryer under mixed mode has been proposed and different parameters have been evaluated for climatic condition of Indian Institute of Technology Numerical computations have been done with the help of program made on MATLAB 2013a and the results are validated with experimental values.	 ig. 3. Hourly variation of cell temperature, greenhouse temperature, crop emperature and ambient air temperature with experimental validation.  **Fig. 6.** Daily variation of mass evaporated (drying curve).

3	Ahmed Djebli et al.	Science direct, Solar energy 2019	A new approach to the thermodynamics study of drying tomatoes in mixed solar dryer	The results of an experimental study and thermodynamic study of solar drying of tomatoes of the KAWA type, where the drying experiments was carried out in a large scale mixed solar dryer.	 Fig. 6. Variation of moisture ratio over time.  Fig. 4. Variation of solar radiation over time for tomatoes.  Fig. 5. Variation of temperature over time for tomatoes.

4	**Rasaq et al.**	Science direct, Solar energy 2018	Recent advances in sustainable drying of agricultural produce: A review	**a** state-of-the-art review on the contributions of combined power and drying, application of phase change materials and hybrid drying systems with regard to agricultural products.	 Fig. 3. Food drying curve [36].

2.6 Literature review summary

The follwing table (Table 2.2) describes the qualitative and quantitative outputs of articles reviewed for the study.

Table 2.2 Qualitative and quantitative outputs of previous works on solar dryers

No	Title	Research output							Reference
		Qualitative output	Quantitative output						
			Drying air temperature (℃)	Effective moisture diffusivity (m^2/s)	Activation energy (KJ/mol)	Moisture content initial (%)	Moisture content final (%)	Drying time (Days)	
1	Modelling of thin-layer drying characteristic of unripe Cardaba banana (Musa ABB) slices	Wang and Singh model is an efficient and best thin-layer model suitable for describing the drying curve and it could be used in dryer designing and processing of Cardaba banana. Among the thin-layer models, Wang and Singh model with R2 of 0.9953, RMSE of 0.0223 and χ2 of 4.94 ×0−4 was found to best explain the drying behavior of the Cardaba banana slices.	50 - 70℃	4.25×10^{-8}	38.46	79.80 % (wb)	11.34		(Olawoye et al. 2017)

2	Experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana	Solar drying of peeled longan and banana in solar greenhouse dryer resulted in considerable reductions in drying time as compared with the open-air sun drying and the products dried in the solar greenhouse dryer are high-quality dried product. This model can be used for providing design data for solar greenhouse dryers and also for optimization of this type of solar dryer.	30 ℃ to 60 ℃			70% (wb)	24% (wb)	4 days while 5-6 days in an open sun drying	(Janjai et al. 2009)
3	A greenhouse type solar dryer for small-scale dried food industries: Development and dissemination	Solar drying of osmotically dehydrated tomato in solar greenhouse dryer resulted in considerable reductions in drying time as compared with the open-air sun drying and the products dried in the solar greenhouse dryer are high quality dried products. The problem of drying interruption by rain and cloudy period has been solved.	35°C to 65°C			54 % (wb)	17% (wb)	4 days	(Janjai 2012)

4	A new approach to the thermodynamics study of drying tomatoes in mixed solar dryer	The solar heat collector used in the mixed solar dryer is equipped with fins and provides an average temperature of 50 °C at the entrance of the greenhouse using two fans, which meet our needs and improve the dryer's thermal efficiency. It also eliminates the problem of temperature differences between the lower and upper trays of carts. product in the shape of flat slices takes the least amount of time to dry when compared to the wedge shape. Furthermore, the drying rate is higher for the thinnest slice thicknesses.	56.9°C	$2.3E^{-9}$	121	93%	Between 18 and 25%	1 to 3days depending on the thickness of the product	(Djebli et al. 2019)
5	Mathematical modelling of solar tunnel drying of thin layer organic tomato	This model will help producers to cut the monetary value of drying and to obtain better quality dried products.	41.6°C	1.31×10^{-9}		93.35% w.b.	11.50%	4 days. whereas under the open sun drying it took five days.	(Sacilik et al. 2006)

CHAPTER 3:
MATERIALS AND METHODS

This chapter describes how the greenhouse solar dryer is designed and the material selection parameters based on articles reviewed. The solar dryer contains two basic units, which are, the greenhouse structure and the solar collector. The design parameters are performed in order to achieve maximum handling capacity with low space and high solar absorption quality. The detailed discussion will be presented as follows.

3.1 Geometry and coordinate system

The performance parameters that control temperature condition of the greenhouse dryer includes Solar Daily Normal Irradiance (DNI), green house geometry and orientation, weather conditions, heat losses, material to be dried, airflow through the greenhouse and the absorption quality of the solar air heater (Odhiambo 2015). The following block diagram shows the general process layout of the research.

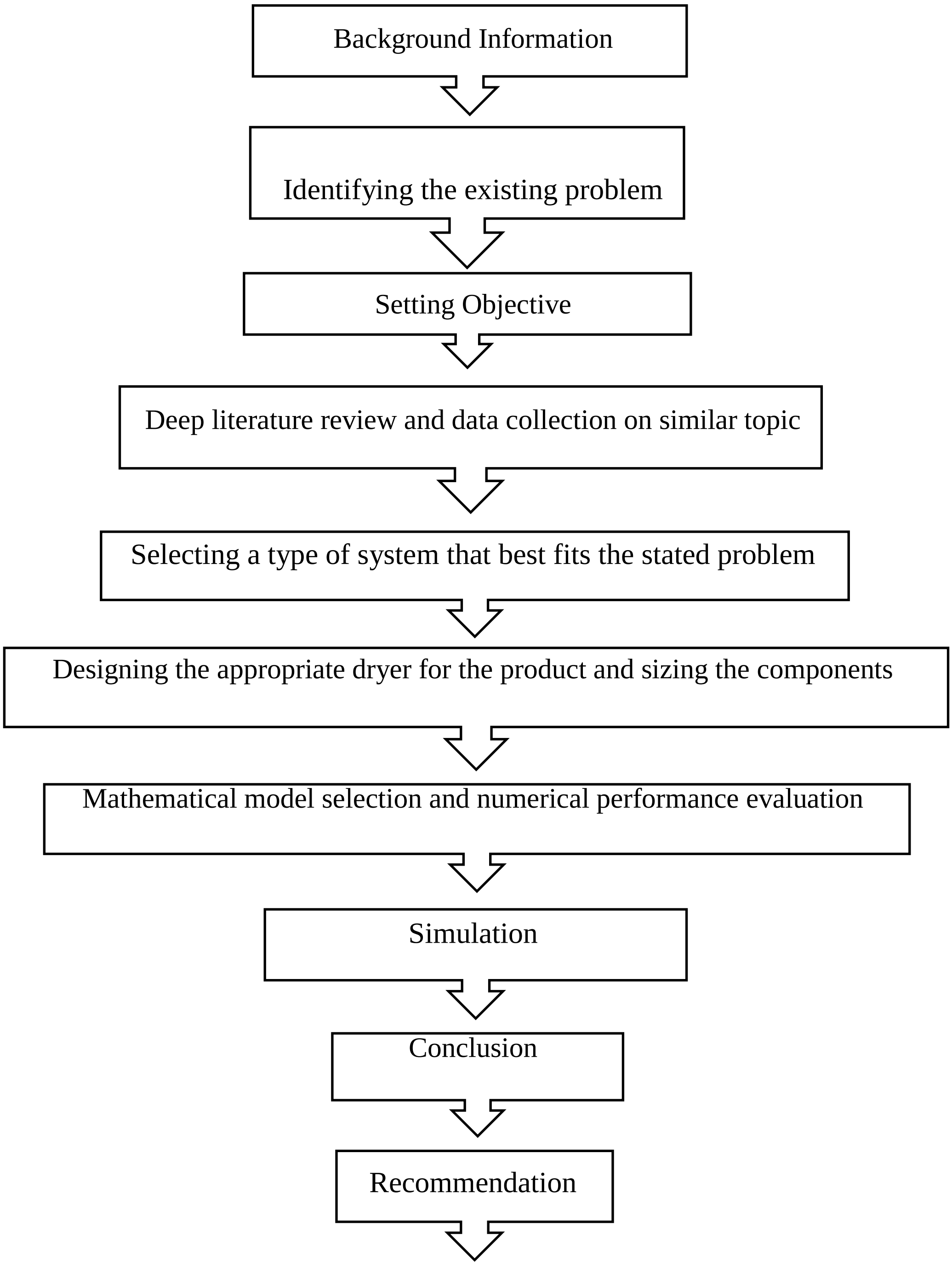


Figure 3.1: General layout of the process of the research

3.2 Greenhouse Dryer

The greenhouse dryer is a system that uses the standard greenhouse structure to function as a solar dryer. It is an enclosed structure, which traps short wavelength solar radiation and stores long wavelength thermal radiation to create a favorable drying environment. The product is placed in trays receiving solar radiation through the plastic transparent cover, while moisture is removed by natural convection. Among the advantages of a greenhouse dryer are simple structure, large load capacity and relatively good thermal performance.

Solar dryers are normally oriented to maximize and capture the available solar irradiation. Therefore, for Arbaminch located at 6°2′N 37°33′E, the north-south orientation is recommended to maximize all-year sunlight irradiation into the greenhouse. An arc-roof shape greenhouse dryer is selected here (Figure 3.1) since, it can prevent rain from entering to the chamber.

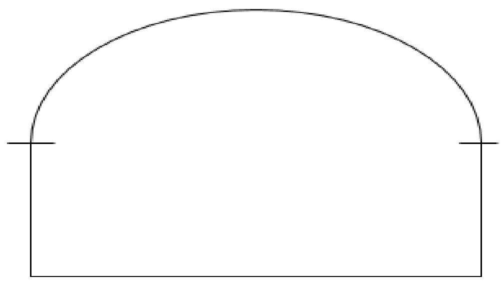


Figure 3.2: Arc roof shape(Odhiambo 2015)

The greenhouse structure mainly has these three main parts, frame of the dryer, cement floor and polyethylene plastic cover. Inside the structure a wire meshed trays placed to handle the sliced banana. The wire meshed structure is selected to let air pass through it from the bottom side, which is very useful to remove moisture from the product easily. The trays are sited on a shelf standing which can hold two trays side by side. The trays are sited on the shelf in a slanted way forming triangular shapes.

3.3 Solar Collector

The function of solar collector is to absorb the heat from the incoming solar irradiation. The total heat absorbed is depending on the material's thermal conductivity and the surface area. The top surfaces of the collector were concentric and inclined at an angle of 10° and painted black to maximize the capturing of solar irradiation. Besides, it has a corrugated surface which provides large area which consequently increased the total heat absorbed. A corrugated metal sheet has a larger area than flat plate collector hence it gives high performance (Odhiambo 2015). Figure 3.3 shows the side view of the solar collector.

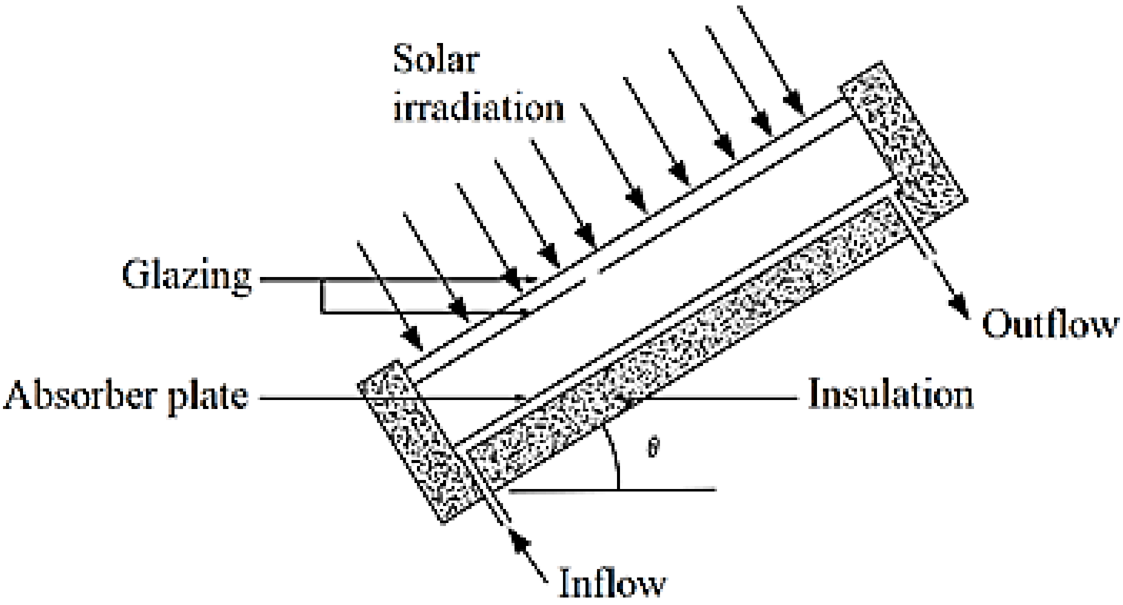


Figure 3.3: Solar air collector

3.4 Material selection

The materials selected for each part of the dryer depends on the availability of the materials, durability, cost effectiveness and reliability for the product to be dried. Therefore, we will discuss each material with their property. Table 3.1 discusses the material property of the greenhouse structure with its different parts.

Table 3.1 Green house structure material and properties

Parts		Material type	Properties
	Cover material	Polyethylene plastic cover	Strong, cost effective, transparent and highly heat conductive.
Green house	Floor	Cement floor	High heat absorber and easily available
Structure	Wall and standings	Galvanized Pipes	Strong and flexible

For the solar air heater, the cover material should have high thermal conductivity, adequate strength and good corrosion resistance. Solar collector plate has main contribution to the heat transfer process. According to Table 3.2, the material for absorber is copper. It is generally preferred because of its high thermal conductivity and resistance to corrosion. A corrugated surface had been used instead of flat surface since it provides larger area.

Table 3.2 Properties of absorber plate materials

Material	Density(kg/m)	Specific heat(J/kg.K)	Thermal Conductivity(W/mk)
Aluminum	2719	871	202.4
Copper	8954	383	386
Zinc(pure)	7144	384	112
Brass (70/30)	8522	385	111
Steel	7833	465	54

In addition, the nature and color of the coating on the incident angle determines the amount of solar energy absorbed by solar collector. A low emissivity, good thermal conductivity and thermally stability during operation and stagnation are among the factors that influence the absorbance of irradiation. In addition, the solar air heater has insulator under the absorber plate, this is used to minimize heat loss from the system, it should be fire resistant and not subject to out-going gassing and should not be damageable by moisture or insect.

3.5 Design Calculation

The design of solar dryer entails all the mathematical approaches and formula used in obtaining the dimensions. This step began with setting assumption of boundary condition and a mathematical calculation. The presented design calculation was based on drying of 500kg of green banana basis. After the correct dimensions are calculated, the pictorials of the extended machine being designed.

3.5.1 Design Parameters

The selection of the design parameters was based on the studies of solar dryer and solar air heater journal articles and books. The dryer was assumed to have near collector air temperature, T_1around 55ºC with the surrounding temperature, T_{amb} of 25ºC. The drying chamber temperature T_{ch} is around 50 ºC to 65ºC. The selected temperature is suitable for drying all types of product and able to inactivate the growth of microorganism. The assumed outlet dryer temperature, T_{od} is 35ºC, it is slightly low since it contains the picked-up moisture content. Based on the assumptions above mathematical modelling and numerical solutions will follow.

3.5.2 Climate data collection

A mixed mode greenhouse solar dryer is selected to be installed at Arbaminch. The climate here is tropical. In winter, there is much less rainfall in Arbaminch than in summer. The solar radiation data was collected from satellite(CAMS Radiation Service December 2020) and the temperature, wind speed and humidity of Arbaminch is found from Ethiopian national meteorological agency.

3.5.3 Mathematical Formulation

The drying phenomenon was modelled by considering a wire meshed fruit handling tray shelves inside the Quonset shape plastic cover greenhouse dryer. By consecutively calculating the air and moisture changes that occur during short intervals of time as the drying air passes from one layer to the next, the continuous drying process was simulated. The procedure adapted assumes that each layer is dried for a short time interval, dt, using air leaving the preceding layer. The process is repeated with consecutive short increments of time until the desired final moisture content of the crop bed is achieved. Four independent partial differential equations are normally needed to predict the changes in the crop temperature and moisture content, and the air temperature and relative humidity values, these four equations are:

- The drying rate equation:
- The mass balance equation on the drying air:
- The heat balance equation on the drying air:
- The heat balance equation on the crop:

3.6 Numerical solution

The mathematical model was performed using MATLAB software. The program, serves to determine the average temperature and moisture content variation of the material being dried and the variation in the properties of the drying air. To study the performance of greenhouse solar dryer with air heater, simulations had been carried out.

CHAPTER 4:

Design of greenhouse solar dryer with air heater for green banana flour production

The design criteria for this dryer are first the dryer is specifically designed for drying unripen banana in Arbaminch location but it can also be a multi-purpose dryer, which means, it can be used to dry various types of fruits like mango, apple, pineapple…etc. and the design can also be applied in other hot places, too. The maximum loading capacity required is approximately 500 kg of unripen banana slices per batch.

4.1 Description of the greenhouse dryer

The theoretical design of this dryer has a dome shape shade in order to make the structure of the dryer simple and be able to withstand rain and storm. The position of the greenhouse is facing south and extending to north. This position is a better position in order to get best sun radiation(Chang 2009).

Polyethylene plastic cover was selected to be the transparent cover for the dryer, because it has a transmittance of visible light of 0.89 and transmitance of infrared radiation 0.77, thus creating a good greenhouse effect inside the dryer (Cemek et al. 2005).

The floor of the dryer is made of concrete mixed with black powder paint to serve as a basement of the dryer as well as a solar radiation absorber. As (Singh et al. 2017) discussed in his experiment, concrete has relatively maximum value of overall heat transfer coefficient, lower relative humidity, higher room temperature and it prevents heat loss to the ground. A small window is made at the bottom of the front side of the dryer to allow the fresh air intake into the dryer. Metallic shelves with four levels of drying trays were constructed and were placed inside the dryer for placing sliced GB’s to be dried.

The dryer has additional hot air supplier from the solar air collector in order to speed up the drying process of the product. There is no additional energy source other than solar energy. This is due to the fact that other systems like PV installed greenhouse dryers or forced convection systems have high investment and operating costs.

4.2 Solar dryer design considerations

To carry out design calculations and size of the dryer, we need to consider the amount of moisture to be removed from the given quantity of green banana slice, the daily sunshine hours for the selection of the total drying time, the quantity of air needed, daily solar radiation to determine energy received by the dryer per day and wind speed for the calculation of air vent dimensions (Pardhi et al. 2013). Table 4.1 shows assumptions which are made based on the requirements of this research and optimum values obtained from different scholarly articles and books.

Table 4.1 Design specification and assumptions

Items	Optimum values and assumptions	References
Location and latitude	Arbaminch, (6°2'N 37°33'E)	
Fruit	Unripe banana	
Design Capacity	500 kg	
Bulk Density	514.76 kg/m³	(Rayo et al. 2015)
Maximum1 allowable temperature	74 ºC -83 ºC	(LII et al. 1982)
Initial moisture content	73%	(Rodriguez-Sosa et al. 1977)
Final moisture content	10-20%	(Tribess et al. 2009)
Average thickness of GB slice	4mm	
Drying time per day	8hrs	
Drying Period	July	
Wind speed	0.65m/s	Ethiopian National Meteorological Agency
Ambient temperature	23.8ºC	Ethiopian National Meteorological Agency
Incident Solar Radiation (H)	18MJ	
Collector type	Flat plate	
Collector tilt angle	(ϕ+15°) = 21º	(Duffie JA 1980)
Collector Efficiency	30-50%	
Maximum Collector Temperature	70ºC	
Absorber thickness	2mm	
Glazing thickness	4mm	
Thickness of Insulation	4mm	
Vertical Distance between adjacent trays	50 cm	

4.3 Metrological data analysis

The data gathered in this paper is from Ethiopian national meteorology agency for Arbaminch location. These data include temperature, humidity and wind speed.

4.3.1 Temperature

Taking four years data of Arbaminch, from 2008-2011, the average maximum temperature, the average minimum temperature and monthly average temperature is shown in the table below (table 4.2).

Table 4.2 Maximum monthly and yearly average temperature of Arbaminch from 2008-2011

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg Max temp	32.32	33.33	33.15	31.07	29.2	27.91	27.74	28.57	29.44	29.90	30.22	30.3
Avg Min temp	16.17	17.11	18.13	18.1	18.04	17.67	17.9	18.05	17.73	17.22	16.04	14.94
Monthly avg	24.24	25.22	25.64	24.58	23.62	22.79	22.82	23.31	23.58	23.56	23.13	22.62
Yearly average	23.8℃											

The graph below (figure 4.1) shows maximum average temperature and minimum average temperature of each month in four years.

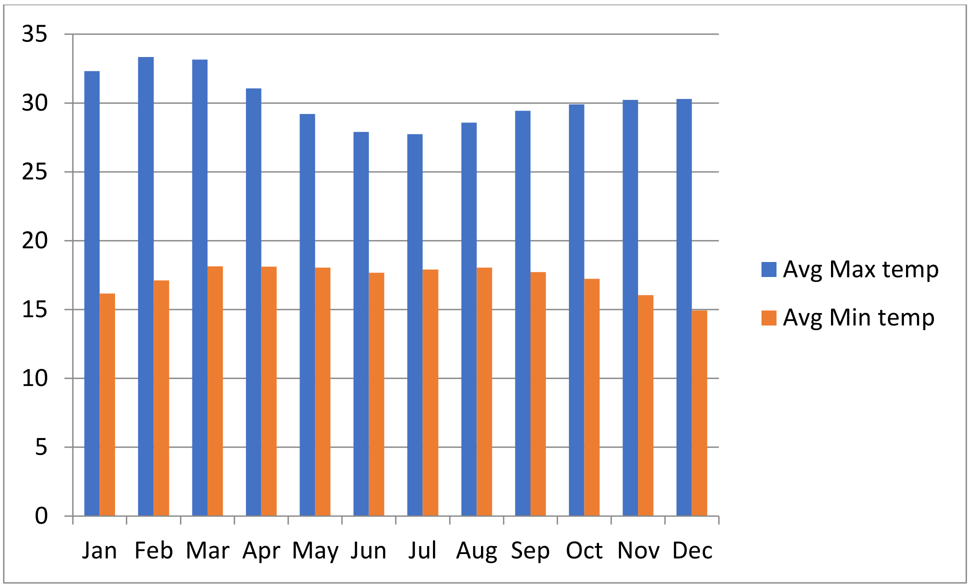


Figure 4.1: Graph of maximum and minimum average temperature

4.3.2 Wind speed

Similarly, for the case of wind speed four year monthly average wind speed has taken and yearly average wind speed calculated. Average wind speed of Arbaminch location from 2005-2008 shown in the table (Table 4.3) and figure (Figure 4.2) below.

Table 4.3 Monthly and yearly average wind speed of Arbaminch from 2008-2011

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly average wind speed	0.65	0.65	0.76	0.69	0.66	0.710	0.72	0.74	0.63	0.55	0.48	0.52
Yearly average wind speed	0.65m/s											

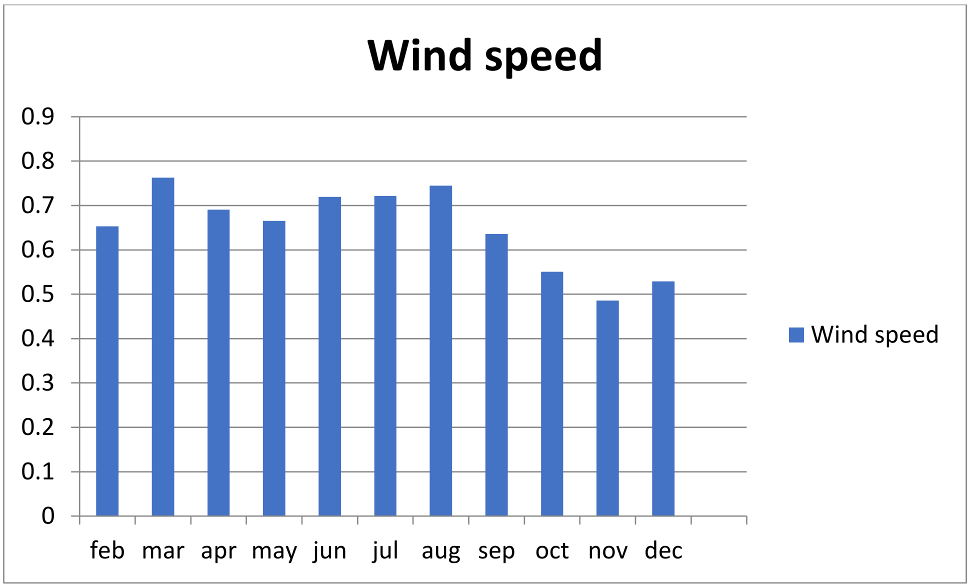


Figure 4.2: Graph of average wind speed

4.4 Design calculations of the greenhouse

4.4.1 Determination of drying heat load

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

$$M_w L_v = \dot{m}_a C_p (\mathrm{T_d} - \mathrm{T_a}) \ldots\ldots (4.1)$$

Where,

L_v= Latent heat of vaporization of water from the GB slices surfaces (kJ/kg).

M_w= mass of water evaporated from the GB (kg)

$\mathrm{T_d}$ = temperature of outgoing air from the drying chamber (°C)

$\mathrm{T_a}$ = ambient air temperature (°C)

The mass of water M_W to be evaporated is estimated from the initial moisture content M_i and the final desired moisture content M_f. The total mass flow of air required for drying is determined from the amount of moisture loss from the crop. The quantity of moisture to be removed is given by the following relationship:

$$M_W = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4.2)$$

Where,

M_{we} = mass of the wet GB slices (kg)

M_i = initial moisture content on wet basis (% wb).

M_f = final moisture content on wet basis (% wb)

Initial data: M_{we}= 500kg,$M_f = 20\% = 0.2$, M_i =73%= 0.73 Therefore

$$M_W = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right]$$

$$= 500kg\left[\frac{0.73 - 0.2}{1 - 0.2}\right]$$

$$M_W = 331.25\text{kg}$$

Therefore, the heat load is determined by the amount of fruit to be dried, it's initial and final moisture contents and the time required to complete the drying operation.

$$Q_{load} = M_w L_v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...… (4.3)$$

Where,

M_w= amount of moisture to be removed (kg)

L_v= latent heat of vaporization of water from the green banana slice, 2.26×10^6 J/kg

Therefore,

$$Q_{load} = 331.25\text{kg} * 2.26 \times 10^6 \text{ J/kg}$$

$$Q_{load} = 748.625\text{MJ}$$

4.4.2 Determining volumetric air flow and mass flow rate

The total volume of air required for removing the moisture from 500 kg of GB slices is evaluated from equation (4.4).

$$V_a = \frac{M_W L_v R_a T_a}{C_p P_a (\mathrm{T_o} - \mathrm{T_f})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.4)}$$

Where, $\mathrm{T_f}$ = temperature of air leaving the drying bed obtained from the following relationship.

$$\mathrm{T_f} = T_a + 0.25(\mathrm{T_o} - \mathrm{T_a}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.5)}$$

Where,

R_a= gas constant (kJ/kgK)

$\mathrm{T_o}$= temperature of air at the collector outlet (°C)

P_a= partial pressure of dry air in the atmosphere, (N/m^2)

C_p= specific heat capacity of air, (kJ/kgK)

Here, $T_a = 23.8$°C, $\mathrm{T_o} = 70$°C, therefore;

$$T_f = 23.8°\mathrm{C} + 0.25(70°\mathrm{C} - 23.8°\mathrm{C})$$

$$T_f = 35.35°\mathrm{C} = 308.35\mathrm{K}$$

Therefore, we have

$T_f = 308.35$K, M_W =331.25kg, $L_v = 2.26 \times 106$J/kg, R_a =287J/kgK, C_p =1007J/Kg, $T_a = 296.8$K, $T_o = 343$K

For Arbaminch, 1285m elevation from the sea level, the partial pressure P_a is equal to 84259.7 N/m^2

$$V_a = \frac{M_W L_v R_a T_a}{C_p P_a (\mathrm{T_o} - \mathrm{T_f})}$$

$$V_a = \frac{331.25kg \times 2260\ \text{kJ/kg} \times 287J/kgK \times 296.8\text{K}}{1007J/Kg \times 84259.7\ N/m^2 (343\text{K} - 308.35\text{K})}$$

$$= 21689.89\ \text{m}^3$$

Mass flow rate of air needed to affect the drying is given by equation (4.6)

$$\dot{m}_a = \dot{V}_a \rho_a \quad \text{……………………………………………..…. (4.6)}$$

Where,

$\dot{V}_a$= volume flow rate of the drying air (m^3/s)

t_d= Drying time per day (hrs.)

v_a= total volume of air required for removing the moisture m^3

$$\dot{V}_a = \frac{v_a}{t_d}$$

$$= \frac{21689.89\ \text{m}^3}{259{,}200}$$

$$\dot{V}_a = 0.083\text{m}^3/\text{s}$$

For Arbaminch, the density of air is $0.9885kg/m^3$

Therefore, taking $\rho_a = 0.9885kg/m^3$

$$\dot{m}_a = \dot{V}_a \rho_a = 0.083\text{m}^3/\text{s} * 0.9885\text{kg/m}^3$$

$$= 0.083kg/s$$

4.4.3 Percentage Moisture Loss

The quantity of moisture in percentage of the initial mass of a material can be represented on wet and dry basis and expressed as percentage given by equation (4.7). The initial mass of fresh banana (W wet) and final mass of dried banana (W dry) was measured with the help of Weighing balance.

$$MC = \left[\frac{M_1 - M_2}{M_1}\right] \times 100\% \quad \text{(Wet basis)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.7)$$

Were,

M_1= Initial mass of the GB slices, (kg) = 500kg

M_2= Final mass of the GB slices (kg), which can be found by subtracting the amount of moisture to be removed in kg from the initial mass of the GB slices.

i.e., $M_2 = M_1 - M_W$

M_2= 500kg - 331.25kg

= 169kg

Therefore, $MC = \left[\frac{500kg - 169kg}{500kg}\right] \times 100\%$

MC = 66.2%

4.4.4 Average Drying Rate:

The quantity of moisture removed from the food item over the drying time is given by equation (4.8):

$$m_{dr} = \frac{M_w}{t_d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.8)$$

M_w= mass of water evaporated from the banana slices, (kg)

t_d= drying time per day, assumed to be 3 days.

$$m_{dr} = \frac{331.25kg}{72hr}$$

m_{dr} = *4.6 kg/hr.*

4.5 Dying Chamber Capacity and Other Dimensions

The volume of GB per tray can be obtained from equation given by:

$$V_{GB} = W_T L_T GB_l \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.9)$$

Where,

GB_l= Thickness of the GB slices in the drying chamber = 4mm

W_T= width of the tray =1000mm

L_T= Length of tray, which is equal to length of the chamber = 10000mm

$$V_{GB} = 1000mm * 10{,}000mm * 4mm$$

$$= 40{,}000{,}000mm^3$$

Total volume of the GB slices on the trays in the drying chamber can be obtained as;

$$V_T = nV_{GB}$$

$$= 4*40{,}000{,}000$$

$$V_T = 160{,}000{,}000mm^3$$

Four wire meshed trays each with 10,000mm length and 2000mm width placing two trays vertically on a metallic shelf, the total area needed to place the trays with 500kg GB slices the optimum dimension is 10000mm*8000mm*3500mm. Spacing the drying chamber will allow free air movement between the products and it allows sunlight penetration in each tray. The three-dimensional drawing of the greenhouse dryer is shown in Figure 4.3.

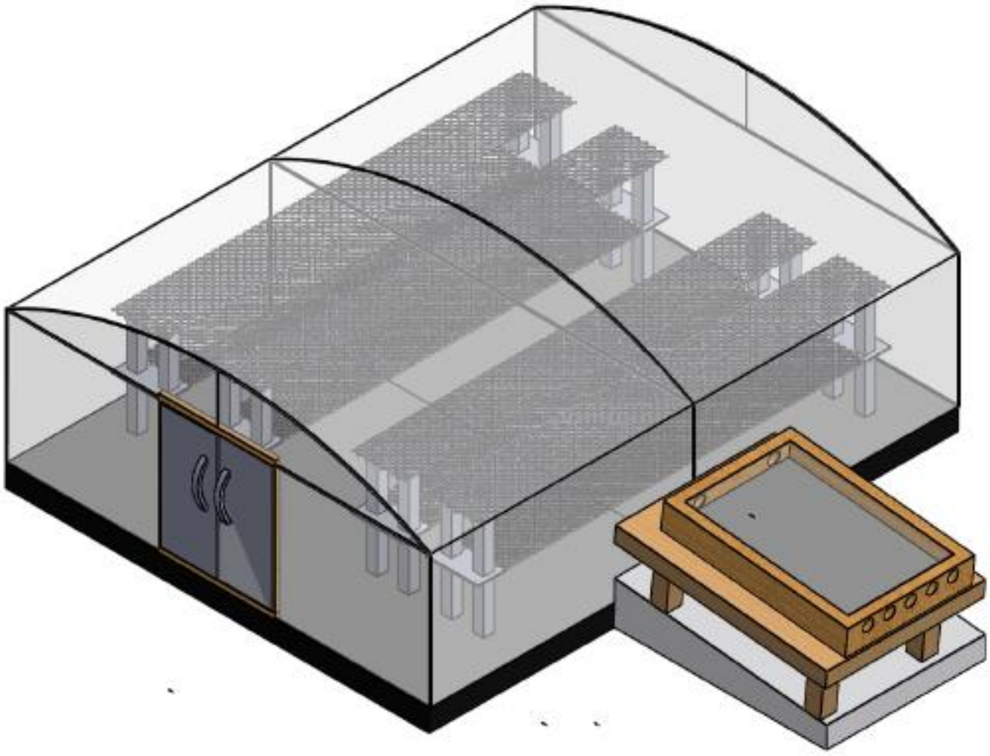


Figure 4.3: 3-D drawing of greenhouse dryer with air heater

4.6 Solar collector Design

The amount of solar-energy absorbed by a solar-energy air heater depends largely on the level of insolation and the solar collector orientation, the absorbance ability of the absorber surface and the transmittance of the cover material.

The useful heat gain by a collector can be expressed as

$$Q_u = \dot{m}C_p(T_o - T_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.10)$$

The following heat balance expresses the thermal performance of a collector under steady-state conditions

$$Q_u = AF_R[I(\tau\alpha)_C - U_L(T_i - T_a)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.11)$$

4.6.1 Sizing the Collector

The collector efficiency is influenced by factors such as temperature, air flow rate, insolation, type of transparent material, absorber plate and insulation used (Struckmann

2008). To achieve an optimal design, average value of collector efficiency of 35% was considered as a design parameter.

As a result, Daily expected energy production by the collector

$$= 18/\frac{MJ}{m^2}/day * 0.35$$

$$= 6.3\,\frac{MJ}{m^2}/day$$

For 3 days (the drying period), the energy production would be

$$= 3 * 6.3 = 18.9\,\frac{MJ}{m^2}$$

The required surface area of the transparent cover for crop drying depends primarily on the heat load of the drying system (Kamble et al. 2013).

$$A_c = \frac{Q_{load}}{\eta I_T t_d} \qquad (4.12)$$

Where,

t_d= drying time, (hrs)

I_T= the total solar radiation incident on the collector surface (W/m^2).

I_T=H×R(Alamu et al. 2010)

H= horizontal radiation (W/m^2)

R= ratio of solar energy on tilted surface to that on the horizontal, (dimensionless)

η= efficiency of the collector which is between 30-50% as given by.

Here, η= 50%, H=18 MJ, R= 1.0035, I_T= H*R= 18.063MJ/m²/day, $Q_{load} = 768.5MJ$

Therefore,"

$$A_c = \frac{748.625\text{MJ}}{0.5 * \frac{18.063MJ}{m^2/day} * 3\ day}$$

$$A_c = 27m^2 \sim 30m^2$$

$$A_c = 27{,}630{,}146mm^2$$

Three solar collectors with $10m^2$ area each are proposed for the greenhouse chamber intake temperature. The design is only for one air collector and later multiplied for three.

Therefore, the absorber surface area A_{ab} is approximately equal to the area of the collector A_c.The recommended collector length to width ratio is in the range of 1-2(Tonui et al. 2014). Therefore, for one collector, length to width ratio is taken as 1.5, which is,

$$\frac{L_c}{W} = 1.5$$

$$L_c = 1.5 * W$$

$$A_c = L_c * W$$

$$10{,}000{,}000\text{mm}^2 = 1.5 * W * W$$

$$W^2 = 10{,}000{,}000/1.5$$

$$W = 2{,}582\text{mm} \quad \text{and} \quad L_c = 3{,}873mm$$

Figure (4.4) shows a 3-d drawing of the solar air heater done by solid works.

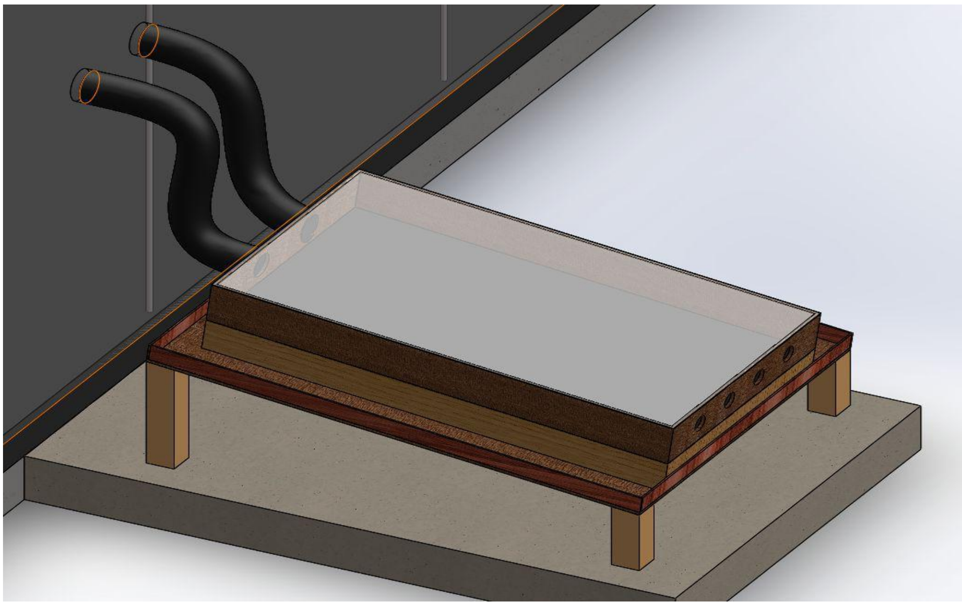


Figure 4.4: Drawing of solar air heater

In solar collector system, the solar energy absorbed by the absorber plate is distributed to useful gain and to thermal losses through the cover glazing, through the insulation from the bottom and edges (Habtamu 2007)

The total heat transmitted and absorbed is obtained from equation (4.13).

$$I_T A_C \tau\alpha = Q_u + Q_L + Q_s \quad (4.13)$$

Where,

Q_s= energy stored which is negligible, (kJ/kg)

Q_l= Heat loss from the collector, (kJ/kg)

Q_u= Useful energy gained by the air, (kJ/kg)

The heat loss from the collector is given by;

$$Q_l = U_l A_C (T_C - T_a) \quad (4.14)$$

And useful energy gained by the air is given as

$$Q_u = Q_a = \dot{m}_a C_p (T_o - T_a) \quad (4.15)$$

$$= 0.084\text{kg/s} * 1007\text{J/ kg. K} * (343\text{K} - 296.8\text{K})$$

$$Q_u = 3{,}907\text{J}$$

Therefore, the collector useful energy under steady-state conditions can be calculated as following,

$$Q_{uc} = AF_R[I(\tau\alpha)_C - U_L(T_i - T_a)]$$

$$F_R = Q_u/A[I(\tau\alpha)_C - U_L(T_c - T_a)]$$

$$= 3{,}907\text{J}/(10.36*(1003.5\ \text{W/m}^2*0.88 - 10.95\text{W/m}^2\text{K}*46.9\text{K})$$

$$= 1.02$$

Therefore,

$$Q_{uc} = 3{,}985.8\text{J}$$

The collector overall heat transfer coefficient is given by;

$$U_l = \frac{I_T A_C \tau\alpha - \dot{m}_a C_p \Delta T}{A_C \Delta T} \quad \text{(4.16)}$$

Here, I_T = 18.063 MJ/m2/day= 1003.5 W/m²

A_C = 10 m^2

$\tau\alpha$ = 0.88

$\dot{m}_a$= 0.084kg/s

C_p=1007 J/ kg.K

ΔT= 70-23.8= 46.2K

$$U_l = \frac{1003.5\ \text{W/m}^2 * 10.36m^2 * 0.88 - 0.084kg/s * 1007\text{J/kgK} * 46.2\text{K}}{10.36m^2 * 46.2\text{K}}$$

$$U_l = 10.95\text{W/m}^2\text{K}$$

Therefore, heat loss from the collector surface area can be computed by inserting the value of U_l in to equation (4.14) and it becomes:

$$Q_l = U_l A_C (\mathrm{T_C} - \mathrm{T_a})$$

$$= 10.95\mathrm{W/m^2K} * 10\mathrm{m^2} * 46.2\mathrm{K}$$

$$Q_l = 5240.7\mathrm{W}$$

Ttable4.4 shows dimensions of the air heater and drying chamber.

Table 4.4 Summary of the solar air heater and drying chamber dimensions

Component	**Width**	**Length**	**Height**	Quantity
Air collector	2, 582mm	3,873mm	500mm	3
Green house	8000mm	10000mm	3500mm	

4.7 Performance Evaluation

4.7.1 Solar Collector Efficiency

A measure of collector performance is the collector efficiency, defined as the ratio of useful heat gain over any time period to the incident solar radiation over the same period. We can, thus, define efficiency as

$$\eta = \frac{Q_u}{IA} \quad \text{...} \quad (4.17)$$

From eqn. (4.15) and (4.14),

$$\eta = \dot{m} C_p \frac{(\mathrm{T_o} - \mathrm{T_I})}{IA} \quad \text{......................................} \quad (4.18)$$

We have, $\dot{m} = 0.084 g/s$, C_p =1007J/Kg, $T_i = 23.8$℃, $T_o = 70$℃ , $I = 1003.5 \frac{\mathrm{W}}{\mathrm{m^2}}$, A= $10.36 m^2$

$$\eta = 0.084 kg/s * 1007\mathrm{J/Kg} \; \frac{(343\mathrm{K} - 296.8\mathrm{K})}{1003.5\ \mathrm{W/m^2} * 10.36 m^2}$$

= 0.38 or 38%

The calculated collector efficiency shows a better efficiency from the assumed.

4.7.2 Dryer Efficiency

The drying efficiency of the greenhouse dryer is defined as the ratio of energy output of the dryer to energy input in the dryer. For natural convection solar dryer, the system efficiency can be expressed as given by (Forson et al. 2007)as:

$$\eta_{dryer} = \frac{\mathrm{Q_{dryer}}}{\mathrm{Q_{solar}}} \qquad (4.19)$$

Solar radiation input on the dryer is:

$$\mathrm{Q_{solar}} = I_T\, \mathrm{A_{dryer}}\, t \qquad (4.20)$$

Where, $\mathrm{Q_{solar}}$ = solar energy input on the dryer, J

I (t) = solar radiation, at time t, W/mm²

$\mathrm{A_{dryer}}$ = dryer area, mm²

$\mathrm{t_s}$= drying time, s

Therefore,

$\mathrm{Q_{solar}}$ = 1003.5 W/m²*80 m²* 2880s = 231,206,400

The output of the dryer in terms of energy required for vaporization is:

$\mathrm{Q_{dryer}} = m_r * L_v$

Where, $\mathrm{Q_{dryer}}$ = energy required for vaporization, J

m_r = moisture removed, kg = 331.25kg

L_v = latent heat of vaporization of moisture, J/kg = 2.26*10^6J/kg

Therefore, $Q_{\text{dryer}} = 333.25kg * 2.26*10^6$ J/kg

$$Q_{\text{dryer}} = 748{,}625{,}000J$$

Thus, drying efficiency of the dryer is then can be calculated by using the following equation (equation 4.22).

$$\eta_{dryer} = \frac{Q_{\text{dryer}}}{Q_{\text{solar}}} \text{ ………………………………………………….... (4.21)}$$

$$= 748{,}625{,}000J / 231{,}206{,}400J$$

$$= 0.32 = 32\%$$

4.8 Summary of design calculations of the greenhouse dryer

The following table (table 4.5) shows the summary of the design calculation for the greenhouse chamber design and for the solar collector design.

Table 4.5 Summary of design results

NO	DESCRIPTION	EQUATION	RESULT
1	Mass of water to be evaporated	$M_W = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right]$	331.25kg
2	Heat load	$Q_{load} = M_w L_v$	748.625MJ
3	Volumetric air flow	$\dot{V}_a = \frac{v_a}{t_d}$	0.07m³/s
4	Mass flow rate	$\dot{m}_a = \dot{V}_a \rho_a$	0.084 kg/s
5	Percentage moisture loss	$MC = \left[\frac{M_1 - M_2}{M_1}\right] \times 100\%$ (Wb)	66.2%
6	Average drying rate	$m_{dr} = \frac{M_w}{t_d}$	*4.6 kg/hr*
7	useful energy gained by the air	$Q_u = AF_R[I(\tau\alpha)_C U_L (T_i\ T_a)]$	3,985.8J
8	collector overall heat transfer coefficient	$U_l = \frac{I_T A_C \tau\alpha - \dot{m}_a C_p \Delta T}{A_C \Delta T}$	10.95W/m²K
9	heat loss from the collector surface area	$Q_l = U_l A_C (T_C - T_a)$	5240.7W
10	Solar collector efficiency	$\eta = \dot{m} C_p \frac{(T_o - T_I)}{IA}$	38%
11	Dryer efficiency	$\eta_{dryer} = \frac{Q_{dryer}}{Q_{solar}}$	32%

CHAPTER 5:
MATHEMATICAL MODELING

In this chapter the detail mathematical formulation necessary to model the solar air heater and the greenhouse dryer will be discussed. The models selected here is a dynamic model to be used for MATLAB /Simulink application. Assumptions and formulas are inserted from different articles and books.

5.1 Mathematical model for air heater

5.1.1 Solar radiation model

The distance between the earth and the sun fluctuates annually since the earth rotates in elliptical orbit around the sun and this makes the amount of energy received on the earth's surface (I'_{sc}) to vary in a manner given by (equation. 5.1)

$$I'_{sc} = I_{sc}\left\{1 + 0.033\cos\left(\frac{360n}{365}\right)\right\} \qquad (5.1)$$

Where,

$I_{sc} =$ Solar constant which is valued at 1367 W/m²

n = is the day of the year which varies from n = 1 to n = 365.

The direct solar radiation (I_b) reaching a unit area of a horizontal surface in the absence of atmosphere can be calculated from (equation 5.2).

$$I_b = I'_{sc}\{\sin(\varphi - \beta)\sin\delta + \cos\delta\cos\omega\cos(\varphi - \beta)\} \qquad (5.2)$$

Where,

φ = is latitude (degrees),

β = is angle of inclination of surface from horizontal (degrees),

δ= is angle of declination (degrees) and

ω = is hour angle (degrees).

The angle, δ; (angle between the sun's direction and the equatorial plane) is evaluated from Equation (5.2a) which is given by(Cooper 1969).

$$\delta = 23.45 \sin\left\{360(\frac{284+n}{365})\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.2a)}$$

On the other hand, ω is computed by Equation (4.2b) given by (Duffie JA 1980).

$$\omega = 15(12 - H_r) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.2b)}$$

Here, H_r is hour of the day. Length of the day, (N) is obtained from equation (4.2c):

$$N = (\frac{2}{15}) \cos^{-1}(-\tan\varphi \tan\delta) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.2c)}$$

Another portion of solar radiation that is scattered downwards by the molecules in the atmosphere is called the diffuse radiation(I_d). It can be estimated as direct radiation incident at 60° on the collector surface by Equation (5.3).

$$I_d = CI_L \cos 60° = 0.5CI_L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.3)}$$

Where, C is the diffuse radiation factor.

Therefore, the total solar radiation incident on the horizontal surface (I_T), is obtained by adding the direct and diffused components of solar radiation as given in equation (5.4). The total solar radiation is of great importance for solar dryers since it captures the required components of solar energy that is harnessed in the dryer

$$I_T = I_b(1 + 0.5C) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.4)}$$

In this research paper the solar radiation model was done using data from(CAMS Radiation Service December 2020), by inserting directly to simulink Matlab model using lookup table. The following diagram(Figure 5.1) shows the simulink model for the solar radiation using lookup table.

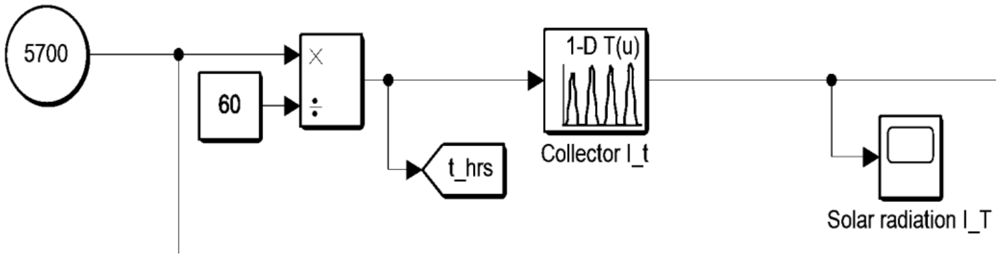


Figure 5.1: Total solar radiation Simulink model

5.1.2 Solar collector model

In this part, we set up a mathematical model for the flat plate solar energy collector. The following assumptions are made in this project:

- The collector is in stable condition.
- The temperature of the air inside the glass cover plate is approximately equal to the outlet temperature of the collector.
- The heat flux of the glass cover plate and the heat absorbing plate is vertically one-dimensional flow.

In steady state, the energy balance equation of the collector is:

$$A_{sc} I_{\theta} (\tau\alpha) = Q_u + Q_l + Q_s \quad \text{(5.5)}$$

Where,

A_{sc} = is the effective collector area of collector in m2,

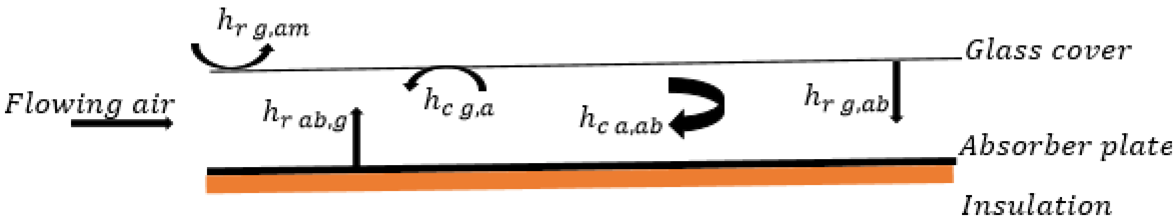
$(\tau\alpha)$ = is the product of the absorption and transmittance of the glass cover plate to the solar radiation,

Q_u = is the useful energy for the collector in W,

Q_l = is the loss energy from the collector in W,

Q_s = is the energy stored in the collector in W.

The following diagram shows the schematic diagram of heat transfer in the solar air collector.



Following equations can be obtained as the steady-state energy balance equations.

For the flowing air:

$$c_a T_{ca} \rho_a T_{ca} V_a \frac{dT_{ca}}{dt} = [h_{c1}(T_g - T_{ca}) + h_{g,ab}(T_{ab} - T_{ca})] p\Delta z$$

For the absorber plate:

$$c_{ab} T_{ab} \rho_{ab} T_{ab} V_{ab} \frac{dT_{ab}}{dt} = G(\tau\alpha) + h_{r1}(T_g - T_{ab}) + h_{c1}(T_{ca} - T_{ab}) + \frac{K_i}{\delta_i}(T_i - T_{ab})] p\Delta z + \pi d_{in} h_f \Delta z (T_f - T_{ab})$$

For the glass cover:

$$c_g \rho_g V_g \frac{dT_g}{dt} = h_{r\_g,am}(T_{am} - T_g) + h_{r+g,ab}(T_{ab} - T_g) + h_{c\_g,ca}(T_{ca} - T_g) + \alpha G] p\Delta z$$

Furthermore, the instantaneous efficiency of the collector is:

$$\eta_{sc} = \frac{Q_j}{A_{sc} I_\theta} = F_r(\tau\alpha)_e - F_r U_l \frac{(T_i - T_a)}{I_\theta} \qquad (5.7)$$

The useful heat gain by a collector can be expressed as

$$Q_u = \dot{m} C_p (T_o - T_i) \qquad (5.6)$$

The following heat balance expresses the thermal performance of a collector under steady-state conditions

$$Q_u = A F_R [I(\tau\alpha)_C - U_L(T_i - T_a)] \qquad (5.7)$$

5.1.3 Simulation model based on MATLAB/Simulink

The dynamic model for the temperature output of the solar collector is based on the above mathematical model (Equation 5.6) is shown below (Figure 5.2). The inputs are total solar radiation, ambient temperature and mass flow rate of the air. Modeling is done by MATLAB/Simulink 2020a.

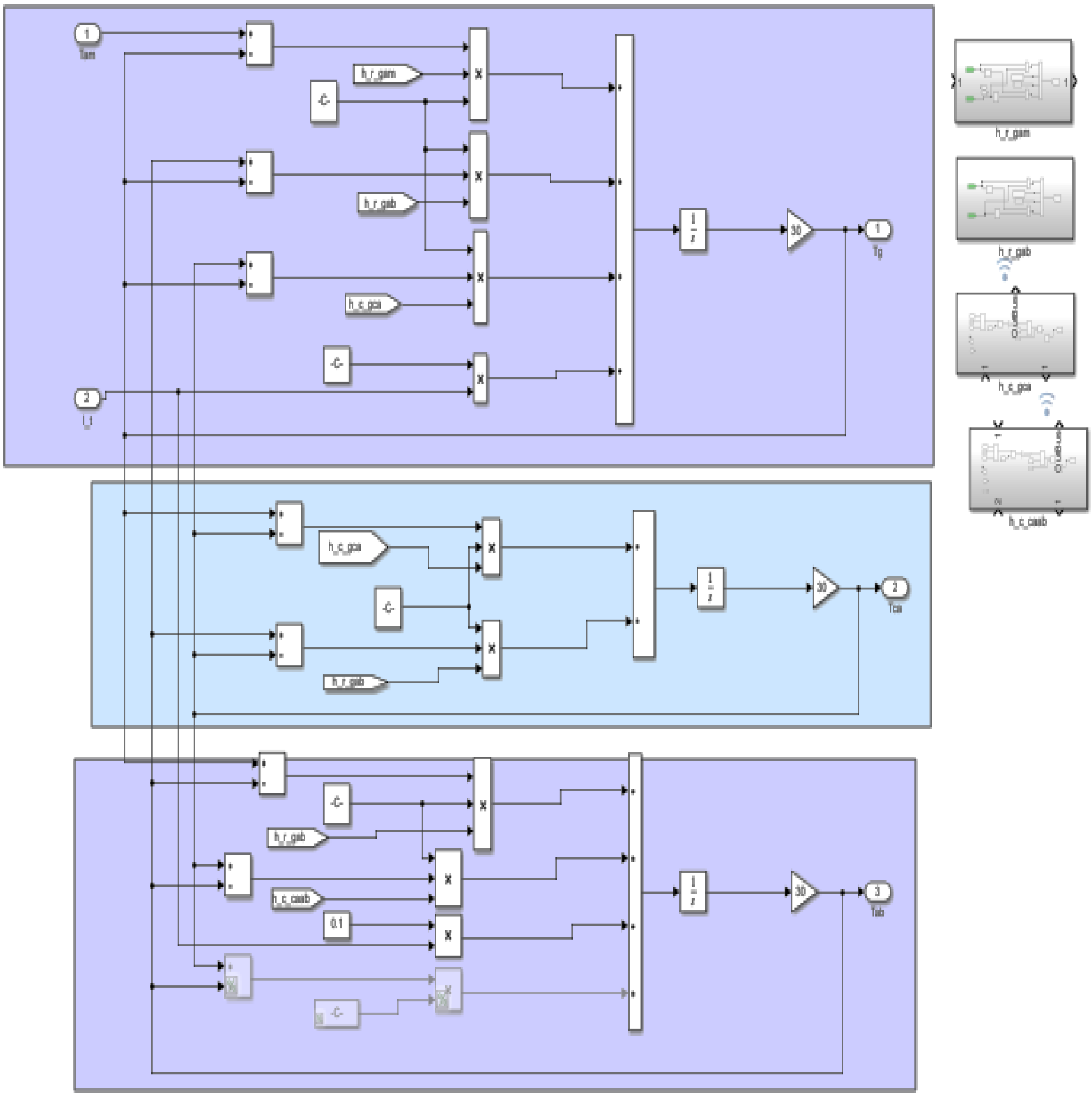


Figure 5.2: Simulink model of out let temperature of the air collector.

5.2 Mathematical model for green house dryer

A mathematical model was developed for predicting the performance of greenhouse natural convection dryer. The assumptions in developing the mathematical model are as follows:

- There is no stratification of the air inside the dryer.
- Drying computation is based on a thin layer drying model.

- Specific heat of air, cover and product are constant.
- (I v) Absorptivity of air is negligible.
- Fraction of solar radiation lost through the north wall is negligible.

Traditionally, there are two different approaches to describe the greenhouse climate: one is based on energy and mass flow equations describing the process, and another is based on the analysis of input-output data from the process by using a system identification approach. This paper deals with the first method for the control of inside air temperature and humidity of a greenhouse, and its physical model describes flow and mass transfers generated by the differences in energy and mass content between the inside and outside air, by control, or by exogenous energy and mass inputs. Schematic diagram of the solar greenhouse dryer is shown below (Figure 5.6).

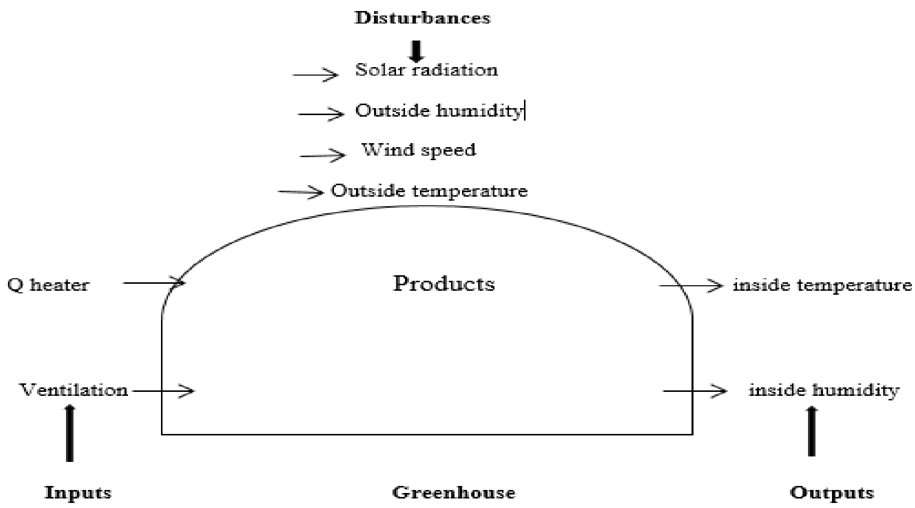


Figure 5.3: Schematic diagram of solar greenhouse dryer

5.3 Greenhouse climate dynamic model

The following describes the heat and mass balance formulations for the Greenhouse solar green banana dryer.

1. Energy balance of the cover
2. Energy balance on the air
3. Energy balance of the product
4. Mass balance equation

5.3.1 Energy balance of the cover

Rate of accumulation of thermal energy in the cover = Rate of thermal energy transfer between the air inside the dryer and the cover due to convection + Rate of thermal energy transfer between the sky and the cover due to radiation + Rate of thermal energy transfer between the cover and ambient air due to convection + Rate of thermal energy transfer between the product and the cover due to radiation + Rate of solar radiation absorbed by the cover.

Heat energy in cover can be shown by following Eq. (equation 5.8):

$$Q_c = Q_{a,c} + Q_{c,am} + Q_{s,c} + Q_{solar} + Q_{p,c} \dots\dots\dots\dots\dots\dots\dots\dots (5.8)$$

Where:

Q_c is heat energy within drying air and cover due to convection,

$Q_{c,am}$ is energy transfer between cover and ambient air,

$Q_{s,c}$ is energy transport among atmosphere and cover owing to radiation,

Q_{solar} is heat absorbed by cover from solar insolation, and

$Q_{p,c}$ is energy exchange between drying product and cover by radiation.

This can be expressed in the form of dynamic model as follows:

$$\frac{dT_c}{dt} = \frac{1}{m_c C_{pc}}(A_c h_{c,c-a}(T_a - T_c) + A_c h_{r,c-s}(T_s - T_c) + A_c h_w(T_{am} - T_c) + A_p h_{r,p-c}(T_p - T_c) + A_c \alpha_c I_t)$$

Where:

m_c is mass of cover,

Ac is area of cover,

C_{pc} is sp. heat of collector,

T_a is drying air temperature,

T_c is cover temperature,

T_s is sky temperature,

T_p is product temperature,

T_{am} is ambient temperature,

$h_{c,c-a}$ is convective heat transfer coefficient,

$h_{r,c-s}$ is radiative heat transfer coefficient,

h_w is convection heat transfer coefficient between cover and atmosphere,

α_c is absorptivity of cover material, and It is solar insolation.

Figure 5.4 shows the simulink model of the energy balance of the cover

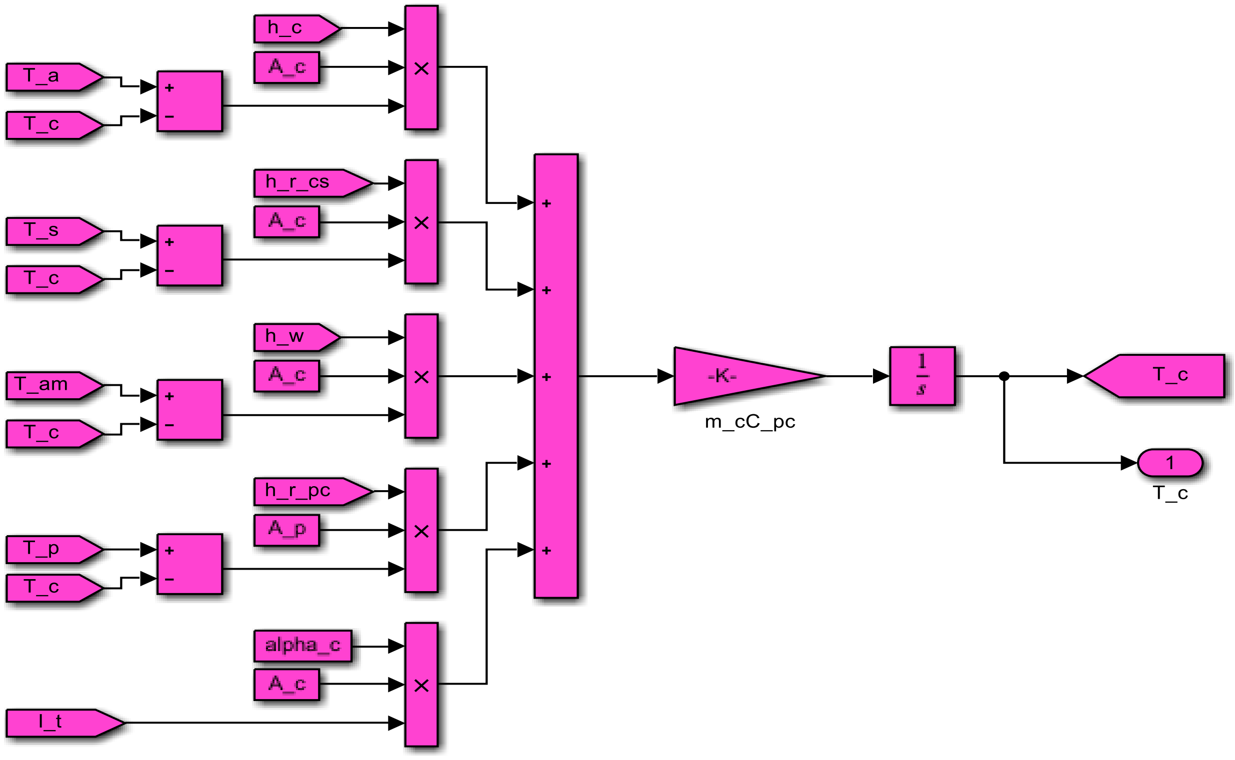


Figure 5.4: Block diagram of energy balance on the cover Simulink/Matlab

5.3.2 Energy balance of the air inside the dryer

This energy balance of the air can be written as:

[Rate of accumulation of thermal energy in the air inside the dryer]=[Rate of thermal energy transfer between the product and the air due to convection]+ [Rate of thermal energy transfer between the floor and the air due to convection]+ [Rate of thermal energy gain of the air from the product due to sensible heat transfer from the product to the air]+[Rate of thermal energy change in the air chamber due to inflow and outflow of the air in the chamber] +[Rate of overall heat loss from the air in the dryer to the ambient air]+ [Rate of solar energy accumulation inside dryer from solar radiation].

The dynamic model of energy balance in the air inside the greenhouse chambers gives:

$$\frac{dT_a}{dt} = \frac{1}{m_a C_{pa}} (A_p h_{c,p-a}(T_p - T_a) + A_f h_{c,f-a}(T_f - T_a) + A_p D_p C_{pv} q_P (T_P - T_a) \frac{dM_p}{dt} + (q_a V_{out} C_{pa} T_{out} - q_a V_{in} C_{pa} T_{in}) + U_c A_c (T_{am} - T_a) + [(1-F_p)(1 - \alpha_r) + (1 - \alpha_{p)} F_p] I_t A_c \tau_c$$

Figure 5.5 shows the block diagram of energy balance on the air

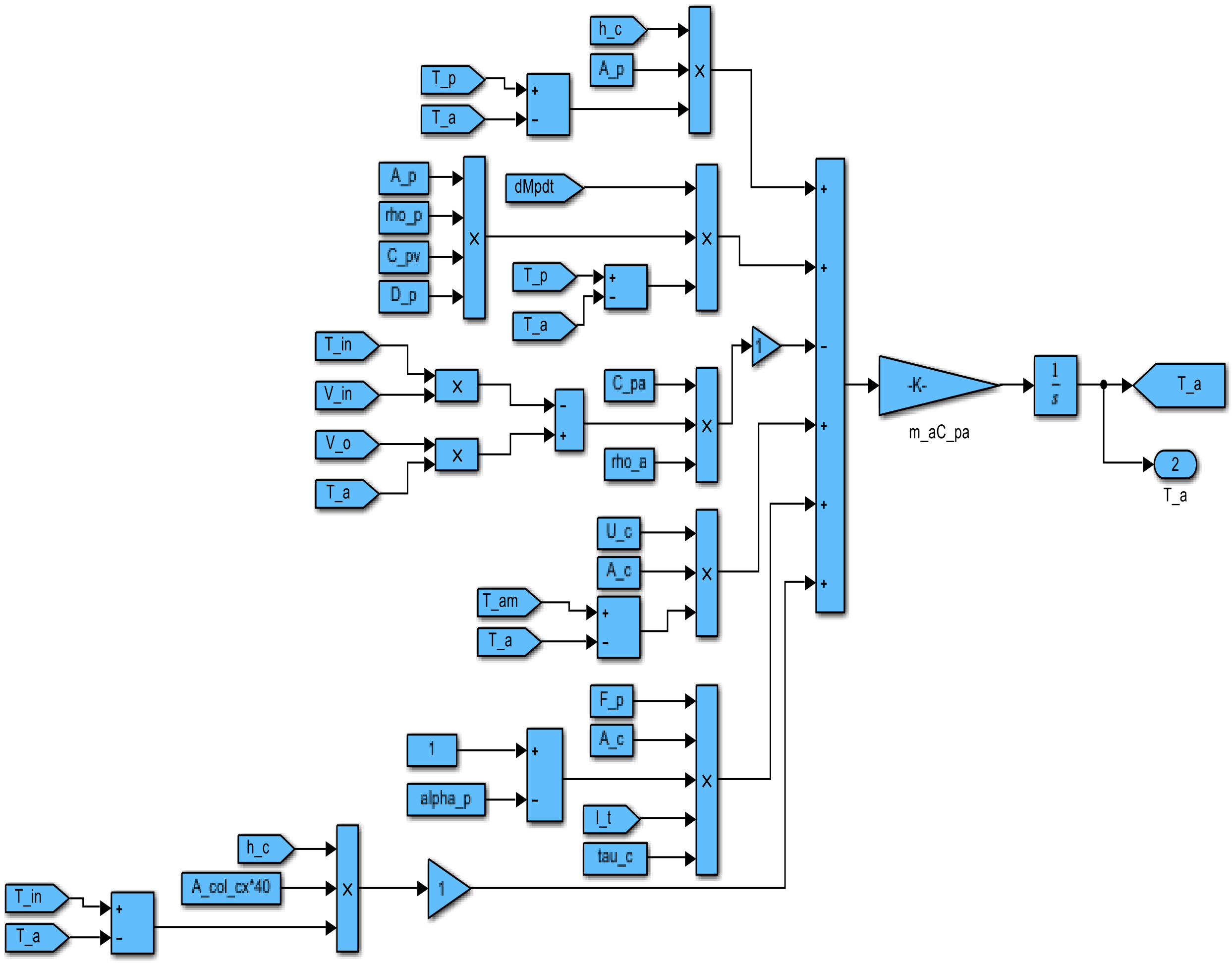


Figure 5.5: energy balance block diagram of the air Simulink/MATLAB

5.3.3 Energy balance of the product

Rate of accumulation of thermal energy in the product = Rate of thermal energy received from air by the product due to convection + Rate of thermal energy received from cover by the product due to radiation + Rate of thermal energy lost from the product due to sensible and latent heat loss from the product + Rate of thermal energy absorbed by the product.

The energy balance on the product gives:

$$\frac{dT_p}{dt} = \frac{1}{m_p\left(C_{pp} + C_{pl}M_p\right)}\left(A_p h_{c,p-a}\left(T_a - T_p\right) + A_p h_{r,p-c}\left(T_c - T_p\right)\right.$$
$$\left. + A_p D_p q_p\left[L_p + C_{pv}\left(T_p - T_a\right)\right]\frac{dM_p}{dt} + F_p \alpha_p I_t A_c \tau_c\right)$$

The following figure(Figure 5.6) shows the energy balance block diagram of the product

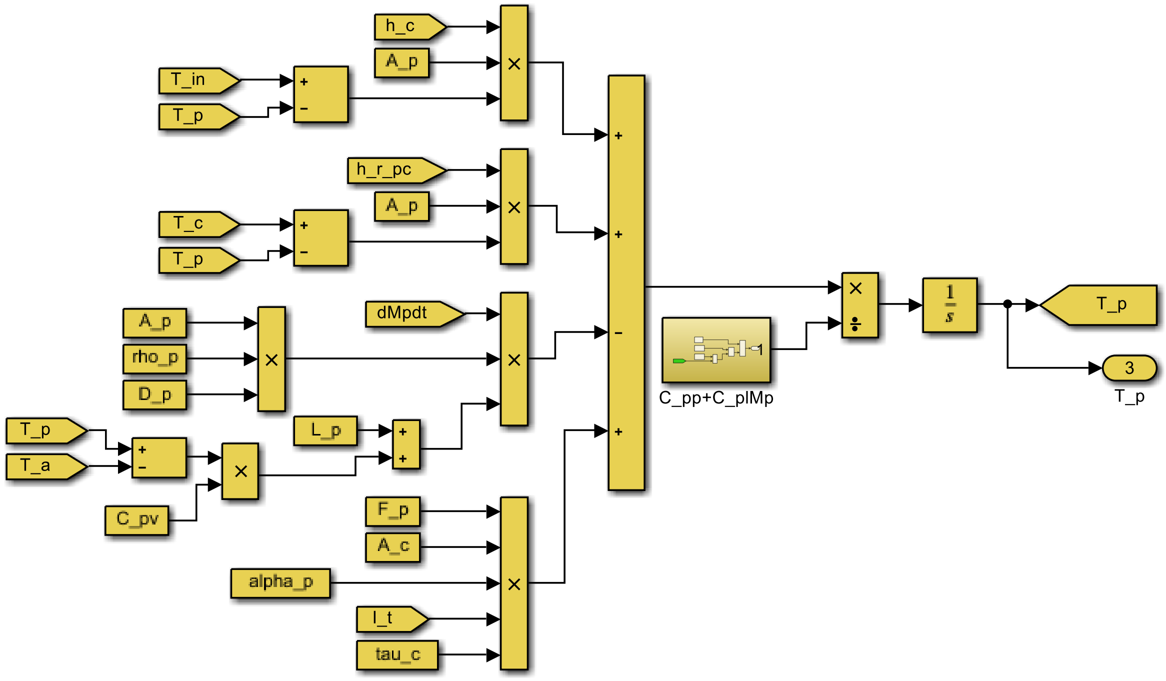


Figure 5.6: Block diagram of energy balance on the product Simulink/MATLAB

5.4 Heat Transfer and Heat Loss Coefficients

Heat transfer coefficient among cover and sky plus product and cover due to radiation is given by equations (5.9 and 5.10), respectively:

$$h_{r,c-s} = \varepsilon_C * \sigma * \left[{T_C}^2 + {T_S}^2\right] * [T_C + T_s]$$

$$h_{r,p-s} = \varepsilon_P * \sigma * \left[{T_P}^2 + {T_C}^2\right] * [T_P + T_C]$$

Where:

$h_{r,c-s}$ is radiative heat transfer from cover to sky

$h_{r,p-s}$ is radiative heat transfer coefficient between product and cover.

Convective heat transfer coefficient from the cover to atmosphere due to wind is calculated by:

$$h_W = 2.8 + 3.0 * V_W$$

Where: V_W is wind speed.

Heat transfer coefficient within the greenhouse dryer used for the cover, product, and floor is found out by using the following correlation(Prakash et al. 2014):

$h_{c,p-a}$=$h_{c,c-a} = h_c$

$$h_c = \frac{N_u k_a}{D_h}$$

$$N_u = C\ (R_a)^n$$

taking both sides on logarithm,

ln (Nu)= ln (*C*) + *n* ln (Ra),

y = *mx* + *c*, this is the linear form of the above equation, which is,

y = ln (Nu), *x*= ln (Re), *m*=*n and c* = ln (*C*)

here, C=e^c

The values of *C* and *n* are calculated in no load condition by (Prakash et al. 2014) and the values are *C*= 0.24 and *n*= 0.54

Therefore, $N_u = 0.24\ (R_a)^{0.54}$

Where, $R_a = G_r$*P_r

$R_a = \frac{g\beta(T_s-T_\infty)\delta^3}{v^2}$*$P_r$

At film temperature of 45°C, which is, $T_{film} = \frac{T_s+T_\infty}{2} = \frac{65+23.8}{2}$ = 44.4°C,

v_a: Kinematic viscosity of air = 1.75*$10^{-5} m^2$/s

k_a: Thermal conductivity of air = 0.02699w/mk

P_r: Prandtl number of air = 0.7241

Therefore, $R_a = \frac{9.8*3.15(41.25)3.5^3}{\left(1.75*\frac{10^{-5}m^2}{s}\right)^2}$*0.7

R_a = 1.7806*10^{11}

The relationship for calculating Nusselt number (Nu) is given as

$$N_u = \begin{cases} 0.59\ {R_a}^{1/4}, & 10^4 < R_a < 10^9 \\ 0.1\ {R_a}^{1/3}, & 10^9 < R_a < 10^{13} \end{cases}$$, in this case $N_u = 0.1\ {R_a}^{1/3}$

= $N_u = 0.1\ (1.7806 * 10^{11})^{1/3}$ = 562.586

$h_c = \frac{N_u k_a}{D_h} = \frac{562.59*0.02699}{\mathbf{3.5}}$

h_c= 4.34w/m^2k

Overall heat loss coefficient (U_c) from the greenhouse cover,

$$U_c = \frac{k_c}{\delta_c} = \frac{0.33w/mk}{0.00025m} = 1320\text{w}/m^2\text{k}$$

Where, δ_c is thickness of cover of greenhouse, and Kc refers to thermal conductivity of insulation used.

Overall heat loss coefficient ($U_{c-\text{col}}$) from the collector glass cover,

$$U_{c-\text{col}} = \frac{k_{c-glass}}{\delta_{c-glass}} = \frac{0.8w/mk}{0.004m} = 200\text{w}/m^2\text{k}$$

5.5 Thin layer drying model selection for banana slice

Thin layer equations describe the drying phenomena in a unified way, regardless of the controlling mechanism. They have been used to estimate drying times of several products and to generalize drying curves.

To obtain the thin layer drying equation of banana slice, many researchers have made experiments under controlled condition of temperature and relative humidity in order to choose the best curve in which one gives the maximum evaporation of the moisture content with minimum amount of time(Fadhel et al. 2011, Omolola et al. 2014, Olawoye et al. 2017).

According to the experiment done by (Olawoye et al. 2017), Twelve thin-layer drying models were fitted to the drying curves so as to select the best model suitable for describing the drying curve of Cardaba banana. The models are presented in the Table 5.1 below.

Table 5.1 Thin layer drying models

Model No.	**Model name**	**Model name**	**Reference**
1	Lewis	MR = exp(−kt)	El-Beltagy, Gamea, and Essa (2007)
2	Page	MR= exp(−kt^n)	Akoy (2014)
3	Henderson and Pabis	MR = a exp(−kt^n)	Meisami-asl, Rafiee, Keyhani, and Tabatabaeefar (2010)
4	Modified page I	MR = exp[−(kt)^n)]	Vega, Uribe, Lemus, and Miranda(2007)
5	Modified page II	MR = k· exp$(-t/d^2)^n$	Praveen Kumar, Hebbar, and Ramesh (2006)
6	Wang and Singh	MR = 1 + at + bt^2	Omolola et al. (2014)
7	Balbay and Sahin	MR = (1 − a) · exp (−kt^n) + b	Balbay and Şahin (2012)
8	Hasibuan and Daud	MR = 1 − at^n · exp(−kt^n)	Ertekin and Heybeli (2014)
9	Two term	MR = a · exp(−kt) + b. exp(kt)	Sacilik (2007)
10	Two-term exponential	MR = a · exp(−kt) + (1 − a) Exp (k.a.t)	Dash, Gope, Sethi, and Doloi (2013)
11	Verma et al.	MR = a a · exp(−kt) + (1 − a) exp(−gt)	Akpinar(2006)
12	Modified Henderson and Pabis	MR = a · exp(−kt) + b · exp(−gt) + c exp (−ht)	Zenoozian, Feng, Razavi, Shahidi, and Pourreza (2008)

(Olawoye et al. 2017)

Similarly, (Fadhel et al. 2011) done Eight different thin layer drying models. Based on nonlinear regression analysis the goodness of fit was determined using three parameters: coefficient of determination (R^2), reduced chi-square χ^2, and root mean square error (RMSE), the equations are as shown below,

$$R^2 = \frac{\sum_{i=1}^{n}(MR_i - MR_{pre,j}) \times (MR_i - MR_{exp,j})}{[[\sum_{i=1}^{n}(MR_i - MR_{pre,j})^2] \times [\sum_{i=1}^{n}(MR_i - MR_{pre,j})^2]]^{1/2}}$$

$$X^2 = \frac{\sum_{i=1}^{N}(MR_{exp,j} - MR_{pre,j})^2}{N - n}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2}$$

A statistical software package was used in the analysis of the raw data obtained from the drying experiments were analyzed using the values of the parameters a, n and the constant k for the models determined. Higher values of (R^2) and lower values of chi-square (X^2) and RMSE indicate better goodness of fit.

According to the experimental results of (Olawoye et al. 2017) , the model that best fit the experimental data was Wang and Singh model with $R2$ = 0.9953, RMSE = 0.0223 and $\chi2$ = 4.94 × 10−4 and the constants and factors of Wang and Singh model (a = −0.1331, b = 0.0058). These findings agreed to previous study reported by,(Fadhel et al. 2011, Omolola et al. 2014) . Therefore, the moisture ratio of the Cardaba banana slices at different stages of drying could be predicted successfully using the following equation.

$$\text{MR} = 1 + a\,t + bt^2$$

$$\text{MR} = 1 + -0.133063943473219\ t \times + 5.75534338743906\text{E-}03 \times t^2$$

The curve of Wang and Singh model can be shown using Matlab software at (t= 6 hrs.) in Figure 5.5 shown below.

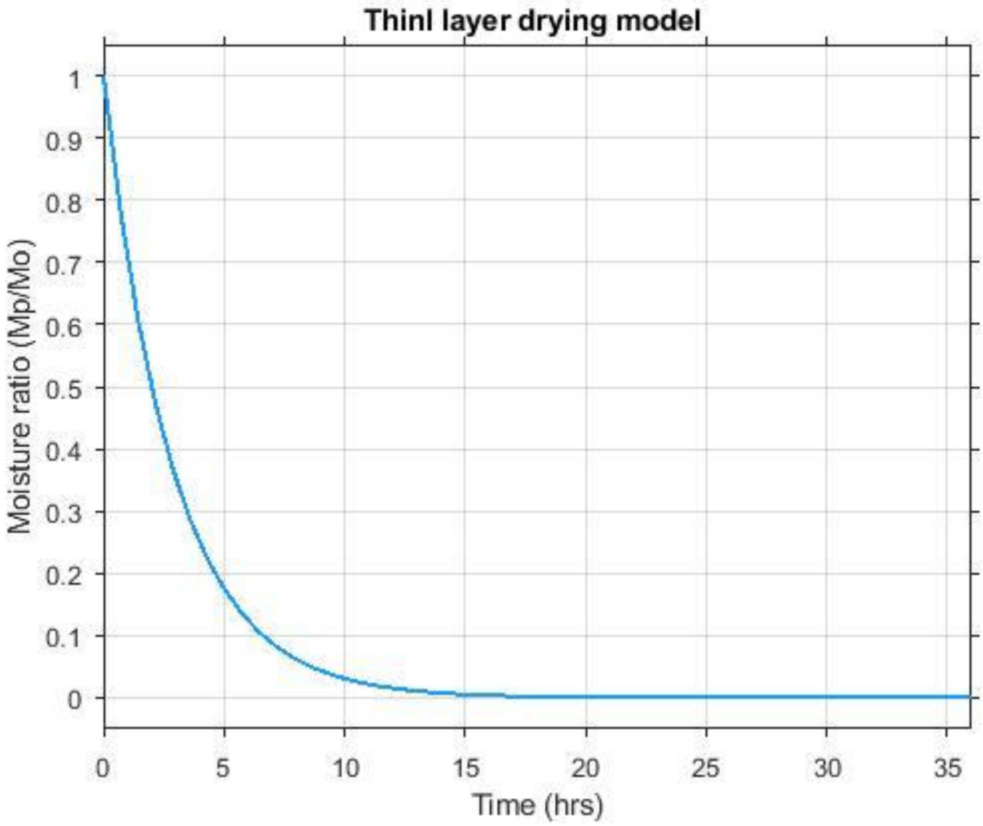


Figure 5.7: Wang and Singh drying rate equation

5.6 Mass balance equation

The accumulation rate of moisture in the air inside dryer = Rate of moisture inflow into the dryer due to entry of ambient air -Rate of moisture outflow from the dryer due to exit of air from the dryer + Rate of moisture removed from the product inside the dryer.

The dynamic model of mass balance inside dryer chamber gives:

$$q_a V \frac{dH}{dt} = q_a H_{in} V_{in} - q_a H_{out} V_{out} + A_p D_p q_p \frac{dM_p}{dt}$$

Below shows the Simulink model for the above formulation (figure 5.6):

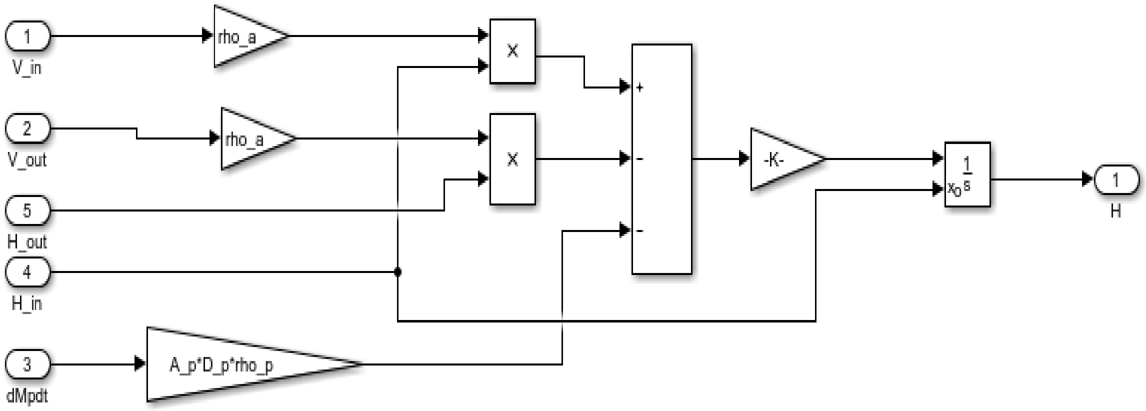


Figure 5.8: Simulink model for mass balance equation

The MATLAB/Simulink model of the GHDSAH is shown below on figure (5.7)

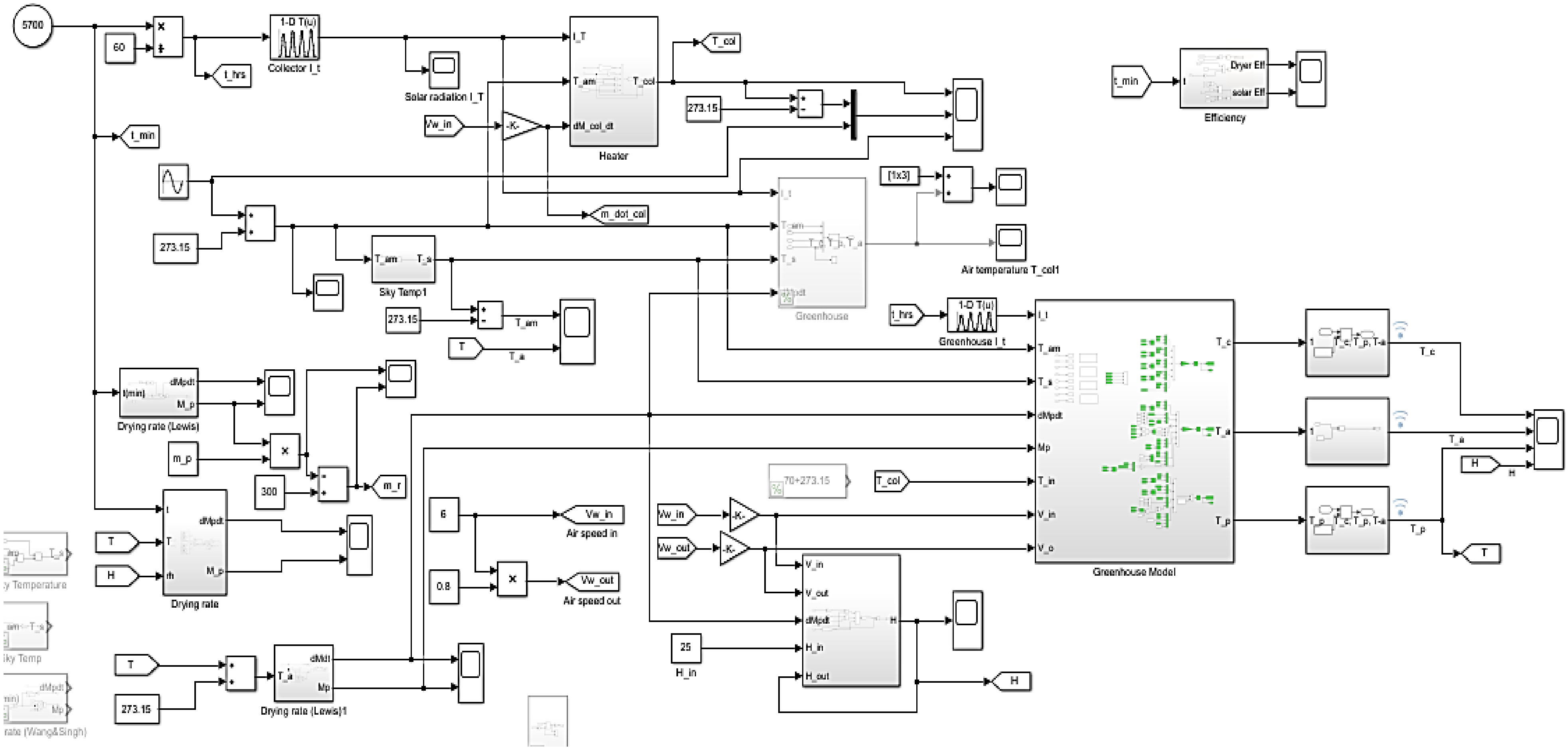


Figure 5.9: Simulink model of Greenhouse dryer with Solar air heater

CHAPTER 6:
RESULT AND DISCUSSION

This section clearly describes the results found from the design parameters and the mathematical formulations of the previous chapters. Simulation was carried out using MATLAB/Simulink for drying of green banana slices for the coldest month of the year from weather data of Arbaminch, which is month of July. This selection of month is performed in order to see the lowest performance of the dryer and to be able to conclude for the rest of the months that the performance of the dryer can be much higher than that of the drying month of July. Four consecutive days were selected for the simulation, from July 2 to July 5. Typical results for drying of green banana are shown from Figure 6.1 to Figure 6.9). Solar radiation varied from 0 w/ m^2 to 1000 w/ m^2 during this drying period considering 24 hours or 1440 min. The solar radiation data was taken from website to get hourly variation, taking for 2020 year of solar radiation data for month of July (CAMS Radiation Service December 2020).

6.1 Simulation results of solar air collector

Figure 6.1 shows the solar radiation of Arbaminch for month of July within four consecutive days for the collector and for the greenhouse. The collector is tilted with 21^o from the ground. As the figure shows, the solar radiation reaches its peak at the mid time of the day for both of the collector and greenhouse, which is in between 800-1000 w/m^2 having similar pattern. It is clearly shown that the solar radiation increases rapidly from morning until it reaches the middle of the day and decreases as the time went to sun set. However, the overall patterns in solar radiation were sinusoidal with a sharp peak at noon. The greenhouse capacity of solar radiation absorption is greater than that of the solar collector, this is due to the area of the greenhouse is greater than the collector area.

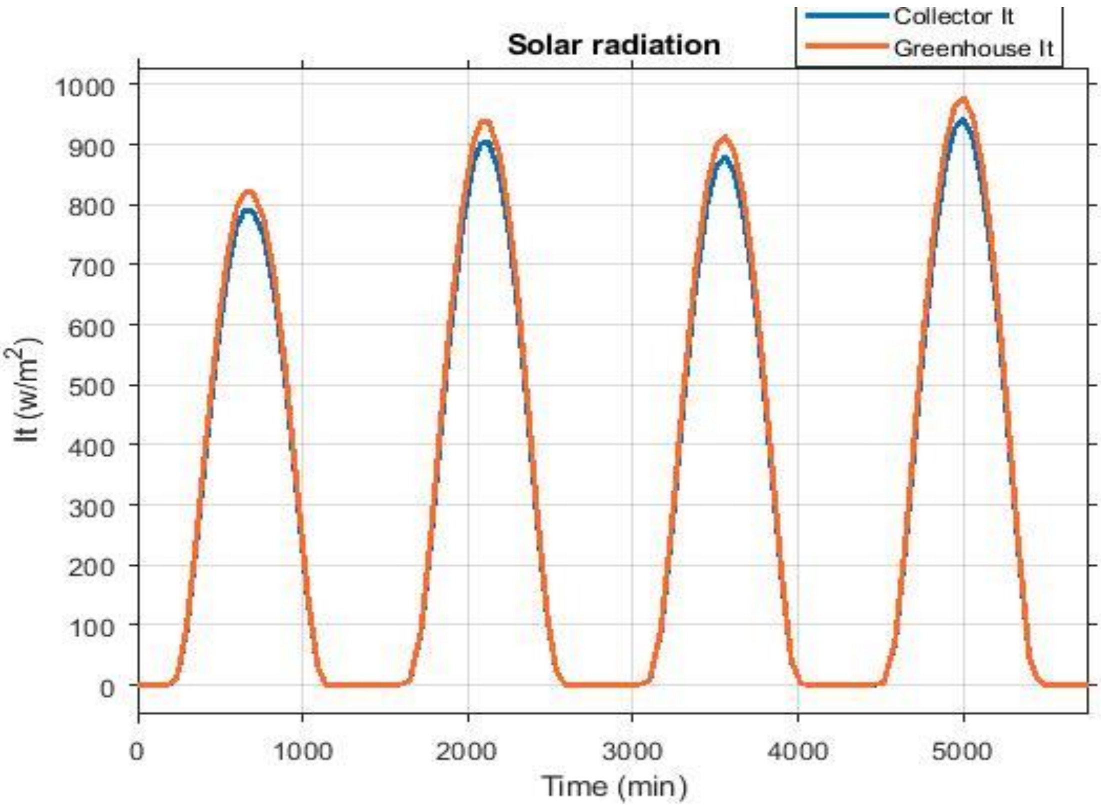


Figure 6.1: Variation of Solar radiation with Time from July 2 to July 5 of year 2020

Figure 6.2 shows, comparison of the solar collector outlet temperature with ambient temperature. The ambient temperature varies from 19℃ to 33℃ throughout the day for the simulation period reaching its peak at noon, where solar radiation reaches its maximum. The collector output temperature shows a big difference from the ambient air temperature, for each days of the simulation period. The difference of the temperature showed double the size of the ambient temperature. The solar air collector outlet temperature reached from 60℃ to 65℃ during the simulation period. This result was higher outputs than that of the research made by (Djebli et al. 2019) in which they made mixed mode dryer and has found the solar heat collector average temperature of 50 °C at the entrance of the greenhouse using two fans.

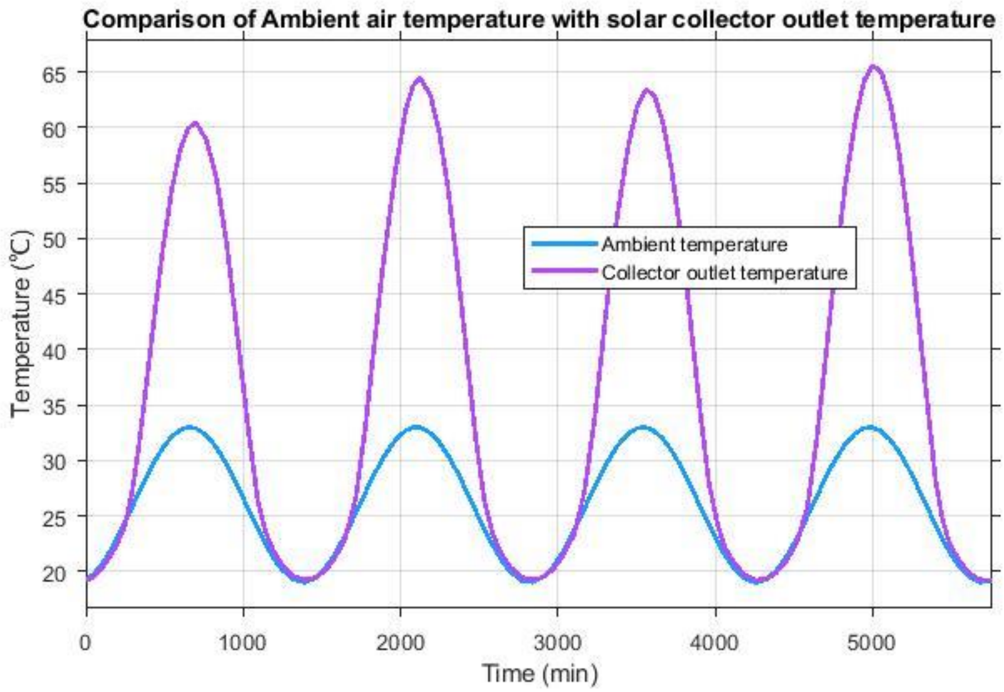


Figure 6.2: Solar air collector output temperature and ambient air temperature with time graph

6.1.1 Effect of wind speed on the outlet temperature of the solar air collector

Wind speed of the ambient air has effect on temperature of the solar air collector as well as the greenhouse inside temperatures. Figure 6.3 describes the variation of solar collector temperature compared with ambient temperature at different wind speeds for month of July. It is clearly seen that, as wind speed increases, the temperature gain inside the solar collector decreases. For example, for July 2, when V_{in} = 0.3m/s, Tout = 80℃, at V_{in} = 0.65m/s, Tout = 60 ℃, at V_{in} = 2m/s, Tout = 43℃ and at V_{in} = 6m/s, Tout = 35℃. This explains how sharply the output temperature decreases with increase of wind speed. This result can be compared with that of the result obtained by and it shows the same effect of windspeed on outlet air temperature. It is also noticed that, the solar collector temperature has significant temperature raise from the ambient air temperature.

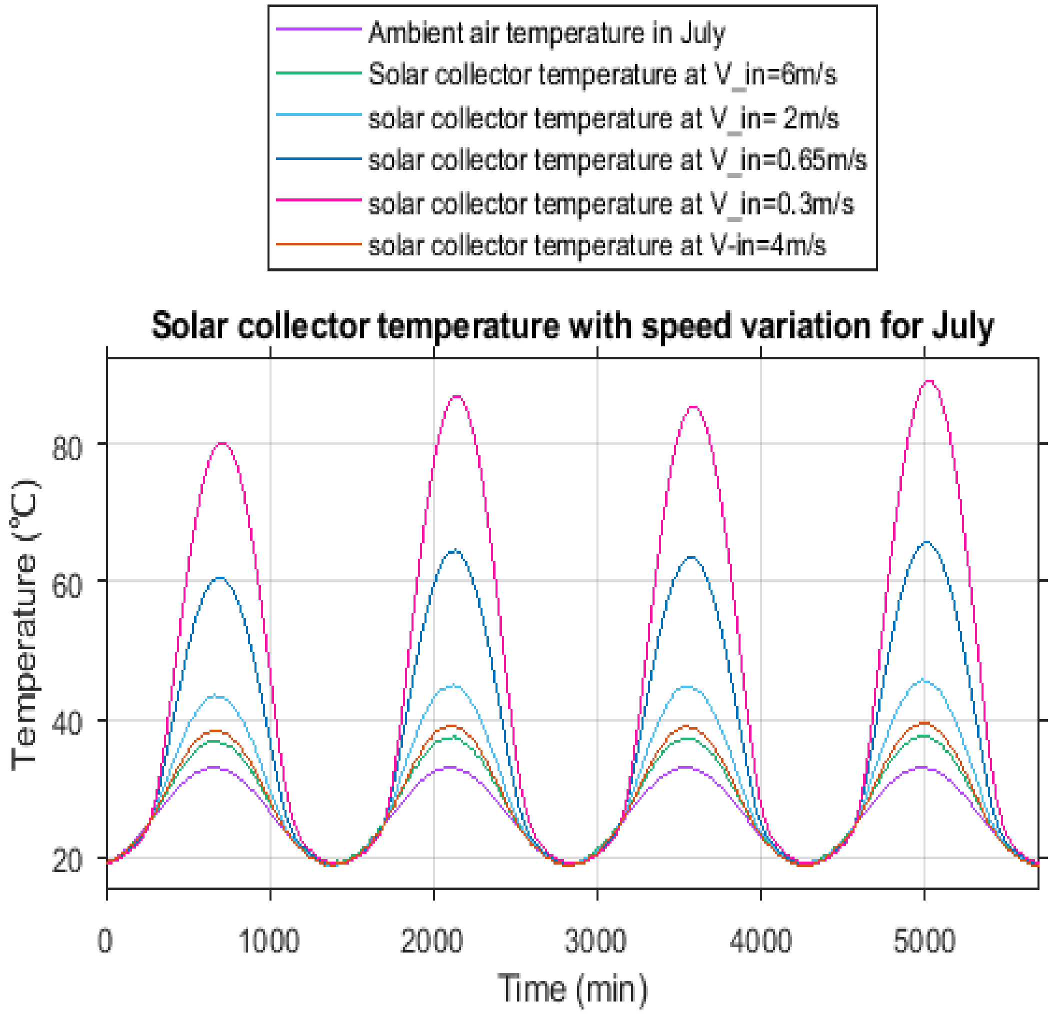


Figure 6.3: Solar air collector output temperature with different wind speeds vs time graph

6.2 Simulation results of greenhouse dryer

Figure 6.4 to figure 6.7 shows the greenhouse inside temperatures with the presence of solar air collector and without solar collector. The cover temperature has a large amount of temperature from that of the product temperature as well as that of air temperature. This is due to the fact that the cover gains direct solar radiation. The product temperature is also higher than that of air temperature. This is due to the solar air heater output temperature directly heats the product and then heat will be exchanged from the product to the inside air temperature.

Figure 6.4 shows that greenhouse air temperature falls at night and it starts to climb to its maximum value at the middle of the day and it reaches around 34℃. And then it starts to fall back until the next day comes. This is similar with all the drying periods. Here, it is noticeable that the existence of the solar collector has a very low significance for the air temperature inside the greenhouse.

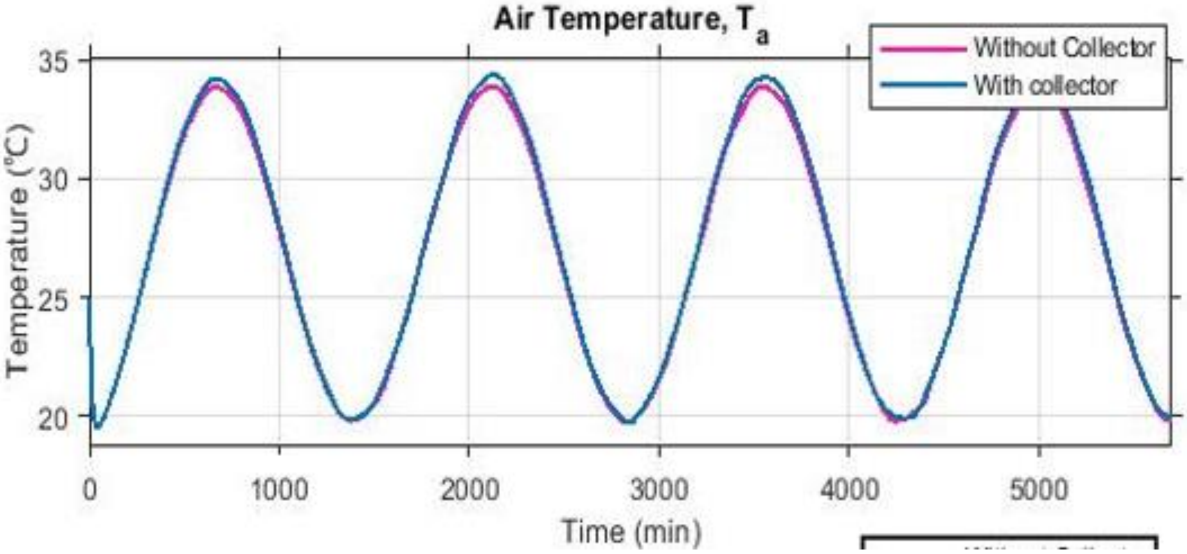


Figure 6.4: Air temperature vs time graph with and without solar collector

Figure 6.5 explains the effect of solar air collector output temperature on the product temperature inside the greenhouse. Here, significant amount of temperature difference is noticed with collector and without collector. The product temperature starts to increase slowly at first and increases until the mid-time of the day. The temperature difference can reach up to 8°C with collector than without air collector and the temperature of the product is higher with 22°C than the ambient temperature. Similar results were found by(Janjai 2012, Olawoye et al. 2017, Djebli et al. 2019)Therefore, the presence of solar air collector contributes significant amount of temperature for the greenhouse temperatures. As we have seen all the temperature lines have similar pattern with the solar radiation, when there is rise in solar radiation, the temperatures will also increase and when solar radiation falls all the temperatures falls to the ambient temperature.

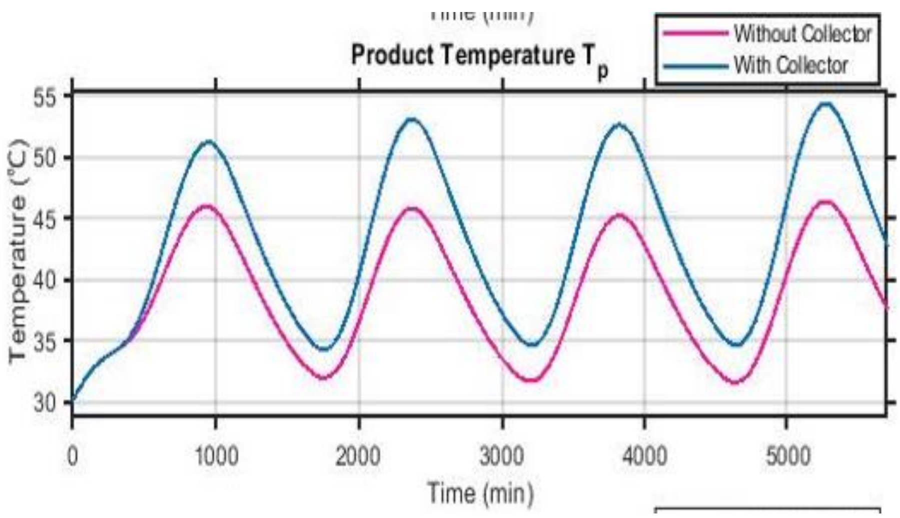


Figure 6.5: Product temperature vs time graph with and without solar collector

Figure 6.6 shows the greenhouse plastic cover temperature and the variation of the temperature due to the existence of the solar collector. As it is clearly shown that the air collector has no significance change for the cover.

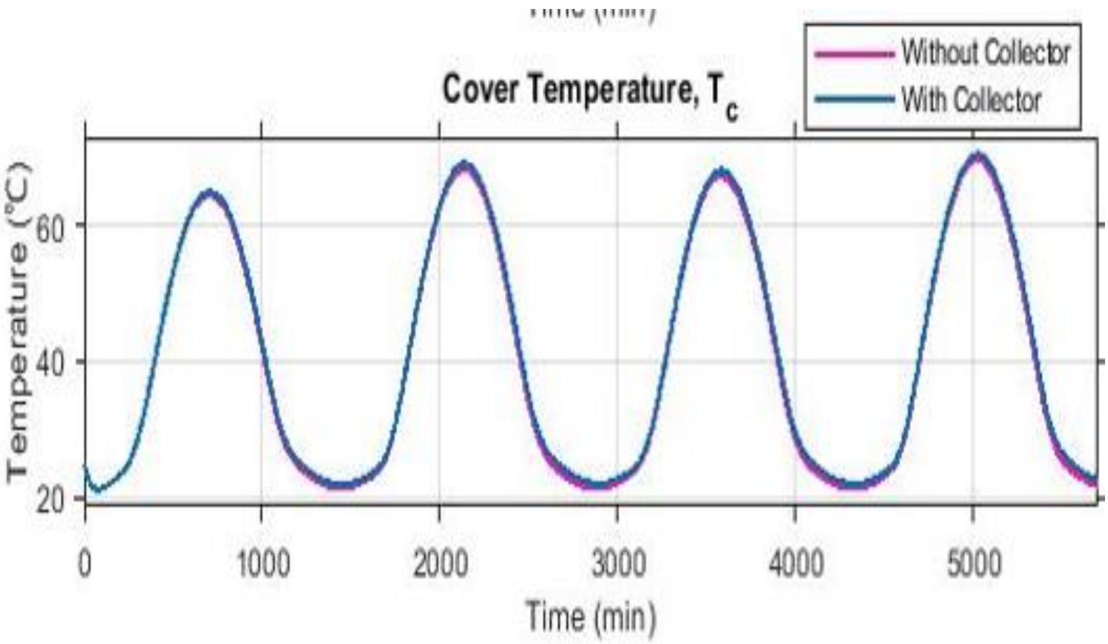


Figure 6.6: Cover temperature vs time graph with and without solar collector

Figure 6.7 clearly describes the comparison of greenhouse temperatures with ambient temperature. The cover temperature is the highest of all the temperatures. The most important temperature among all the temperatures for the drying purpose is that of the product temperature. This results were validated with articles published by (Janjai et al. 2009, Tiwari et al. 2016) having similar temperature rise of the product temperature compared with the ambient temperature.

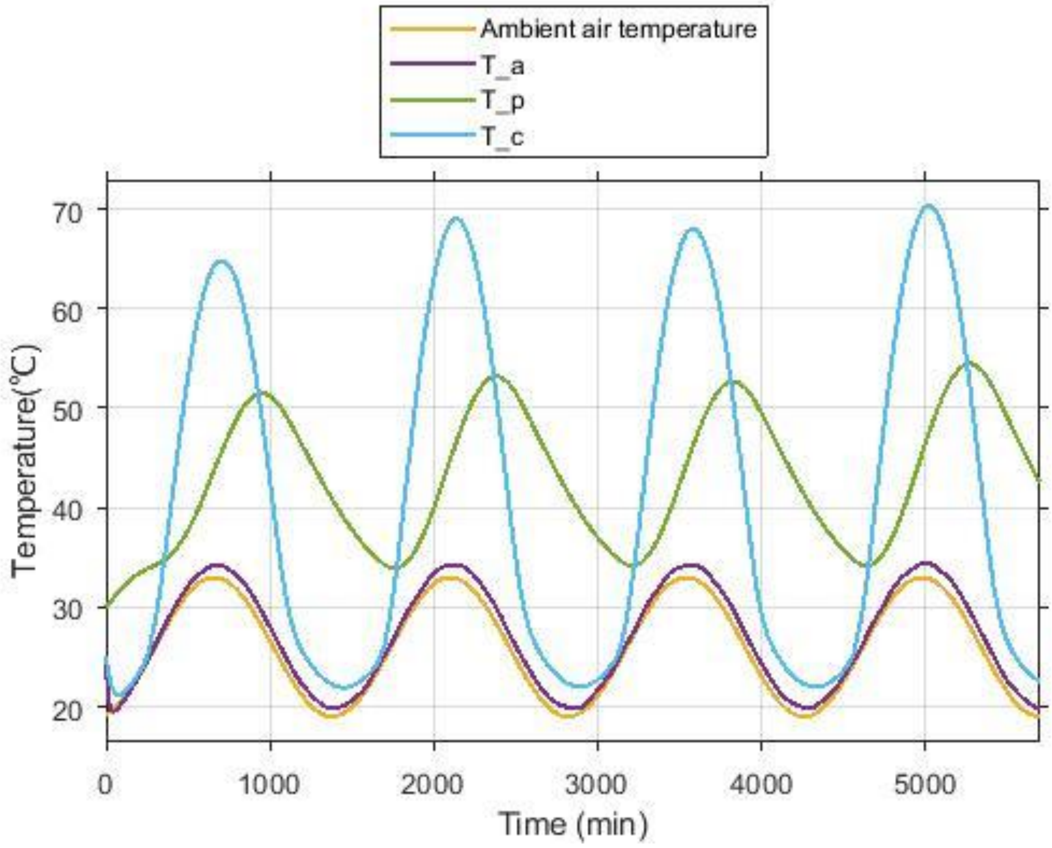


Figure 6.7: Temperature vs time graph of greenhouse temperatures

6.2.1 Effect of wind speed on drying inside the greenhouse temperatures

Figure 6.8 explains the effect of wind speed on the temperatures inside the greenhouse. Wind speed which is directly inters from the solar collector to the greenhouse has effect on the temperatures of the greenhouse. For the air temperature the increase of wind speed increases the temperature of the air inside the greenhouse. However, the effect of wind speed is inversely related with that of the product temperature inside the greenhouse, which is as the wind speed increases from 0.65m/s to 6m/s, the temperature of the product decreases from 53℃ to 46℃.

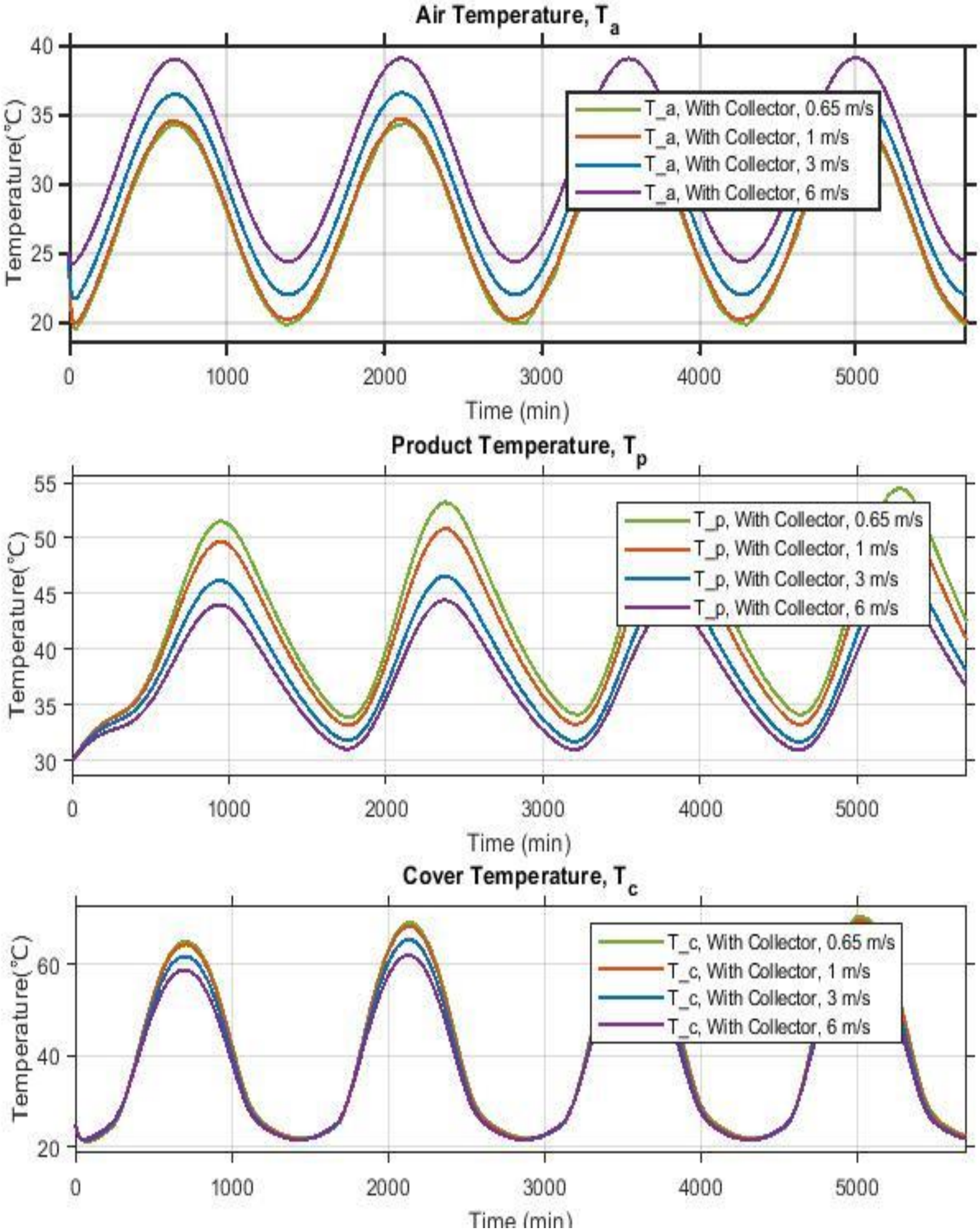


Figure 6.8 Greenhouse temperature vs time graph with different wind speed

6.3 Drying rates and moisture removal results of the greenhouse dryer

Figure 6.9 shows moisture ratio with in the period of drying simulation with the effect of solar air collector presence and with variation of air speed. As the graph shows, the moisture ratio sharply decreases from 1.58% (db) to 0.1% (db) within the first two days and then it starts to decrease slowly for the next days this is because of the decrease of moisture ratio is fast due to easy separation of free water. This result were compared with that of the research on tomato drying by(Djebli et al. 2019) and shows similar pattern of moisture content reduction.in addition, the moisture content decreases faster with the presence of solar air collector.

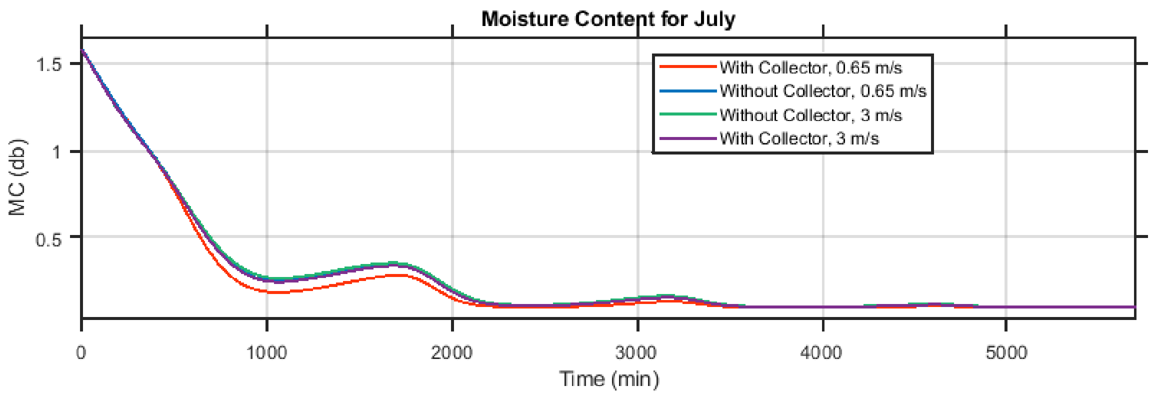


Figure 6.9 Moisture ratio vs time graph

Figure 6.10 shows humidity ratio of air inside the greenhouse dryer during solar drying of banana. Humidity ratio increases over time during the first day and it starts to get constant at 31%. The speed variation has significant change with the humidity gain of the air, which is, at speed equals 3m/s the humidity ratio starts to climb dramatically and at speed of wind equals 0.65m/s the humidity gain of the air is slower.

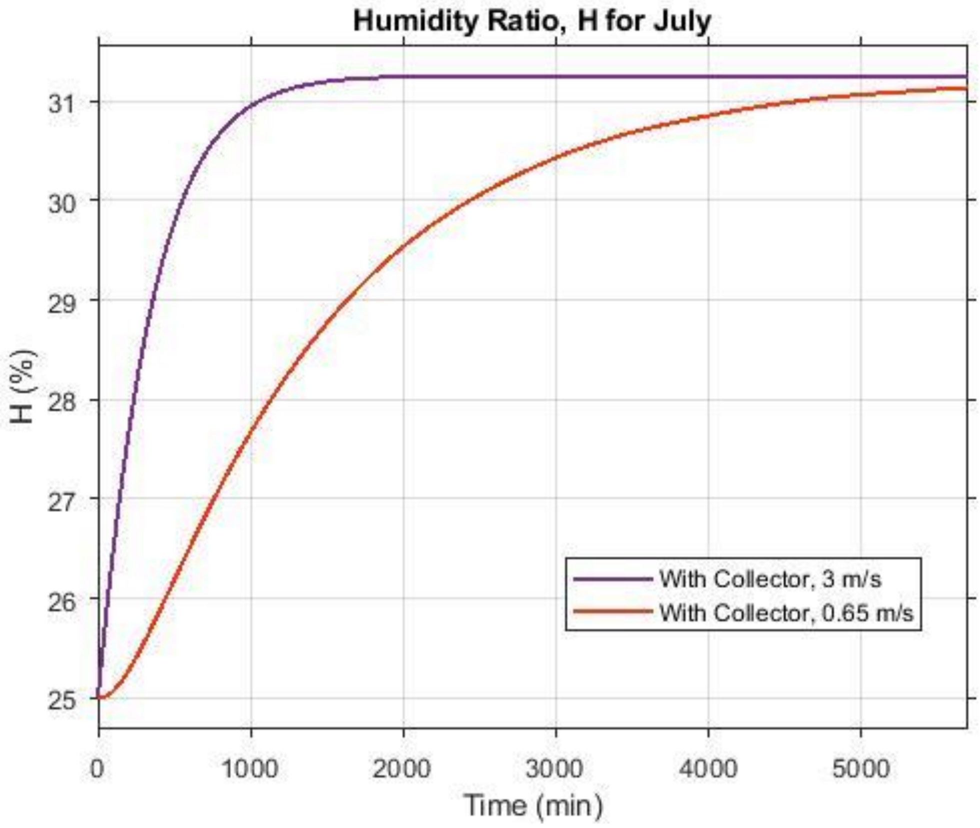


Figure 6.10: Humidity ratio vs time graph

CHAPTER 7:
CONCLUSION AND RECOMMENDATION

7.1 Conclusion

In this study, a system of partial differential equations for heat and mass balance has been used and some model modification was done for the addition of solar air heater with the greenhouse models for solar drying of green banana in order to demonstrate the drying performance of the greenhouse solar dryer. System components were designed and sized based on per-determined capacity of the system. Numerical simulation was conducted for both the GHSD and SAC using MATLAB/Simulink software for the simulation of the model developed. Comparative study was conducted for the GHSD with and without SAC. Effects of wind speed on the drying temperatures inside GHSD was also investigated. Humidity ratio of the air inside the GHSD was determined and drying rate of the product with the loss of moisture content of the product was demonstrated according to the selected thin layer drying model.

Simulation results demonstrated the potential of the designed solar greenhouse solar dryer with air heater for the solar drying of green banana. Solar radiation varies in a small variation during the selected simulation days. There by, the temperature in the greenhouse and solar collector follows the exact pattern of the solar radiation reaching peak value at noon. This means solar radiation value has high effect on the temperature variation. The collector tilt angle also shows a slight increment of temperature out puts compared with the horizontal solar radiation received by the greenhouse which is maximum solar radiation for inclind surface was aroun 990 W/m² while solar radiation on horizontal surface reaches 960 W/m².

Solar drying of green banana in solar greenhouse dryer resulted in substantial reductions in drying time as compared with the open-air sun drying as well as greenhouse solar dryers with no solar air heater. The drying time reduced from 4-5 days in open-sun drying to 3 days with the solar greenhouse dryer with air heater.

The solar air collector temperature has significant temperature rise from the ambient air temperature which is when maximum ambient air temperature reaches 33℃, solar air collector output was 65℃. Wind speed of the ambient air also has a significant temperature difference in which the rise of air speed reduces the temperature output of the collector.

A significant temperature difference has been shown inside greenhouse dryer compared with the ambient air temperature. The result showed that the maximum air temperature, maximum product temperature, and maximum cover temperature, without and with solar air collector are found to be 33℃, 46℃, and 78℃ and, 34℃, 54℃, and 79℃ ,respectively at maximum ambient air temperature of 32℃.

Natural convection system of the greenhouse solar dryer and the solar air collector makes drying to be possible for small scale projects with no power consumption as well as for large scale drying for factories with reduced investment cost. This model can be used for developing of such dryers using the design data provided and optimization can be possible.

7.2 Recommendation

Solar dryers can provide a solution to reduce consumption of electricity and bio-fuels. Dried fruit and vegetable productions can benefit the economy of Ethiopia, if further investigation of solar dryers with low investment cost can be achieved. Some of the suggested future works include:

- Solar radiation must be measured with cloudy sky to be able to measure the real value.
- Greenhouse inside temperatures can be controlled for best design of the solar greenhouse solar drier.
- The designed greenhouse solar drier can be experimentally investigated for further validation of its performance.

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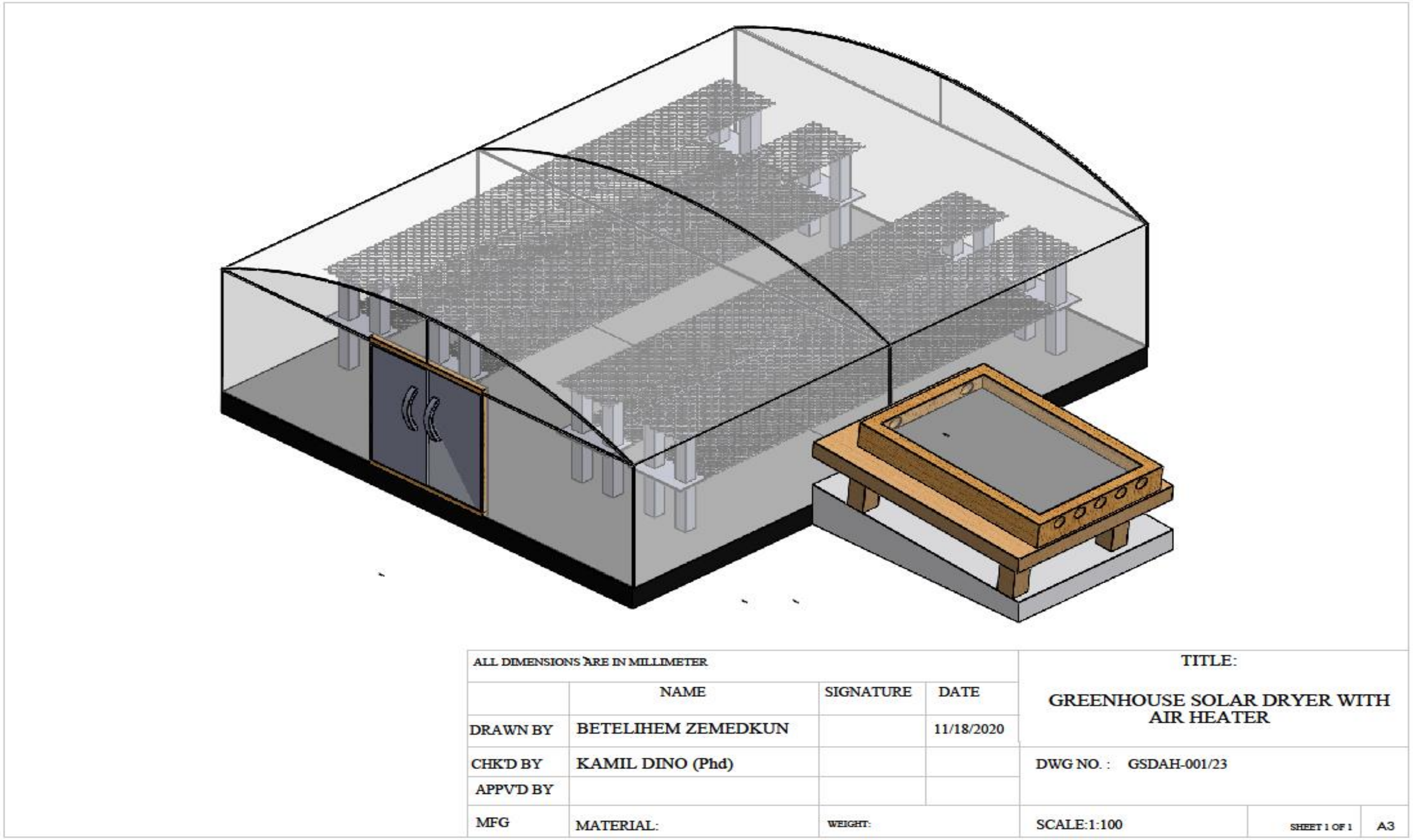
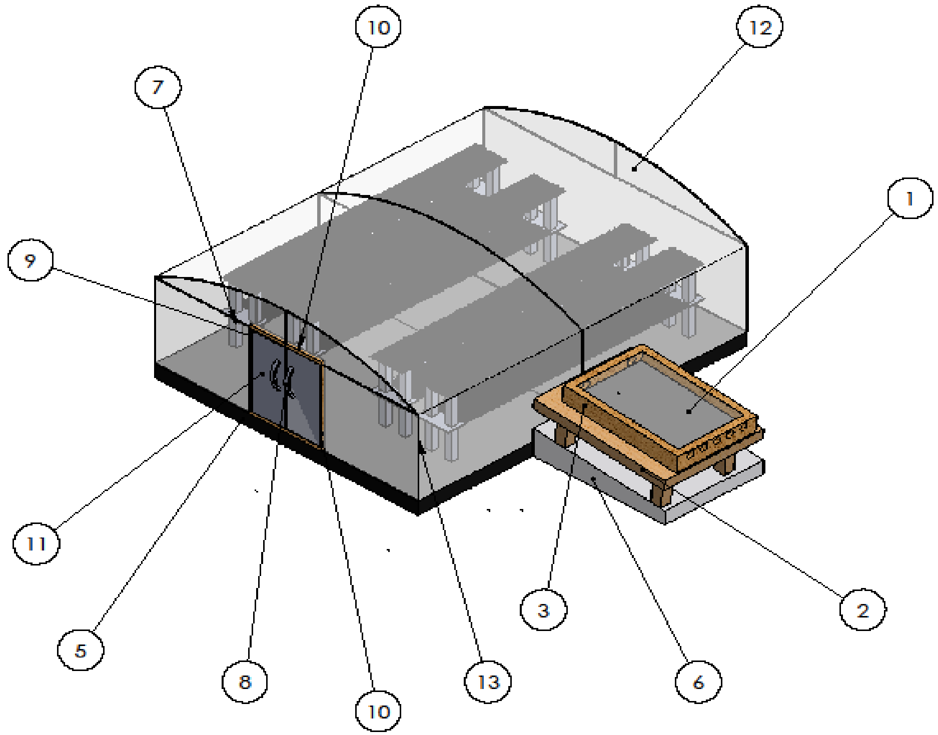
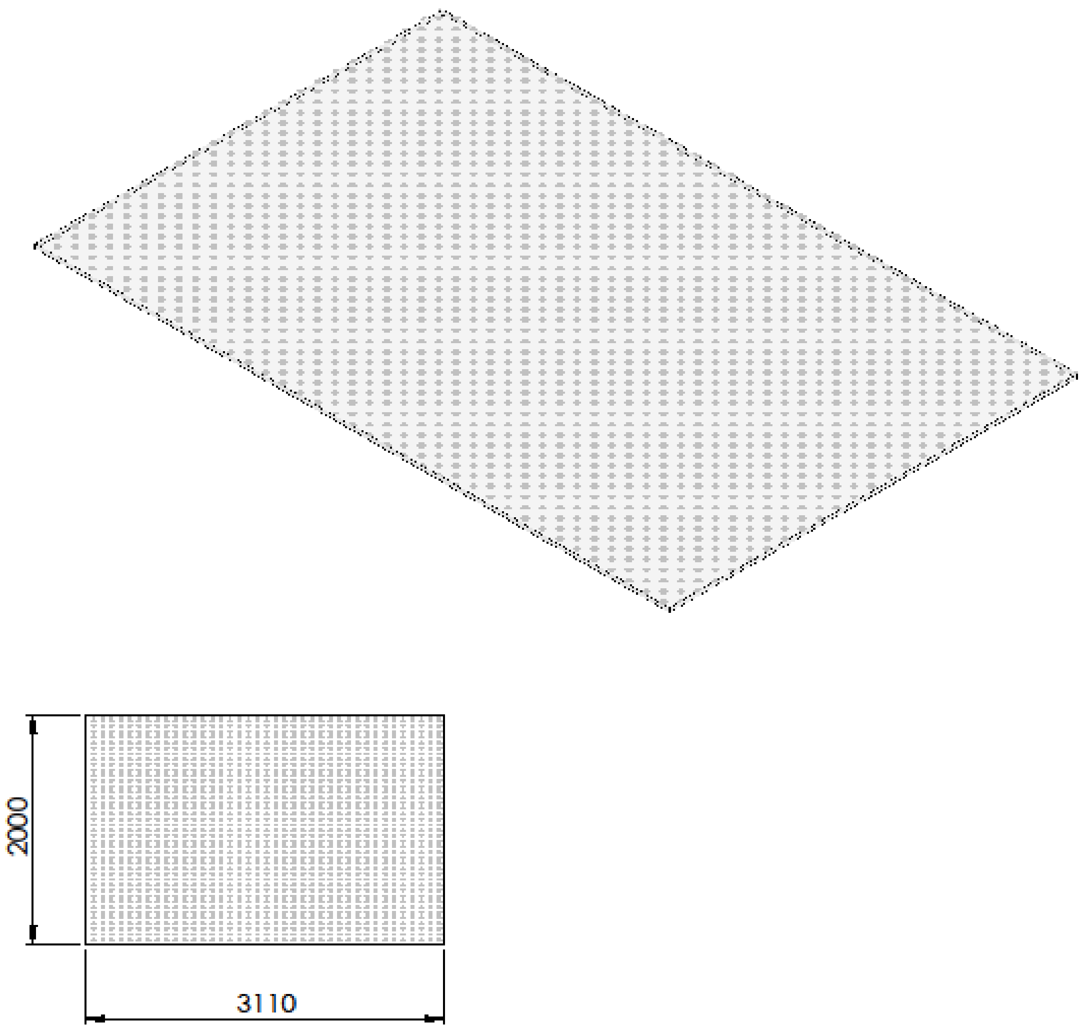
APPENDIX A : Manufacturing drawings of greenhouse solar dryer with air heat



NO.	DESCRIPTION	DWG. NUMBER	QTY.
1	Glass cover	GSDAH-003/23	1
2	Table	GSDAH-004/23	1
3	Heater Frame	GSDAH-005/23	1
4	Absorber	GSDAH-006/23	1
5	Black painted cement floor	GSDAH-007/23	1
6	Cement stand	GSDAH-008/23	1
7	Tray	GSDAH-009/23	4
8	Door handle	GSDAH-010/23	2
9	Hinge Assembly	GSDAH-013/23	10
10	Door frame Assembly	GSDAH-016/23	1
11	DOOR	GSDAH-017/23	2
12	Plastic shade Assembly	GSDAH-022/23	1
13	steel structure	GSDAH-023/23	3

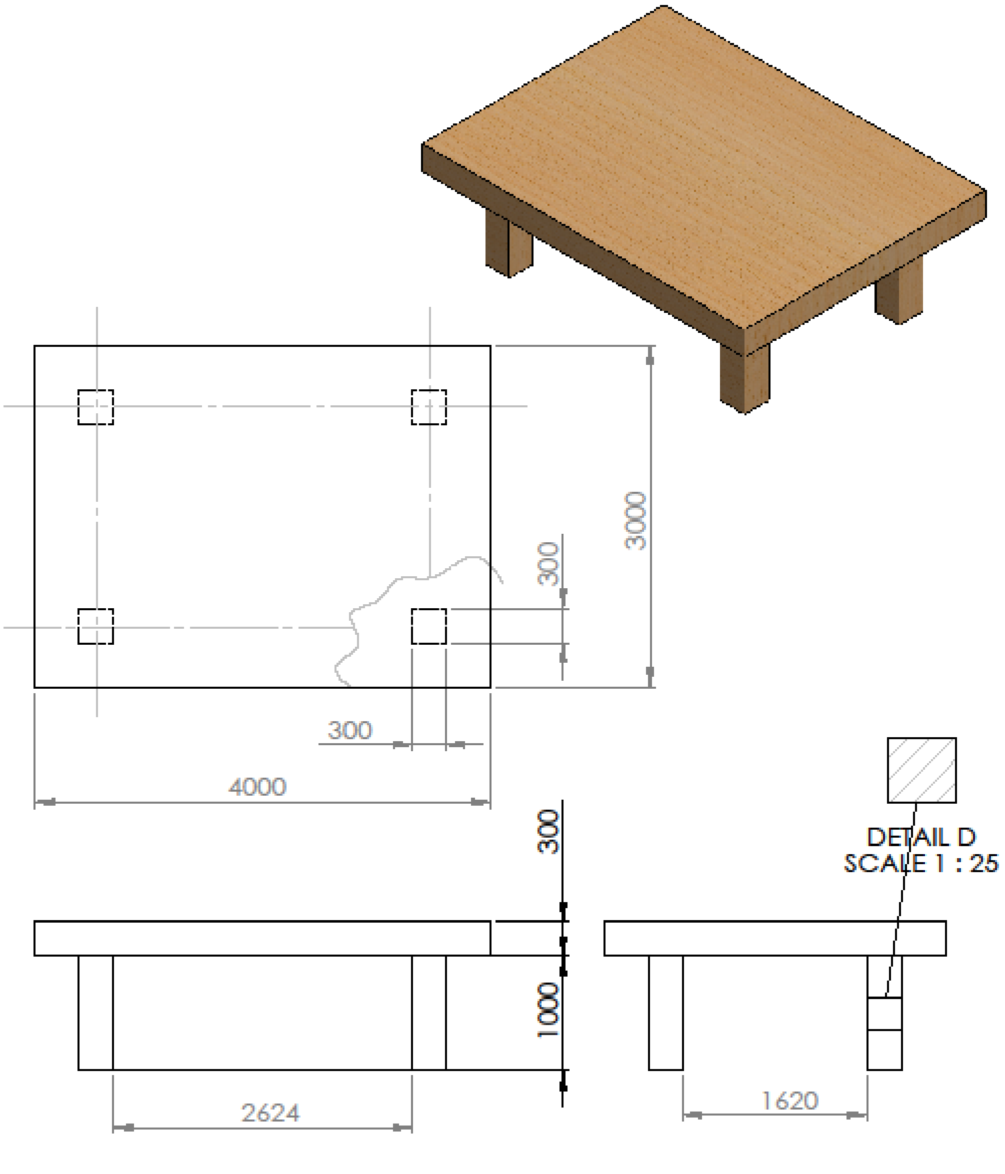


ALL DIMENSIONS ARE IN MILLIMETER				TITLE: GREENHOUSE SOLAR DRYER WITH AIR HEATER
	NAME	SIGNATURE	DATE	
DRAWN BY	BETELIHEM ZEMEDKUN		11/18/2020	
CHK'D BY	KAMIL DINO (Phd)			DWG NO. : GSDAH-002/23
APPV'D BY				
MFG	MATERIAL:	WEIGHT:		SCALE:1:100 SHEET 1 OF 2 A3

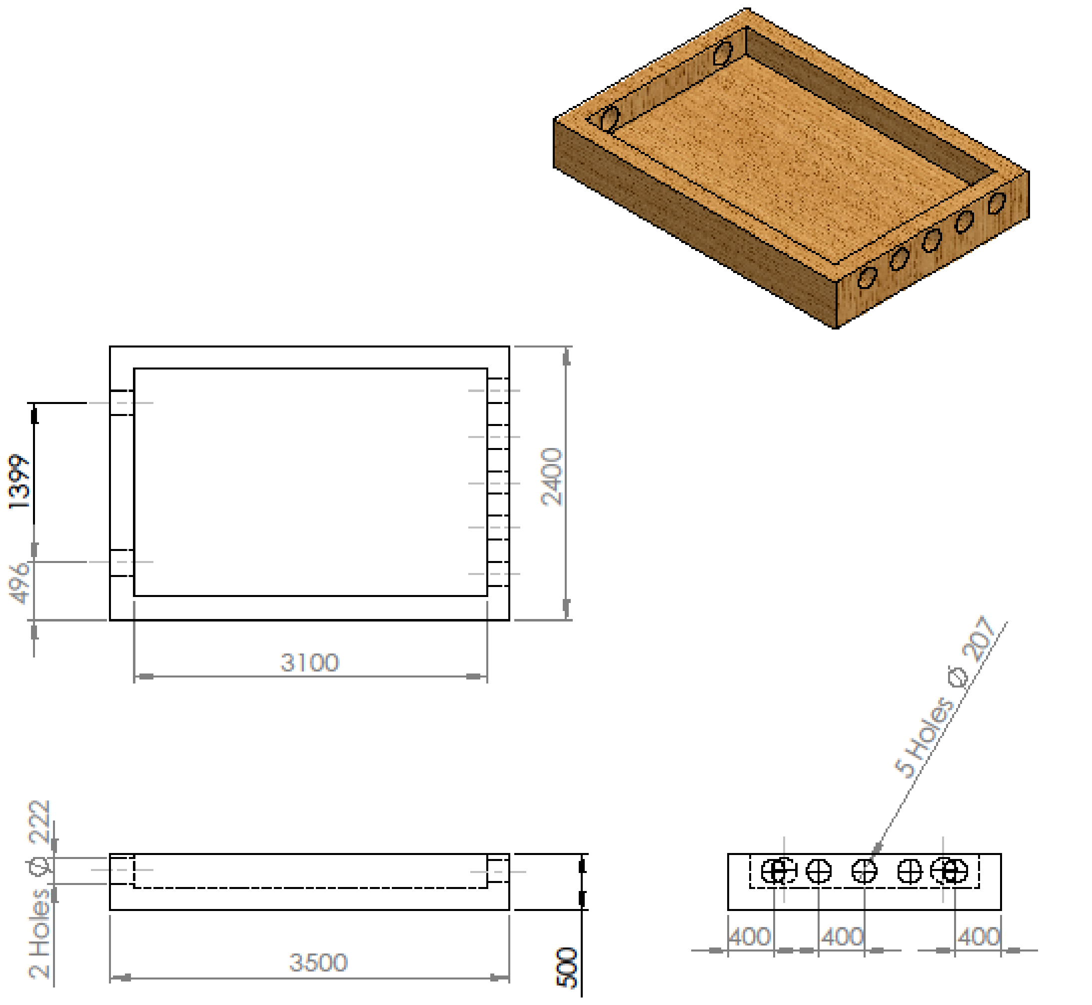


Thickness: 4mm

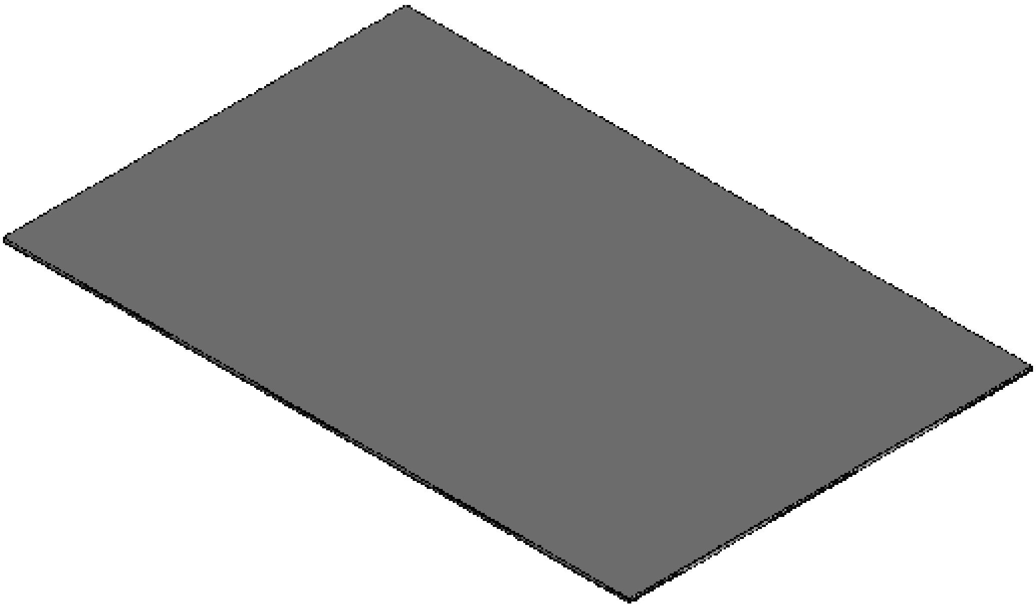
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	GLASS COVER	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL: GLASS				DWG NO. - GSDAH-003/22	A4
MFG	WEIGHT:			SCALE:1:50	SHEET 1 OF 1

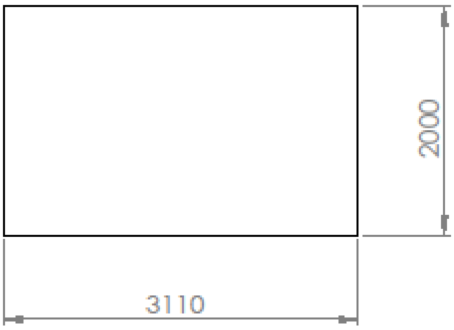


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	TABLE	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:	WOOD			DWG NO. - GSDAH-004/15	A4
MFG	WEIGHT:			SCALE:1:100	SHEET 1 OF 1



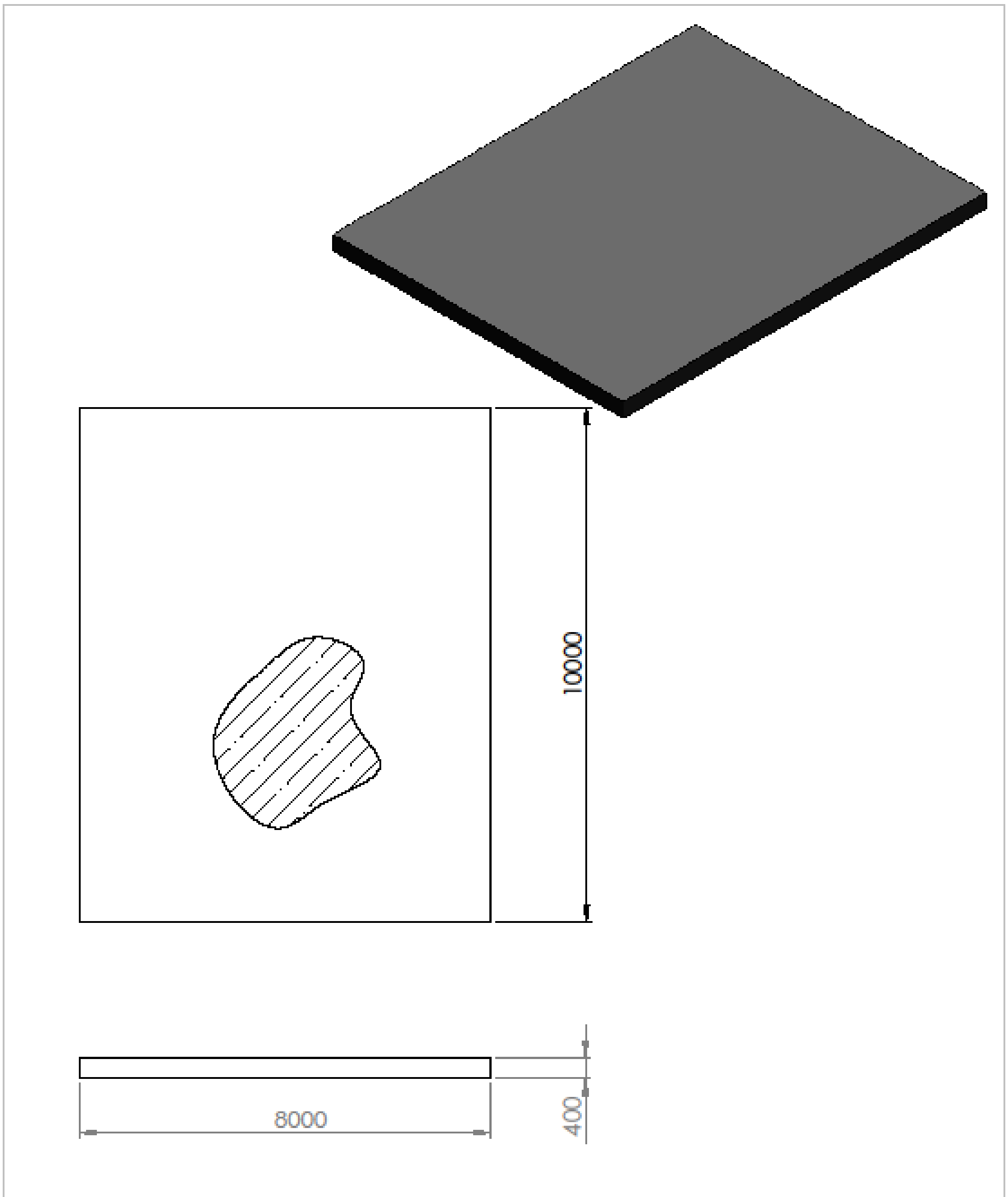
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	AIR HEATER FRAME
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: WOOD				DWG NO. - GSDAH-005/15 A4
MFG	WEIGHT:			SCALE:1:1 SHEET 1 OF 1



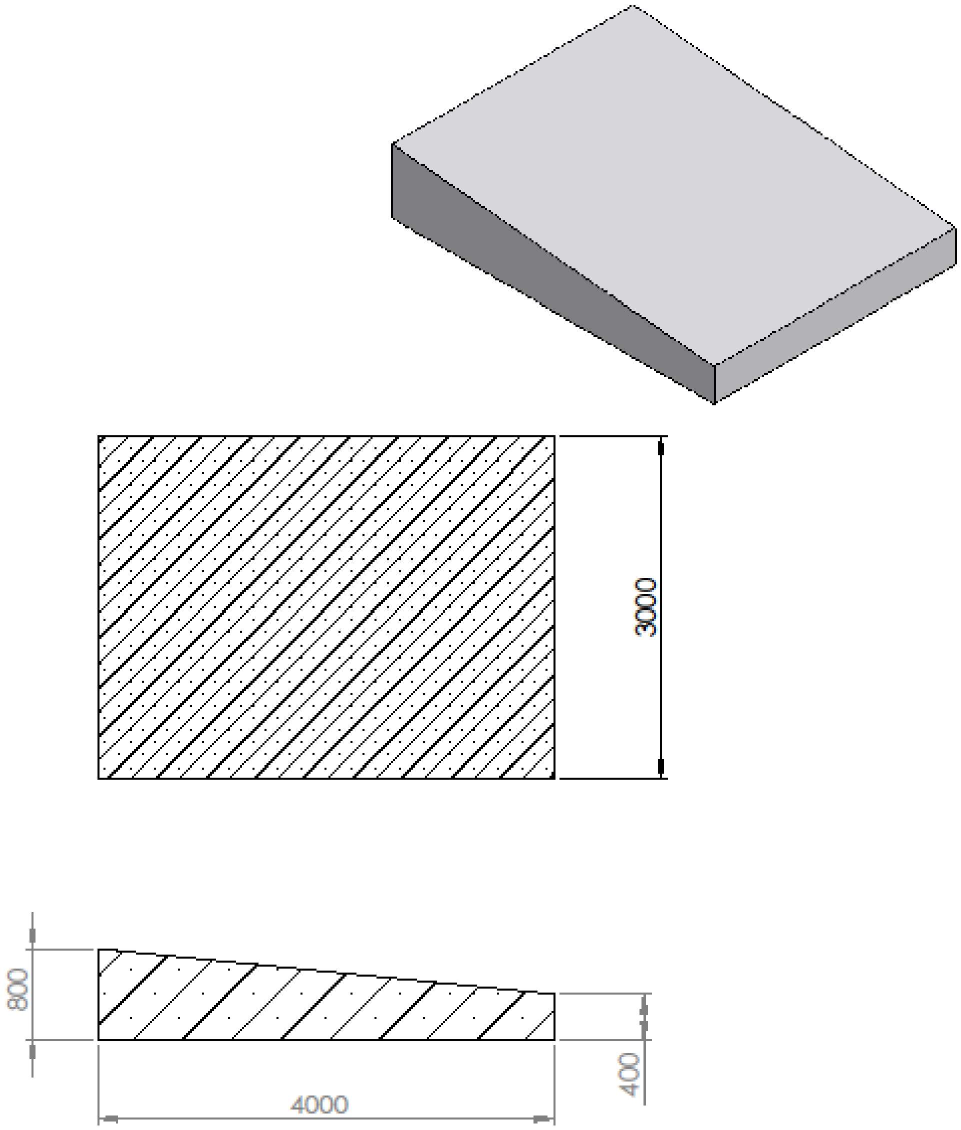


Thickness = 2mm

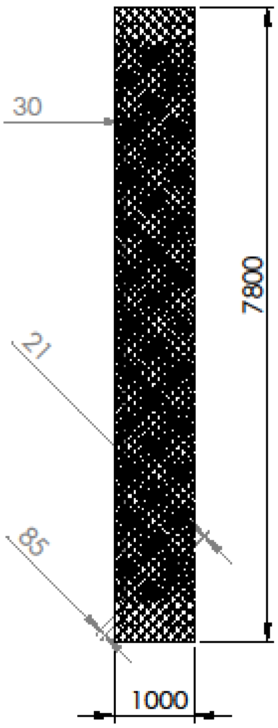
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	ABSORBER PLATE
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: ALUMINUM				DWG NO. - GSDAH-006/22 A4
MFG	WEIGHT:			SCALE 1:50 SHEET 1 OF 1

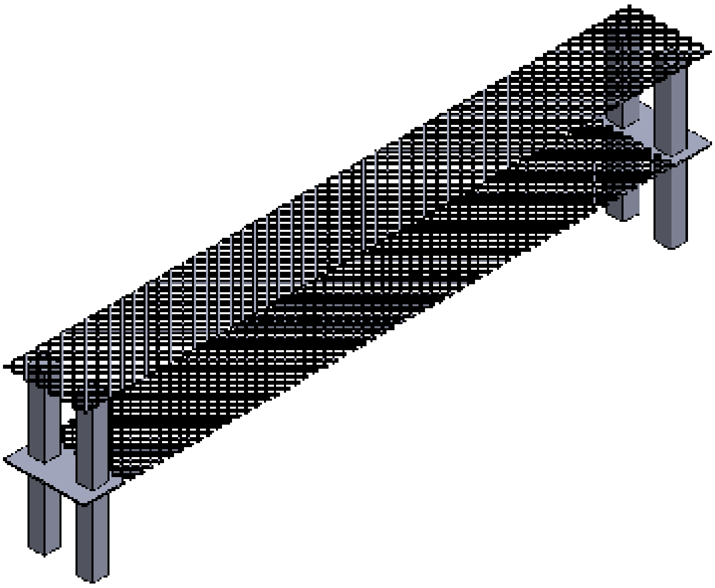


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	BLACK PAINTED CEMENT FLOOR
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL:	CONCRETE			DWG NO. - GSDAH-007/22 A4
MFG	WEIGHT:			SCALE:1:200 SHEET 1 OF 1



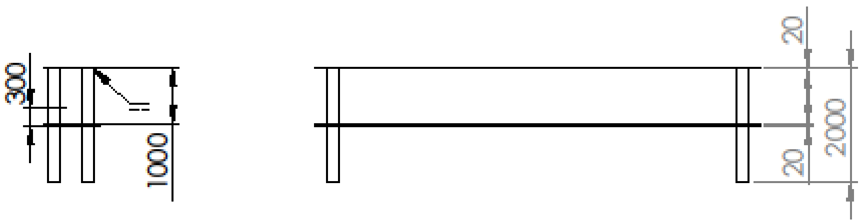
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	STAND	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:	CONCRETE			DWG NO. - GSDAH-008/22	A4
MFG	WEIGHT:			SCALE:1:50	SHEET 1 OF 1



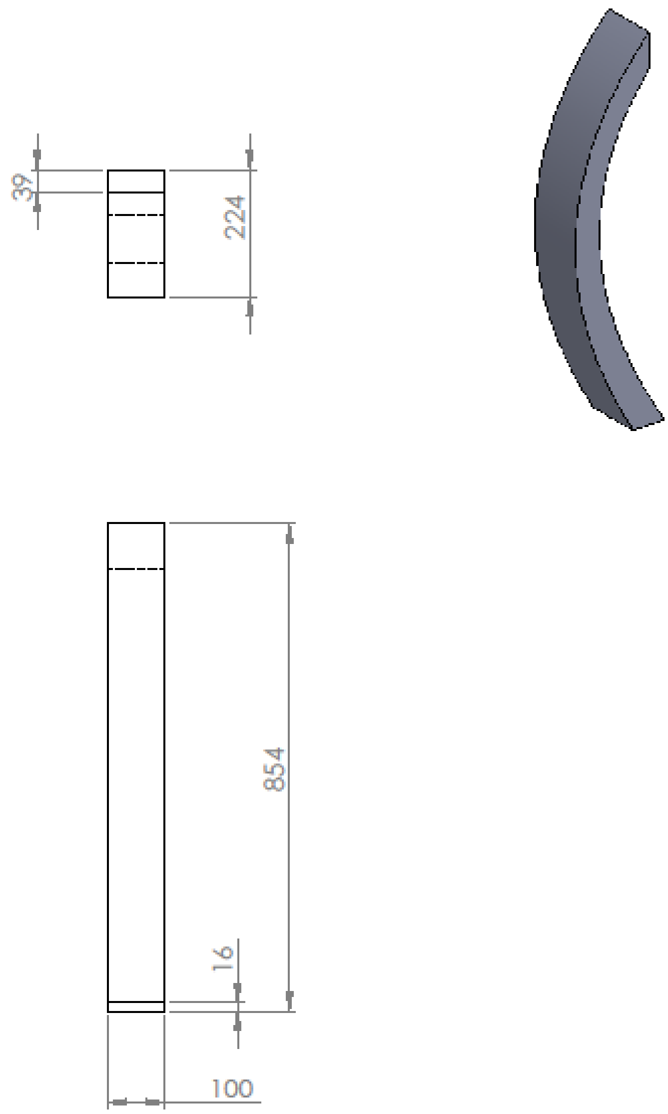


NOTE:

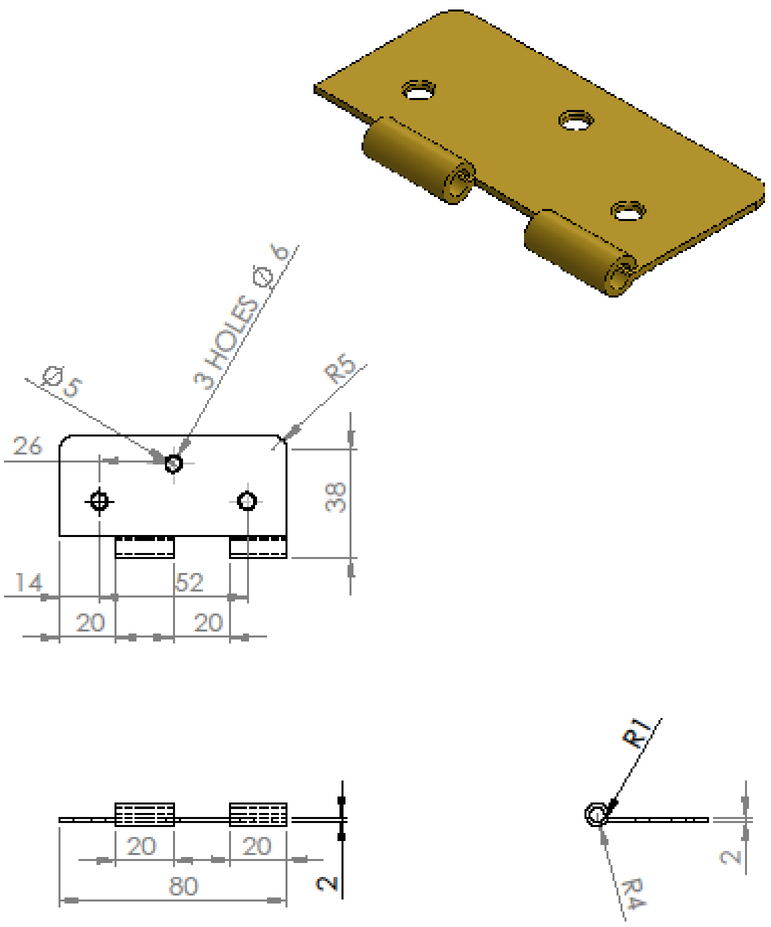
- Wire meshed tray each with 85 mm square hole and 21 mm gap between the holes
- All legs and wire meshes are welded.



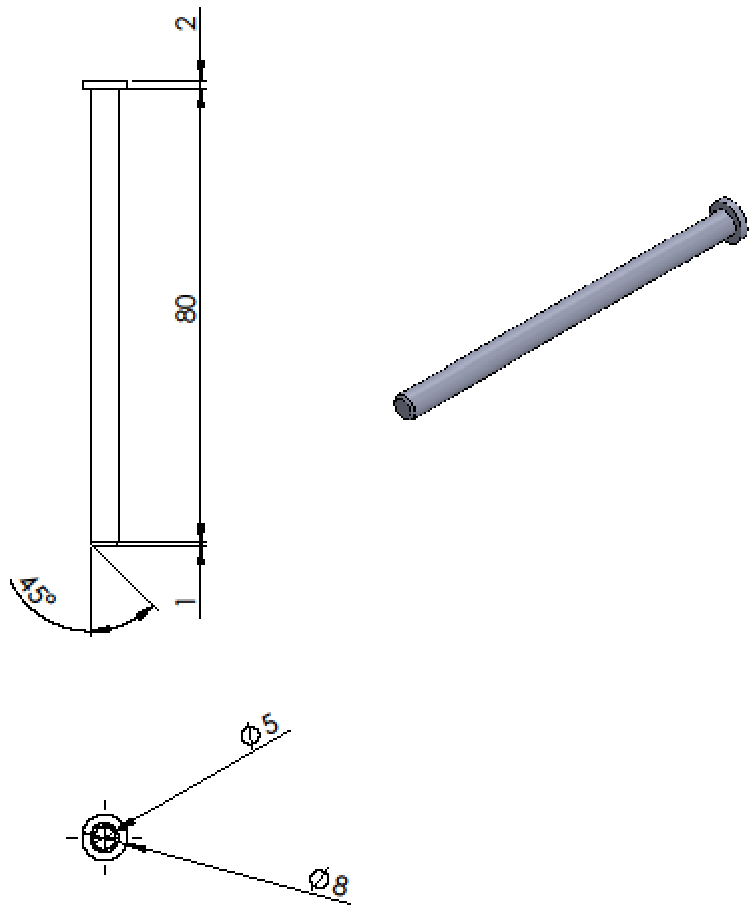
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	Tray	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:				DWG NO. - GSDAH-009/22	A4
MFG	WEIGHT:			SCALE:1:100	SHEET 1 OF 1



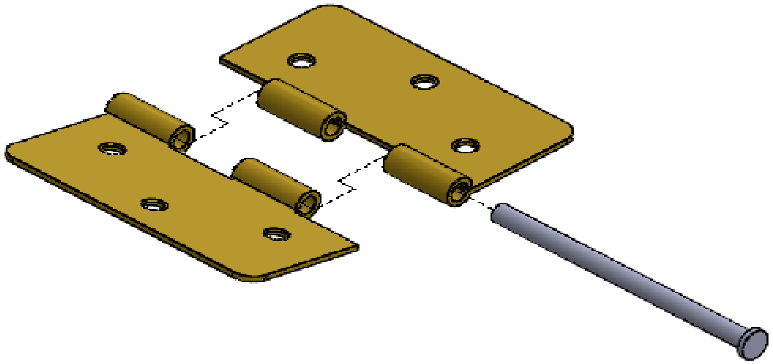
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	DOOR HANDLE
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL:				DWG NO. - GSDAH-010/22 A4
MFG	WEIGHT:			SCALE:1:10 SHEET 1 OF 1

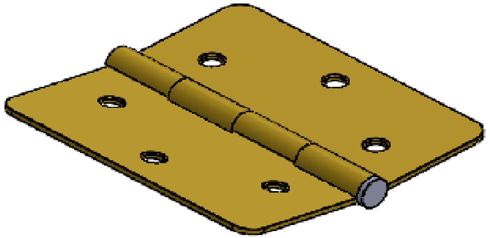


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	HINGE PART 1
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: COPPER				DWG NO. - GSDAH-011/22 A4
MFG	WEIGHT:			SCALE1:2 SHEET 1 OF 1

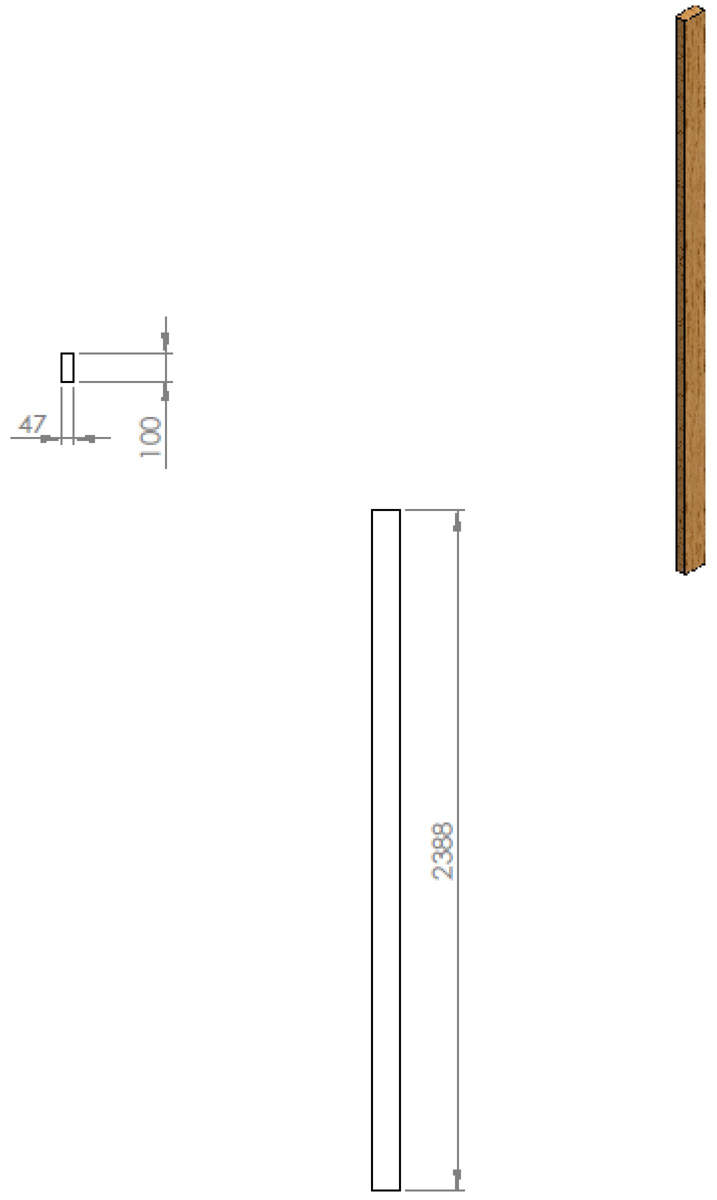


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	PIN
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL:				DWG NO. - GSDAH-012/22 A4
MFG	WEIGHT:			SCALE:1:1 SHEET 1 OF 1

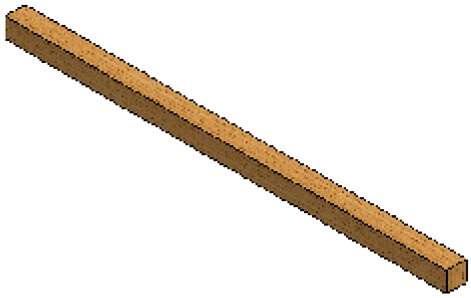


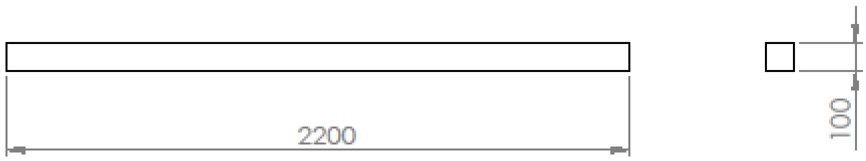


ALL DIMENSIONS ARE IN MILLIMETER				TITLE:
	NAME	SIGNATURE	DATE	EXPLODED VIEW OF HINGE ASSEMBLY
DRAWN BY	BETELIHEM ZEMEDKUN		11/18/2020	
CHK'D BY	KAMIL DINO (Phd)			DWG NO. : GSDAH-013/22
APPV'D BY				
MFG	MATERIAL:	WEIGHT:		SCALE:1:2 SHEET 1 OF 1 A3



ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	DOOR FRAME 1
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: WOOD				DWG NO. -GSDAH- 014/22 A4
MFG	WEIGHT:			SCALE:1:20 SHEET 1 OF 1





ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
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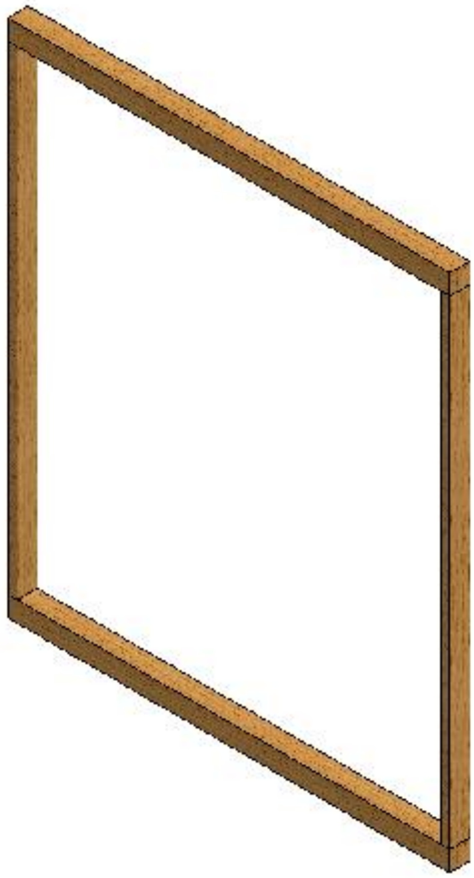
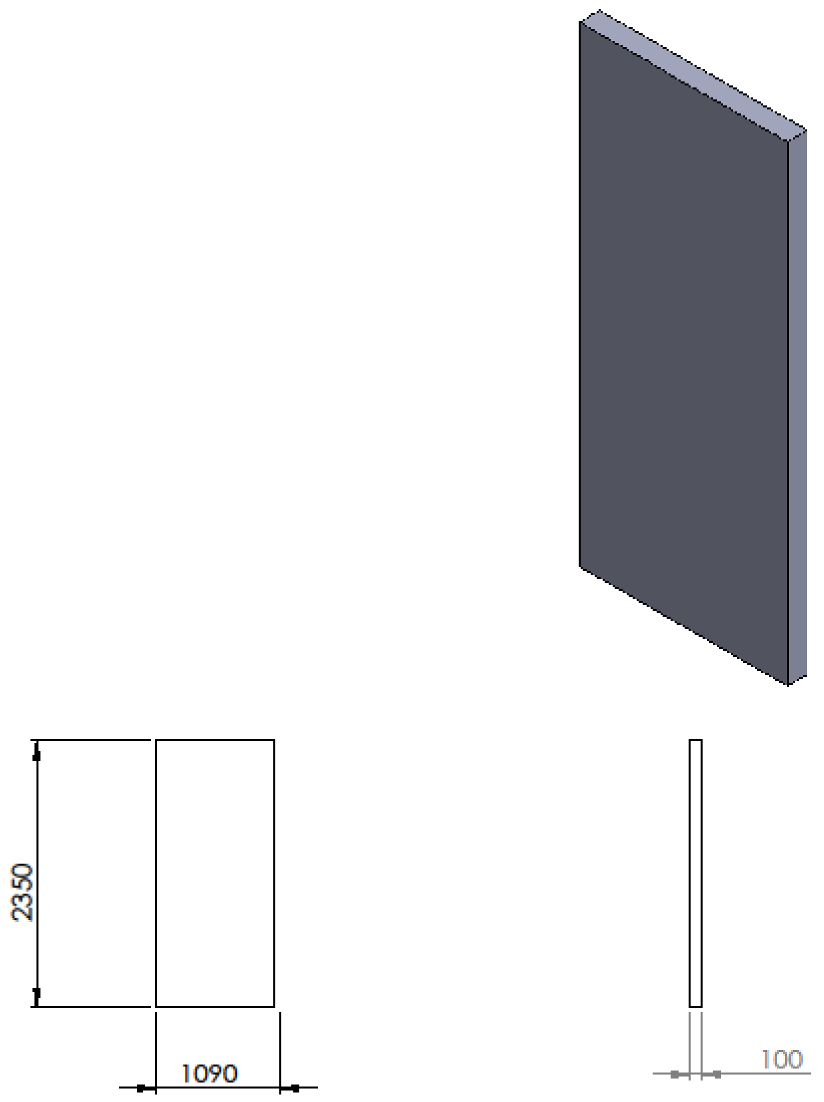
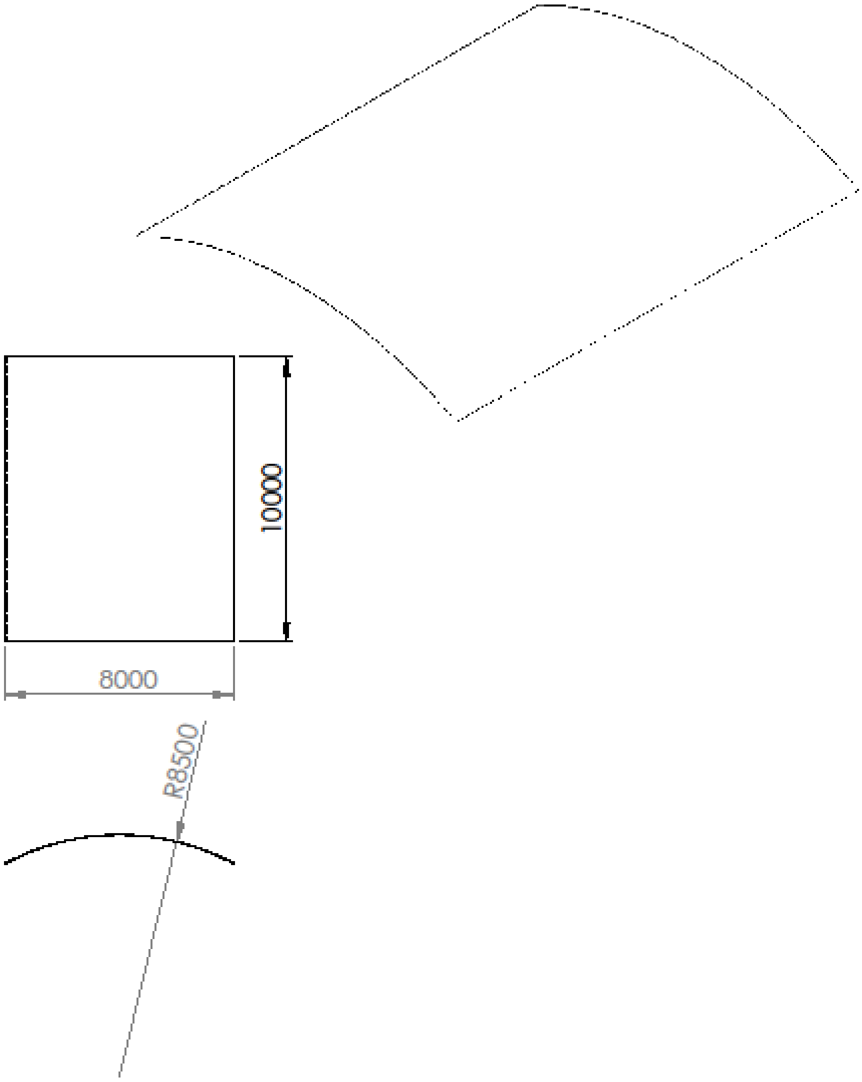
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:	WOOD			DWG NO. - GSDAH-015/22	A4
MFG	WEIGHT:			SCALE:1:20	SHEET 1 OF 1



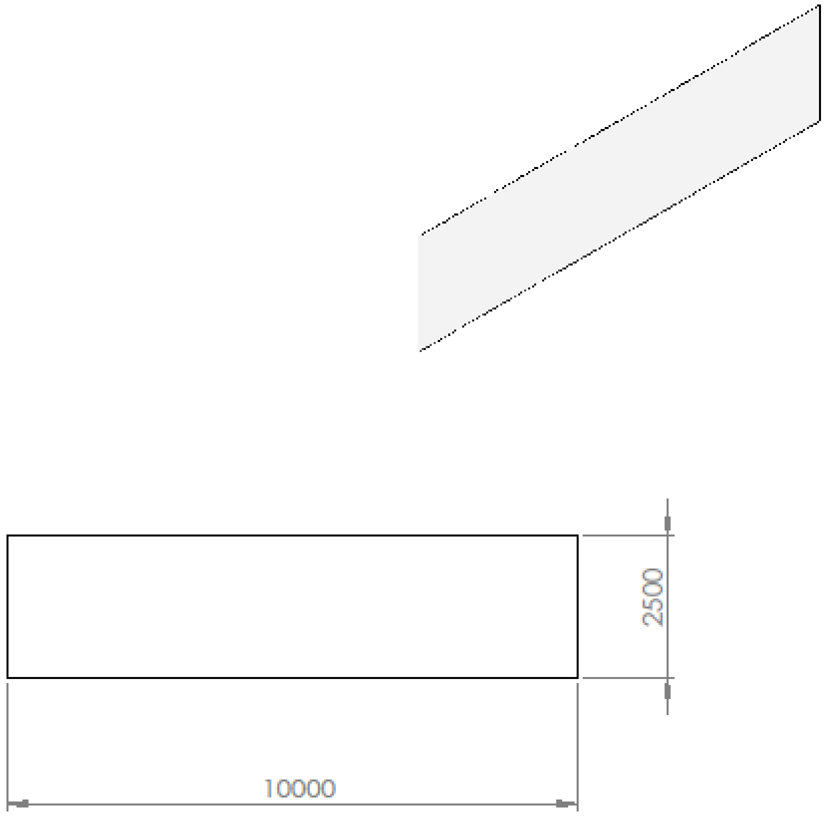
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	DOOR FRAME ASSEMBLY	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:				DWG NO. - GSDAH-016/22	A4
MFG	WEIGHT:			SCALE:1:20	SHEET 1 OF 1



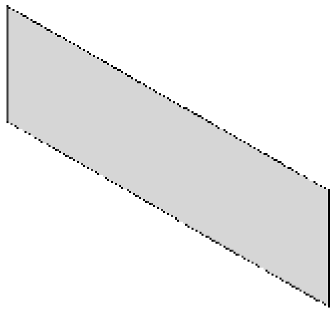
ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	DOOR	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:				DWG NO. - GSDAH-017/22	A4
MFG	WEIGHT:			SCALE:1:20	SHEET 1 OF 1

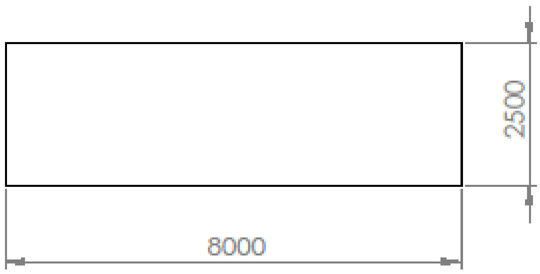


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	PLASTIC SHADE 1	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL: PLASTIC SHEET				DWG NO. - GSDAH-018/22	A4
MFG	WEIGHT:			SCALE:1:200	SHEET 1 OF 1



ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	PLASTIC SHADE 2
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL:	PLASTIC			DWG NO. - GSDAH-019/22 A4
MFG	WEIGHT:			SCALE:1:100 SHEET 1 OF 1





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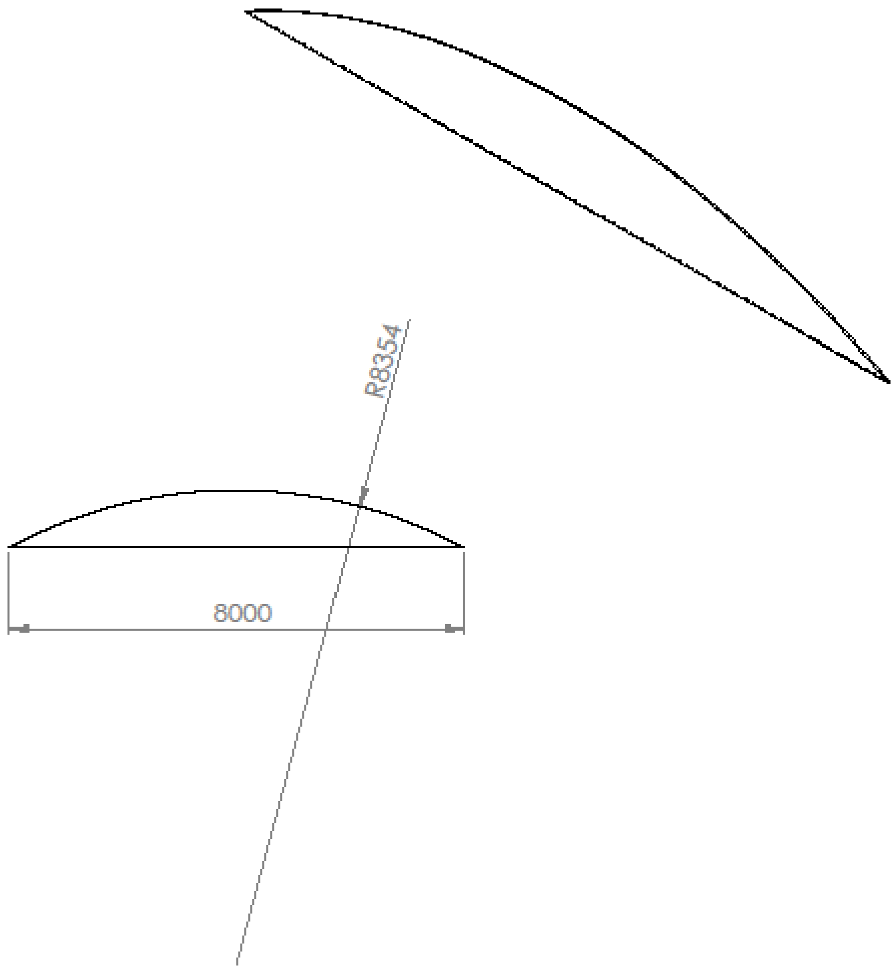
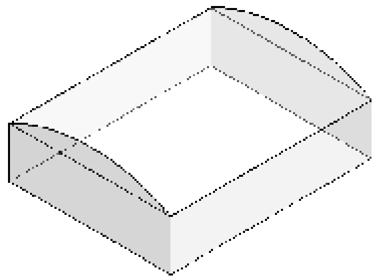
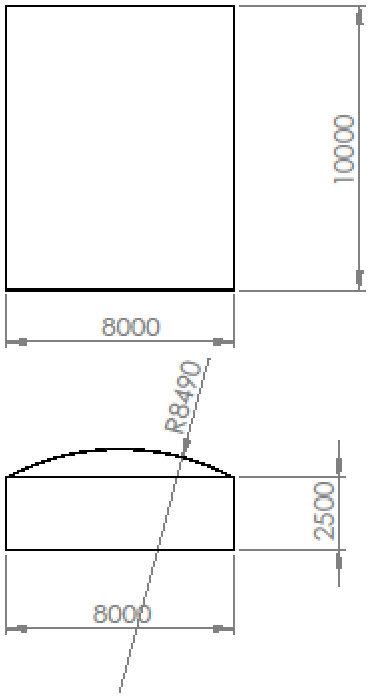
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: PLASTIC				DWG NO. - GSDAH-020/23 A4
MFG	WEIGHT:			SCALE:1:100 SHEET 1 OF 1

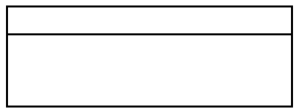


ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	PLASTIC SHADE 4
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: PLASTIC				DWG NO. - GSDAH-021/23 A4
MFG	WEIGHT:			SCALE:1:100 SHEET 1 OF 1

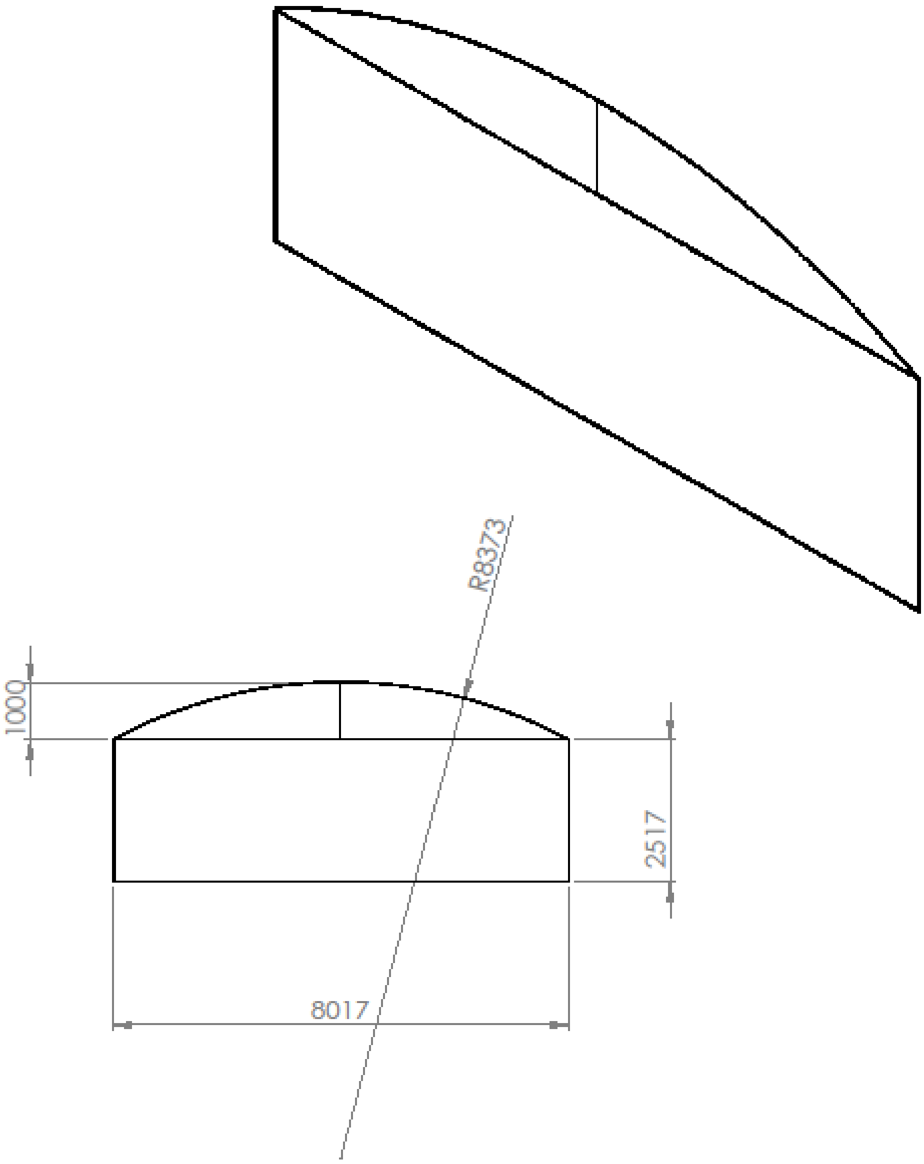




- Each plastic shape parts are to be assembled by pin joint with the steel structureframe.



ALL DIMENSIONS ARE IN MILLIMETERS				TITLE
	NAME	SIGNATURE	DATE	PLASTIC SHADE ASSEMBLY
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020	
CHK'D BY	KAMIL DINO (Phd)			
APPV'D BY				
MATERIAL: PLASTIC SHEET				DWG NO. - GSDAH-022/23 A4
MFG	WEIGHT:			SCALE:1:200 SHEET 1 OF 1



ALL DIMENSIONS ARE IN MILLIMETERS				TITLE	
	NAME	SIGNATURE	DATE	STEEL STRUCTURE	
DRAWN BY	BETELIHEM ZEMEDKUN		11/19/2020		
CHK'D BY	KAMIL DINO (Phd)				
APPV'D BY					
MATERIAL:	STEEL			DWG NO. - GSDAH-023/23	A4
MFG	WEIGHT:			SCALE:1:1	SHEET 1 OF 1