MODELING AND EXPERIMENT OF SOLAR CROP DRYER FOR RURAL APPLICATION

Dawit Abay Tesfamariam, Mulu Bayray, Meseret Tesfay, Ftwi Yohaness Hagos

[1]Department of Mechanical Engineering, Mekelle University, Ethiopian Institute of Technology (EIT – M),Mekelle, Tigray, Ethiopia.

[2]Department of Civil and Environmental Engineering,University of Western Ontario, Boundary Layer Wind Tunnel Laboratory London, On, Canada, N4A 5B9

[3]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

[1]Corresponding Author: Email: Kingdavid1912@yahoo.com

ABSTRACT

An indirect passive convectional solar dryer consisting of a solar air heater and dryer chamber is designed, manufactured and tested for its performance. It plays a major role in reducing crop wastage and opens a way to food preservation. The area of the solar collector required to dry a batch of 10 kg of tomato within two days is calculated. The performance of the collector is improved through the use corrugated absorber to create turbulence for air flow and a highly insulating material to minimize heat losses.

The thermal performance of the solar dryer is tested under the local weather conditions considering the effect of wind, humidity and cloudiness. The average thermal efficiency of the solar collector is calculated to be 21.5% at air flow rate of 0.0564 kg/s. At the same air flow rate, the maximum daily drying system efficiency is calculated to be 25%. Besides the maximum temperature of the solar dryer attained at the absorber plate is 77°C at 12:00 AM when the solar radiation intensity reached 1021 W/m² during no load test.

Regarding the economical feasible it is analyzed using the common economic parameters such as payback period, net present value and benefit to cost ratio analysis methods. Hence the payback period is about eight months that is someone investing in this solar dryer will return his investment with less than a year. Finally the benefit cost ratio is 11.8 since this ratio is much greater than one the solar dryer it is in the acceptable range.

Keywords: Crop dryer; Modeling; Performance; Air heater; Dryer chamber

INTRODUCTION

Solar energy is one of the inexhaustible energy sources due to its renewable nature. And Mekelle is a town located in Northern part of Ethiopia which is geographically located within the solar belt and is endowed with abundant solar energy receiving 5.5 to 6.5 KWh/m2/day of solar insolation. However; it was not utilized as a source of energy except for drying of closes and cereal in a traditional way. Exploiting this abundant resource will contribute in substituting the depleting conventional energy resources, thereby contributing in the socioeconomic development. Meanwhile solar energy has an important role to play in the developing countries especially in the agricultural sector to increase the productivity of the sector. The sun has been used to dry agricultural products traditionally for many years and it is still the most widely used energy source. However, this method of drying is time taking and unsafe due to exposure to insects, rodents, wind and other problems.   Hence, application of solar dryer to preserve agricultural products has multiple uses. It is one of the best ways to preserve food in terms of good quality of the final product and also the abundant and unutilized solar energy will be exploited in a better way. Specifically, the solar dryer will benefit local farmers who are currently suffering due to lack of market that absorb the whole product of agriculture. Therefore, introducing methods of preservation, such as solar dryer for agricultural products especially for the perishable products will benefit not only the farmers but also the consumers.

Thermal analysis of solar collector performance is one of the critical aspects of solar dryers that must be dealt carefully to find a satisfying result of the design of solar dryers. Hence in most of the research reviews made, theoretical models used to simulate the performance of solar collectors can be categorized in two main aspects The first category follows the approach of modeling of mathematical formula relating the main factors that affect the thermal performance of solar collector. Natural convection dryers circulate the drying air without the aid of a fan. They therefore have low air flow rates which tend to give them slower drying rates, compared to traditional open air methods. Despite this disadvantage, experience with these dryers has indicated that they can be of significant use in many rural areas in developing countries.

MATERIAL AND METHODS

The solar drier designed in this study is small scale indirect natural convection dryer. This type is easier to construct and is designed to be more efficient, less expensive than corresponding capacity of a forced convection dryer produced locally. This solar dryer is made of wooden cabinet and metal supporting frames. The capacity of a small scale dryer is designed to accommodate 10 kg per batch. Furthermore the drier comprises two basic components. Based on the result of this small scale design, the work is to be extended for medium scale drier for rural application

The solar collector: The solar collector is covered with a transparent material commonly glass. It is a heat exchanger that converts radiant solar energy into heat. The solar collector acts as energy convertor with the help of the absorber. The converted energy is then carried away to the drying cabinet by the flowing air. The item to be dried is subjected to the streaming hot air inside the drying chamber.

The drying chamber: This is insulated wooden box with three perforated shelves for the crops to put and allow air to circulate. Since the crop to be dried is going to be sliced, the compartment should be able to accommodate the 10 kg sliced tomatoes. Besides to the drying cabinet and collector area, it is designed to have chimney which increases air flow. It is manufactured as a modular concept, which makes it easy to transport and install the solar dryer. For design and calculation purpose, it is important to focus on selected crops and specific area. Therefore; in this thesis tomato is found to be important crop to work on for the following reasons. The bulk of fresh market tomatoes are produced by small-scale farmers. The farmers are interested in tomato production more than any other vegetables for its multiple harvests, which result in high profit per unit area.

Besides tomatoes have short shelf life and highly perishable then it need suitable preservation. Furthermore the solar dryer is designed to dry tomatoes which have 90% to 95% moisture on wet basis. This implies that the solar dryer can easily dry other crops which have less moisture content than tomato.

Determining the size of the collector: In the design of the indirect natural convection solar dryer, to determine the size of the collector the following parameters were considered.

- The amount of moisture to be removed from 10 kg of tomatoes,
- average daily sunshine hours,
- daily solar radiation to determine energy received by the dryer,
- wind speed, and
- The dry and wet bulb temperature of the surrounding.

The desired amount of tomatoes to be dried in one batch is 10 kg. Fresh harvested tomato has about 90% of moisture in wet basis. Hence, the target is to design the size of a solar dryer collector area needed to dry 10 kg of tomatoes within 16 sunshine hours based on and taking the geographic locations of of Mekelle. The annual average solar radiation for Mekelle town is 734 W/m^2.The annual monthly average sunshine hour is 8.2 hours. Hereafter, these basic input data are used to design the collector area of the solar dryer. The surface required for the collector of solar dryer is determined from the energy demand of the dryer. In most solar dryers, drying takes place in stages only a small part of a dryer is used for drying of continuous material flow. In the case of drying in stages, the energy demand is not constant. The drying energy is greater at the beginning of the drying process and decreases as drying proceeds. For dimensioning the collectors, the starting point must be the drying requirements thus the drying characteristics of the material and the amount of moisture to be removed from sample. The amount of moisture that needs to be removed from the product, m_c [kg] is calculated using the following equation.

$$m_c = \frac{M_p(M_i - M_f)}{100 - M_f} \qquad (1)$$

Energy required to dry the product: The output of the solar dryer in terms of energy required for vaporization (Q_d) is the product of latent heat of vaporization (h_{fg}) and the amount of moisture (m).

$$Q_d = h_{fg} * m \qquad (2)$$

The latent heat of vaporization (h_{fg}) for water is considered 2.44 MJ/kg from steam tables.

Area of Collector: Area of the collector is calculated as follows.

$$A_c = \frac{Q_d}{I * t_d * n_c}$$

Chimney: The chimney increases the amount of air flow, through the solar dryer by speeding up the flow of the exhaust air. Hence the effects of natural convection will be improved by adding a chimney in which exiting air is heated even more and enhance the buoyant flow of air. This will have a vital role to the overall design of solar dryers. Some study showed that the installation of three small fans and a photovoltaic cell is equivalent to the effect of a 12 m chimney. However, due to the air passing through the drying food item pick moisture and it possess a high relative humidity, its temperature may reach equal or lower than ambient. In such a case the generation of buoyancy force will be insignificant.

To improve such conditions, heating the solar chimney above the ambient temperature would be advisable. The chimney should be designed so that the rate of heat losses within the chimney should be considered in determining the optimum height of the chimney so as not to exceed the height at which the chimney air cools to same temperature as ambient. The design will maintain mean chimney temperatures above ambient temperature.

In the convectional solar dryer there are two basic conditions of air flow:

No flow condition: In this condition the air temperature and humidity inside the chimney and outside i.e. the ambient is similar. In this case there is no density difference hence there will be no flow through the chimney.

Flowing condition: In the flowing condition on the other hand, the mean temperature inside the chimney is relatively higher than the ambient air temperature. In this case, there exists a pressure head which creates an upward air flow. Therefore the relation among the buoyancy force that is the pressure drop that creates the air flow, the height, density difference of the ambient air and chimney is related as follows.

$$P_b = g*H*(\rho_a - \rho_{ch}) \qquad (4)$$

The out let area or diameter of the chimney is designed as follows: Assuming no loss, the velocity of the air passing through the chimney.

$$\dot{m}_a = \frac{\pi}{4} * D^2 * C * \rho_a \quad D = 1.128 * \left(\sqrt{\frac{\dot{m}_a}{C*\rho_a}} \right)$$

Then the mass of the air flowing through the cross-section of the chimney is given as follows.

$$\dot{m}_a = A * C * \rho_a \ [kg/s] \qquad (6)$$

During designing chimney of solar dryer, the most important emphasis should be on keeping the air temperature inside the chimney relatively higher than the ambient temperature. However; pressure drop due to the wall friction is commonly negligible. Therefore, an efficient solar chimney is designed to have mean inside temperature that is above the ambient air temperatures during operation. An experimental solar chimney consisting of a 5.3m high and 1.64m diameter is able to reach change in temperature of the chimney ranging between 6^0C -15°C above ambient during fairly high insolation period. Furthermore, as suggested by Bassey, the use of tall black or unpainted chimneys is considered unsuitable under atmospheric conditions where cloudy cover, low solar radiation intensifies and wind may exist. Under these conditions a 50 cm chimney painted black and covered with transparent plastic is recommended. However under clear sunny conditions, tall chimneys may prove to be more advantageous.

Energy balance on the collector: In solar collectors the incident solar energy is partially absorbed in the glass and absorber surface, some amount of this energy is transferred to the fluid inside the collector and the remaining is lost to the environment. Thus an energy balance is developed basically that the useful energy gain is the difference between the absorbed solar energy and the thermal losses as shown in figure 2. Then it is solved by equating the total heat gained by the absorber to the total heat loss of the solar collector. Then, it is expressed as follows.

$$I*A_C = Q_u + Q_{cond.} + Q_{conv.} + Q_{rad} + Q_{ref} \qquad (7)$$

To audit all the energy balance the following heat components must be considered. The incident solar radiation (I_T), top heat loss coefficient, coefficient of convective heat transfer between cover and air, coefficient of convective heat transfer between plate and air ($Q_{conv.}$),coefficient of radiation heat transfer between plate and cover($Q_{rad.}$) , bottom heat loss coefficient, ambient temperature, collector air temperature and mean plate temperature.

Useful energy collected: The instantaneous hourly steady-state useful energy, Q_u collected by a solar flat-plate collector of surface area A_C.

$$Q_u = A_c F' [I_T \tau\alpha - U_L(T_{mc} - T_a)]$$

The plate efficiency factor F' is a factor that measure the quality of heat transfer between the fluid and the absorber plate. The product of the transmittance and absorptance ($\tau\alpha$) is the optical efficiency of the cover and absorber of the collector. In this case it is assumed to be 0.96 from table absorptive and emissivity of common selective surface. However using this equation to calculate the useful heat gained and determine the performance of the collector is inconvenience due to the quantity mean fluid temperature, T_{mc} of the collector. To overcome this problem, Bliss expresses the performance of a solar collector using an energy balance as follows .

$$Q_u = A_c F_R [I_T \tau_a - U_L(T_{Ci} - T_a)] \qquad (9)$$

This equation, known as the classical Hottel–Whillier–Bliss (HWB) equation, assumes the mean plate temperature to be equal to the collector inlet air temperature. The plate efficiency factor F' is substituted with a heat removal factor, F_R where it is a measure of the solar collector performance as a heat exchanger given by.

$$F_R = \frac{\dot{m}C_p}{A_c U_L} \left[1 - \exp\left(-\frac{U_L F' A_c}{\dot{m} C_p} \right) \right]$$

One of the parameters, U_L is the overall heat loss coefficient of the collector, which is cumulative effects of three coefficients: heat transfer from top covering (U_t), from the bottom plate (U_b), and from the edges (U_e), hence expressed as follows.

$$U_L = U_t + U_b + U_e \qquad (11)$$

Energy loss through the top cover of the collector

$$U_t = \left\{ \frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm}-T_a)}{(N+f)}\right]} e + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{(\varepsilon_{p+0.00591\,Nh_w})^{-1} + \frac{2N+f-1+0.133\,\varepsilon_p}{\varepsilon_g} - N}$$

(12) Where

For $70^0 < \square < 90^0, \square = 15^0,$

f: $(1+0.089h_w - 0.1166h_w\square_p)(1+0.07866N)$, e: $0.430(1-100/T_{pm})$

$$h_w = \frac{8.6 * V^{0.6}}{L^{0.4}}$$

$$c = 520(1 - 0.000051\beta^2) \ for \ 0^0 < \beta < 70^0$$

Energy loss through the bottom of the collector: The energy loss from the bottom of the collector is transferred through the insulation and then by a combined convection and infrared radiation to the surrounding ambient air. Then it is calculated by

$$U_b = \frac{1}{\frac{t_b}{k_b} + \frac{1}{h_{c,b-a}}} \qquad (13)$$

However the temperature of the bottom of the collector is low, then the radiation loss is commonly neglected; hence the energy loss.

$$U_b = \frac{K_b}{t_b} \left[\frac{W}{m^2 \cdot K}\right] \qquad (14)$$

Energy loss through the edges of the collector: In a similar fashion, the heat transfer coefficient for the heat loss from the edges of the collector is calculated.

$$U_e = \frac{1}{\frac{t_e}{k_e} + \frac{1}{h_{c,e-a}}} \qquad (15)$$

Neglecting the radiation loss, the final edge loss is calculated.

$$U_e = \frac{K_e}{t_e} \left[\frac{W}{m^2 \cdot K}\right] \qquad (16)$$

Standard efficiency of solar dryers: Commonly the efficiency of solar dryers is evaluated either based on the thermal performance or the drying rates (system drying efficiency) of the products. The thermal analysis of a solar collector is quite complex. However, according to the ASHRAE 93-77 standard, the thermal performance of the solar collector is determined in part by obtaining values of instantaneous efficiency for a combination of values of incident radiation, ambient temperature, and inlet fluid temperature. This requires experimental measuring the rate of incident solar radiation on to the solar collector as well as the rate of energy addition to the transfer fluid as it passes through the collector, all under steady state or quasi-steady state conditions. Therefore the instantaneous efficiency of a collector is expressed as follows.

$$\eta_c = \frac{\text{Useful energy collected}}{\text{Incident solar energy}} = \frac{Q_u/A_t}{I_T} \qquad (17)$$

When the useful energy is expressed in terms of mass flow rate and the change in temperature the collector efficiency is stated as follows.

(18)
$$\eta_c = \frac{(m*c_p)(T_o - T_i)}{A_c I_T}$$

The other important measure for efficiency of solar dryers is the drying rate or the system drying efficiency. The system drying efficiency is defined as the ratio of the energy required to evaporate the moisture from the product to the heat supplied by the drier. That is [13].

$$\eta_s = \frac{h_{fg} * m_w}{I * A_c} \qquad (19)$$

Average drying rate: Average drying rate, d_r [kg/hr], is determined from the mass of the moisture to be removed by solar heat and drying time by the following equation.

$$d_r = m_c / \tau_d \qquad (20)$$

RESULT AND DISCUSSION

Simulation Result Geometry and meshing of solar dryer: The geometry of the solar dryer is modeled and meshed in Gambit 2.3.16 as shown in the Figures 1 and 2 below. The mesh near to the walls is finely meshed to see the effect of the thermal and velocity boundary layer formation.
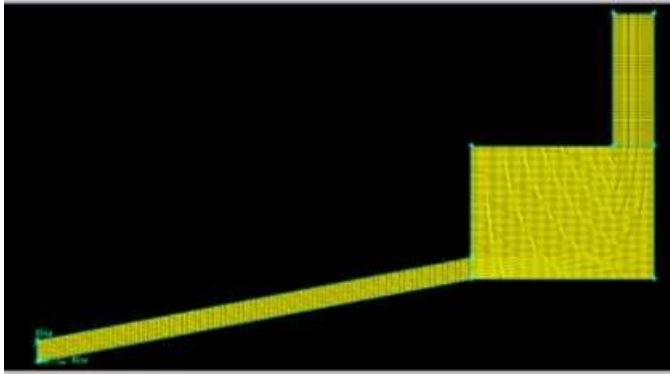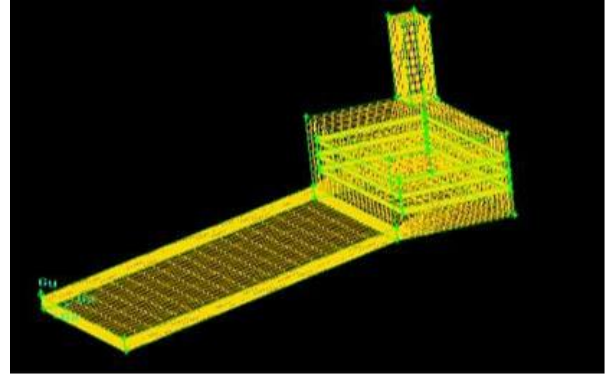

Figure 1:2D mesh of the solar dryer

Figure 2: Solar dryer 3D mesh

Defining boundary conditions: In this study the boundary conditions were defined as function of meteorological and previous experimental data as follows:

Velocity inlet: the inlet of the dryer is specified as velocity inlet. According to the meteorological data, velocity of 2.1 m/s is used as velocity magnitude at the entrance of the solar collector. Direction of air flow is considered normal to the air inlet and the air at ambient temperature is considered to be 300 K.

Walls: at the food cabinet walls, no slip boundary conditions were used.

Glass: temperature is considered equal to 310 K which is 10 degrees above the ambient. **Absorber:** temperature of the absorber plate of the solar dryer is set to 350 K according to experimental data. An adiabatic condition is assumed both in the absorber and cabinet walls. **Outlet**: The outlet of the solar dryer that is the chimney is considered as pressure outlet boundary condition. And it is assumed a gauge pressure of zero Pascal at the outlet chimney.

Solving the equations iteratively
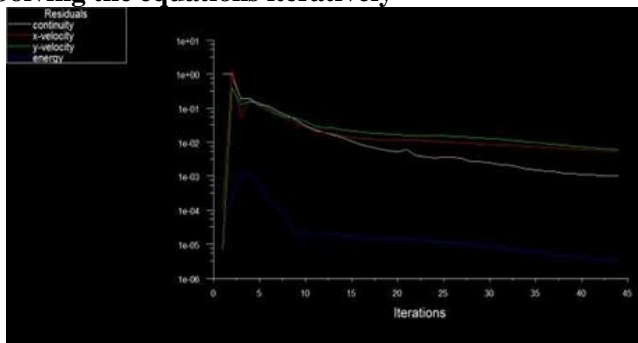
Figure 3: Iteration of y and x velocities, continuity and energy from top to bottom
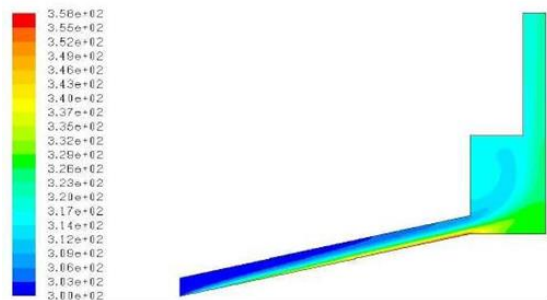
Figure 4: Contours of Static Temperature

The defaults of pressure based solver, implicit formulation, steady flow and laminar flow is the used to solve the problem. To determine temperature distribution the energy equation is activated. The momentum is solved with second Order Upwind.

Analysis of the result of the Simulation: The flow is simulated considering a steady state laminar flow operating condition. The air inside the dryer is assumed as an ideal gas. The above contour of static temperature distribution shows the distribution of temperature in the solar dryer. The maximum temperature is about $70^{0}C$ and the minimum temperature is about $27^{0}C$ which is the ambient temperature. The static temperature shows uniform and evenly distributed in the drying chamber this shows that the drying process will be efficient.
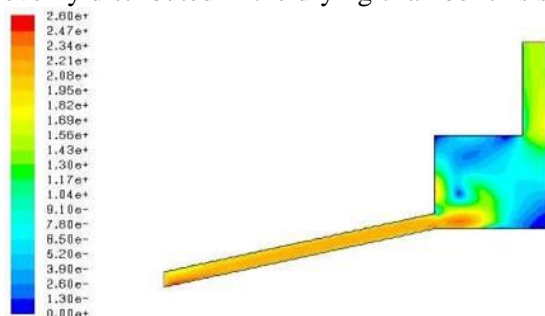

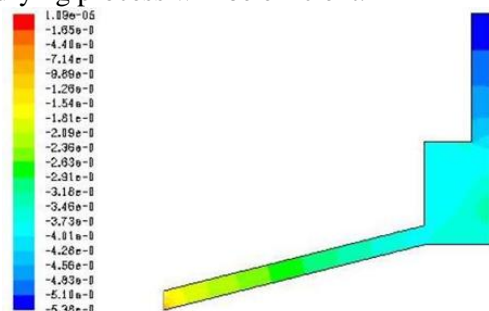
Figure 5: Contours of Velocity Magnitude (m/s)

Figure 6: Contour of Static pressure

In the contour of velocity magnitude the two extreme corners of the dryer are almost stagnant. However the rest part of the solar dryer shows evenly flow of air implying the hot streaming air will reach the food cabinet.
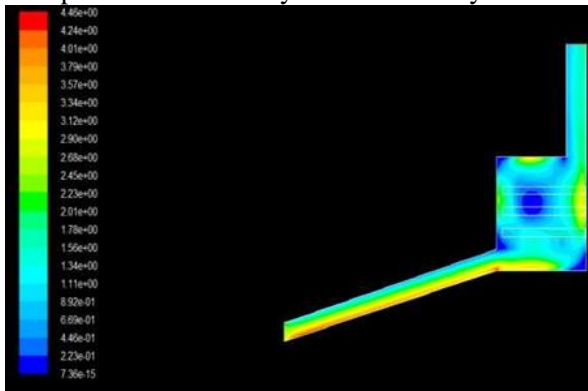

Figure 7: Contour of dynamic pressure

Figure 8: Experimental setup of the solar dryer with the data logger

The pressure at the inlet of the solar dryer and chimney outlet is observed as having about 5 Pascal difference. This pressure difference creates flow from the inlet to the chimney outlet.

Experimental Result: The area where the test performed is Mekelle University, Mechanical Engineering Department Solar Demonstration Center. In order to determine the results, drying parameters such as the solar energy input, weight of the sample, temperature and moisture content of the air at different points of the solar dryer were measured during the experiment.

No-load test: During the no load test as displayed in figure 8, the solar dryer is tested without any load. The air temperature is measured at the inlet of the collector and at the outlet of the collector that is at the inlet to the cabinet. This indicates the temperature of streaming hot air flowing to the item to be dried. In addition to read the mean absorber temperature, a thermocouple is connected at the center of the absorber as shown in figure 8 below. During no load test the cabinet is empty hence the air temperature in the cabinet is almost equal with the temperature coming from the collector outlet as shown in figure 9. That is the case that the temperature of the air in the tray and the air temperature coming from the collector out let are overlapping in the graph.
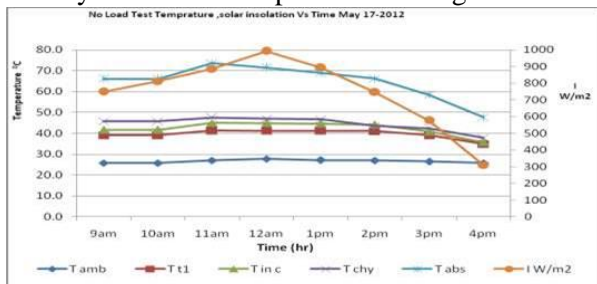

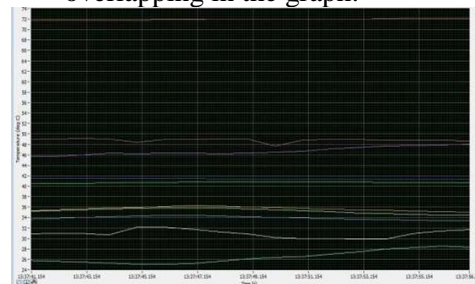**Figure 9: No load dry-bulb air temperatures and solar insolation**

Figure 10: Temperature Measured During Calm Condition

The measured average hourly solar insolation of the day is 745 W/m^2 which is almost similar with the annual monthly average used to design the solar dryer. Figures10 and 11 are actual temperature measurements from the data logger. This depicts in the steady state the temperature from the absorber (maximum) to the ambient (minimum) is almost straight line steady condition as in figure 10.
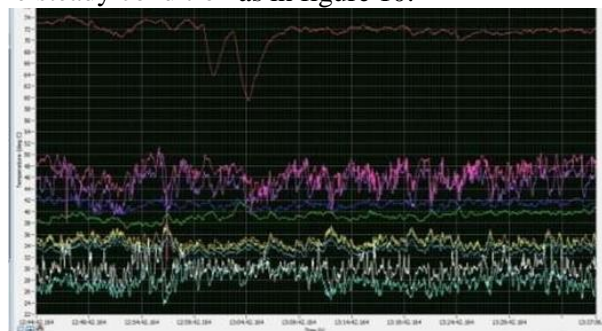

Figure 11:Temperature measured during wind blowing condition

However when the wind start to blow the wind driven fan, the air flow inside the dryer, except the absorber temperature ,gets some turbulence as shown in figure 11.Hence this condition is contributing in fasillitating of drying of the sample by increasing the air flow.

Half load test: After performing no load test, the solar dryer is loaded with about 5 kg of tomatoes which is half of the designed capacity of the solar dryer. The tomato is sliced approximately with 1.3 cm thickness and 1 cm wide. The type of sample tomato used is the common one found in the local market. It is Roma type tomato shown in the figure 12. After preparing the tomatoes in the tray, the instrumentation set up to measure the solar radiation, dry and wet bulb temperature commenced.

Figure 12: Sample Roma tomatoes

Figure 13: Prepared sliced tomatoes

Figure 14 summarizes the ambient temperature, dry bulb air temperature at the outlet of the collector, cabinet dryer, chimney outlet, the mean absorber temperature and the solar insolation of the first day of the experiment. The absorber temperature is fluctuating unevenly with time and the input solar energy, the hot air streaming to the cabinet also follows the same fashion but with less degree. However the temperature inside each tray is almost equal. The solar radiation is forming almost a zigzag due to the cloud cover that is shading the sun some hours in the day intermittently. The average hourly solar radiation of the day is 640 W/m^{2}which is below the design value. Figure 15 also summarize the drying condition of the second day of drying condition.

The relation of the temperature of the absorber and hot streaming air to the cabinet is not uniform. However the temperature in the trays is almost uniform. In contrary to the data of May- 18 2012, the solar radiation is almost uniform forming as bell curve and the hourly average of the day is 734 W/m^2. The relation between the chimney dry bulb temperature and that of the ambient air temperature shows that the temperature of the chimney outlet is greater than the ambient temperature. This creates low density that develops buoyancy force in the solar dryer.
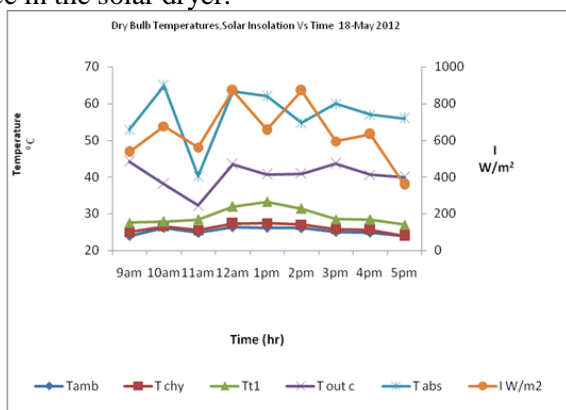

Figure 14: Half load dry-bulb air temperatures and Solar Insolation (18-May, 2012)

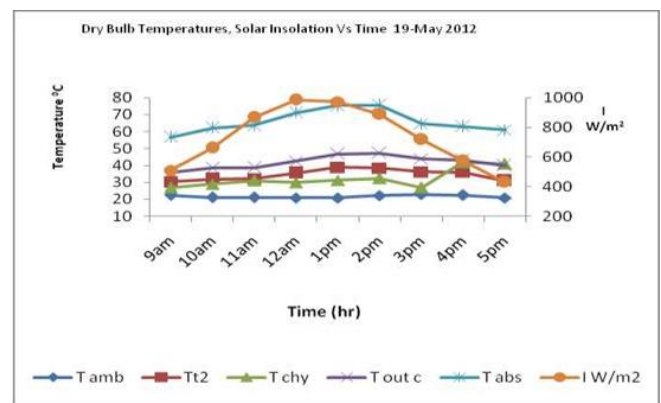**Figure 15: Half-load dry-bulb air temperatures and solar insolation (19 May, 2012)**
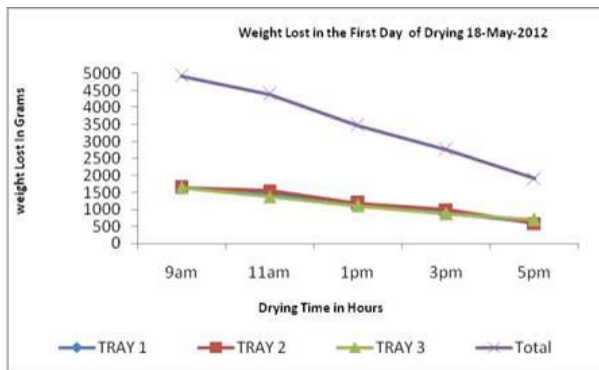
Weight lost from the sample

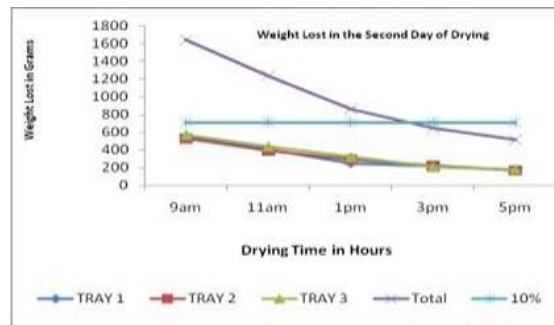**Figure 16: Day One weight lost from sample**

Figure 17: Weight lost from sample (May 19, 2012)

After loading about 5 kg of tomatoes, to determine the weight loss, the sample is weighed every two hours using the digital weighing balance. Hence the weight loss of May18, 2012 is expressed in Figure 16. In the first day of drying, three of the graphs are almost conciding, which implies there is uniform drying in all the trays. The amount of weight lost from tray1,2 and 3 is 1021,1049 and 944 grams respectively. The total weight lost from the three trays is 3014 grams which is 61.3 % of the total mass.The weight loss of May19,2012 is also expressed in Figure 17. In similar fasion, the second day of drying is followed with the amount of weight lost from tray 1, 2 and 3 is 372, 360 and 395 grams respectively. The total weight lost from the three trays is 1128 grams which is 22.9% o f the total mass. Hence in one day and half d r y i n g time or 12 hours of sunshine the sample lost 84.2% of the toal weight. Thus, this condition is safe to preserve tomatoes. Figure 18 shows the difference in weight loss in each tray of May18, 2012.

Due to the high fluctuation of the solar insolatoion of May-18-2012, the difference in weight loss in the trays varies intermittently. The difference in weight loss of May-19-2012, is also shown in figure 19 in each tray. The difference in weight lost in the second day is almost uniform and the same is true for the solar radiation. The difference in weight lost in the first two hours is high. However in the last hours of drying time the difference in weight lost is minimal and then finally it gets stable. Figure 20 below shows summary of two days or 16 hours of drying conditions. After the sample losses the predetermined amount of weight, the graph become almost horizontal line.
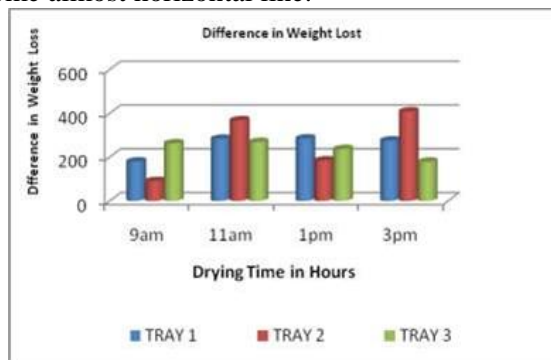

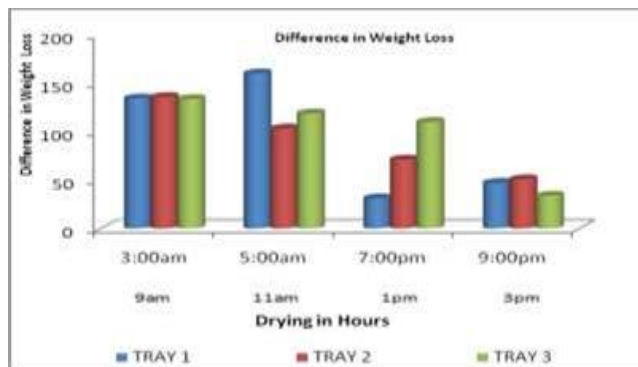**Figure 18: Difference in weight loss May18, 2012**

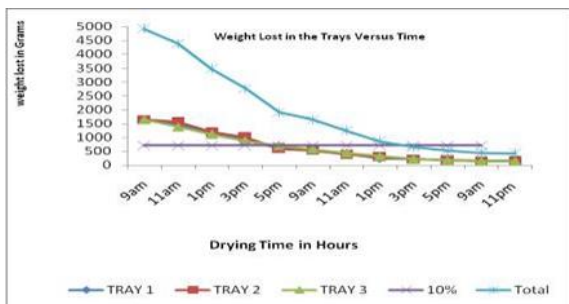**Figure 19: Difference in weight loss of Drying(19 May, 2012)**

Figure 20: Total weight loss

Figure 21: Total difference in weight loss

The total initial mass of the tomatoes in the three trays is 4920grams. Then after the first phase of four drying hours it lost 29 % of its weight. In the second phase four drying hours 32 % of the total mass is lost. However in the third phase four drying hours it lost only 16 % of the total mass. In the fourth phase 7 % of total mass is lost. Finally within two hours the sample lost only one percent.
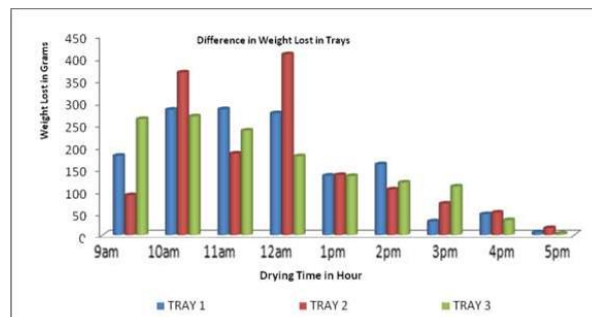
Mass balance of the half-load test: The ten percent horizontal line indicates measured with the digital weighing balance PT 600, the remaining mass of the sample is 640 grams at 3 pm. But the mass balance is also done with the following formula:

Mass $_{final}$=Mass $_{initial}$(1-Moisture Content $_{initial\ wet\ base}$) (21) Mass final = 4920(1-0.87)

Then the final mass ready to be preserved is 640 grams. Therefore the horizontal line of the total weght loss implies the mosture content of the sample is almost extracted to the required amount. Hence it is safe to be preserved.The difference in weight loss in 16 sunshine hours is also summarized in Figure 21. Initially the sample has 87% of moisture in wet basis. Hence the weight lost from 9 am to 5pm in the first day is more than 50% of the total mass. However, in the last hour of drying that is at 5pm of the second day the differnce in weitht loss is almost negligible.

Full-load Test: After performing half load test, the solar dryer is loaded with about 10 kg of tomatoes which is the designed load capacity of the solar dryer. The tomatoes were sliced similar with the half load test approximately with 1.3 cm thickness. The type of sample tomatoes used is also same Roma type tomatoes. The result of the first day experiment of the dry bulb temperature and solar insolation is summarized in the Figure 22.
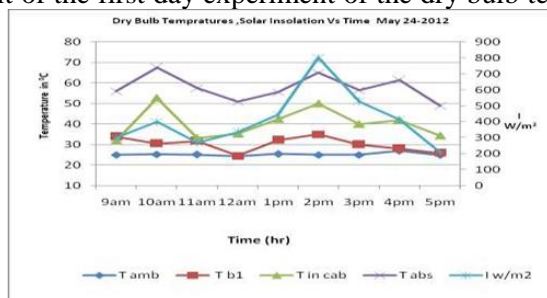

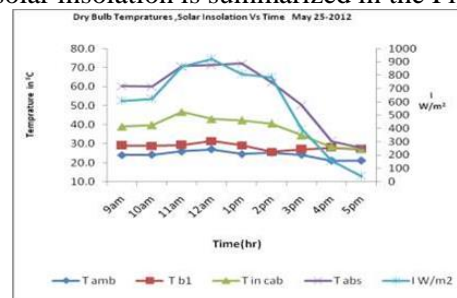| Figure 22: Full-load test dry-;bulb temperature and solar insolation | Figure 23: Full-load test dry-bulb temperature and solar insolation |

Similar to the first day of the half load condition, the relation of the temperature of the absorber and hot streaming air to the cabinet is reaching maximum at 10 am and 2pm. This creates fluctuating air temperature in the trays.This dictates to drop to low temperature at noon which makes the air temperature of tray one equal to the ambient air temperature. Hence the hourly average solar insolation of the day is 411W/m^2 which is far below the designed value due to the cloud cover of the day. The condition of the second day is summarized in Figure 23 as follow. The average hourly solar insolation of the second day is 628 W/m^2 which is higher than the first day but still lower than the designed value due to the cloud cover of the day. Though the sun is shaded some hours of the day, the temperature inside the collector is fairly enough above 60°C. Besides, the hot air streaming through the cabinet T in cab is fairly above 40°C.
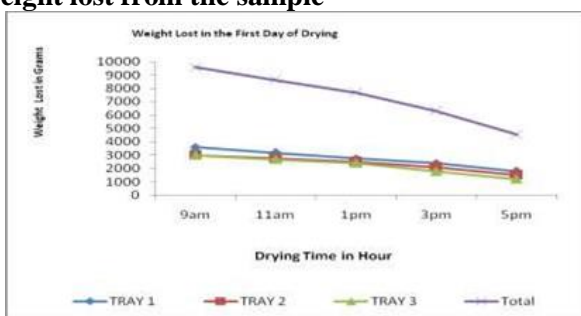
Weight lost from the sample

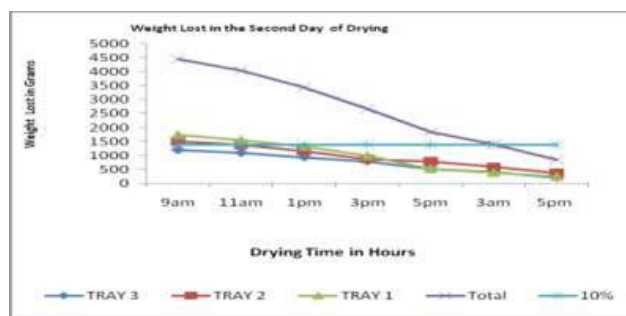| Figure 24: Full-load test weight loss (May 24,2012) | Figure 25: Full-load weight loss (May 25, -2012) |

In May 24,-2012 ,that is the first day of drying, the amount of weight loss from tray 1,2 and 3 is 1860,1486 and 1897 grams respectively. The total weight lost from the three trays is 5245 grams which is 54.6 % of the total mass as shown in Figure 24. In similar manner, the amount of weight lost from tray 1,2 and 3 is 1245, 926 and 788 grams in the second day (May 25, 2012). The total weight lost from the three trays is 3059 grams which is 31.8% of the total mass as shown in Figure 25. Hence, in two days of drying time as shown in Figure 26 the tomatoes lost 86.4% of the toal weight and is safe to be preserved.

Mass Balance: The ten percent horizontal line indicates measured with the digital weighing balance PT 600, the remaining mass of the sample is 1296 grams at 3pm. But the mass balance is also done with the following formula: Mass$_{final}$=Mass$_{initial}$ (1-Moisture Content$_{initial\ wet\ base}$) Mass final = 9600(1-0.87). Then the final mass ready to be preserved is 1248 grams. Therefore the horizontal line of the total weight loss implies the moisture content of the sample is almost extracted to the required amount. Hence it is safe to be preserved. Generally the average moisture content on wet basis is found to be 87%. Then finally before the sample is packed

the moisture content of the tomato is 9.3% on wet basis. Even though the solar radiation is below the design value, the solar dryer is able to dry the designed capacity. This implies that the solar dryer is effective for areas which have similar weather conditions to Mekelle town.
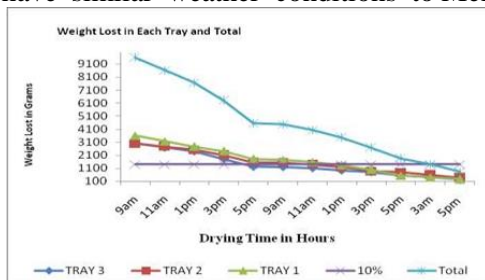

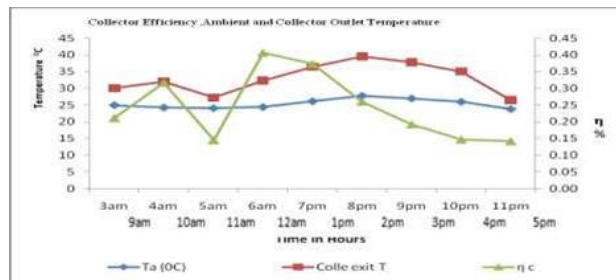**Figure 26:** Fullload total weight loss

Figure 27: Collector efficiency, ambient and collecor outlet temperature

Collector efficiency: The efficiency of the collector is one of the critical factors that affect the drying of the products. Hence as expressed in Standard Efficiency of Solar Dryers (section 2.2.1) the inlet and exist temperature of the air to the collector is a measure of the efficiency of the solar collector. As shown in Figure 27, the average ambient temprature is 26°C which is similar to the designed value. However the efficiency of the collector drop down to 11% at 11 am. But this does not affect the drying efficiency which is 27% at 11 am. And this is due to the heat retaining ability of the solar dryer. In May 24, 2012, the drying of the full-load condition, the cloud is causing the solar radiation to drop to 270 w/m^2 at 11am. The effect is easily noticable as shown in Figure 28 that the collector efficiency is dropped to 11%. However, the average driying efficiency is not affected that much attaning 21%.As shown in Figure 29, the relation among solar radiation, collector efficiency and system drying efficiency is uniform. Therefore, this gives an average collector and system efficiencies of 21% and 19%, respectively.
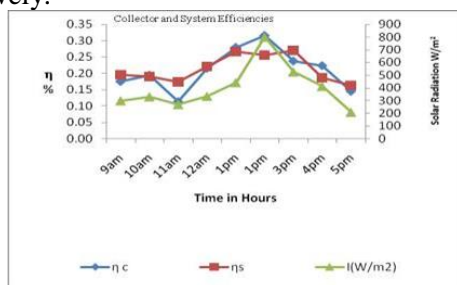

Figure 28: Solar radiation ,collector and system efficiency (May 24, 2012)
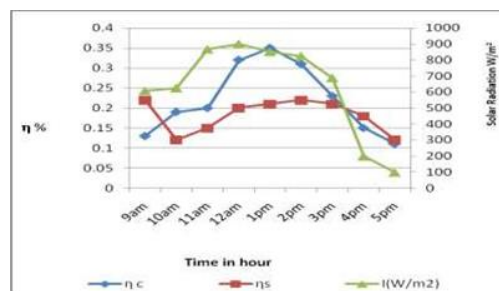

Figure 29: Solar radiation,collector and system ffficiency (May 25, 2012)

CONCLUSIONS

The manufactured natural convectional solar dryer has the capacity of attaining maximum absorber temperature of 77^{0}C when the peak solar radiation is 1021 W/m^2. The average temperature of the hot streaming air from the collector is 42°C which is sufficient to dry the tomatoes and other crops. However; the maximum temperature of the hot streaming air reaches up to 57 ^{0}C. The performance of the solar dryer measured in terms of thermal efficiency is 21.5 % which is good enough for crops to dry. The average air mass flow rate is 0.0564 kg/s which are better than the average common air mass flow rate for convectional solar dryer. The system efficiency which is commonly used to measure the drying rate of the product is 19%.The theoretical average drying rate that is weight lost from the product expressed with respect to time is 0.568 kg/hr however the practical average drying rate is 0.457 kg/hr. The deviation of the theoretical drying rate and the practically drying rate of the solar dryer implies an efficient solar dryer.

REFERENCES

Ethio Resource Group, (2009), Diversity and Security for the Ethiopian Power System, A Preliminary Assessment of Risks and Opportunities for the Power Sector, Heinrich Boll Foundation, Forum for Environment (FfE).

Yaldiz, O. and Ertekin, C. (2001), Mathematical Modeling of Thin Layer Solar Drying of Sultana Grapes, Energy 26(5): 457-465.

BASSEY, M.W (1991), Improving the Performance of Indirect Natural Convection SolarDryers, International Development Research Centre, Dakar, Senegal.

BASSEY, M.W. (1982), Potential Use and Performance of Indirect Free Convective Solar Crop Dryers in Sierra Leone, IDRC Research Project, Department of Mechanical Engineering, University of Sierra Leone.

DRC Research Project No. 3-P-78-0113,