Simulink Design and Analysis of Universal Solar Dryer with Tracking Device

Muhammadu Masin Muhammadu[1]*, Ishkrizat BinTaib[2] and Muhammad Sule-Sarki[1]
[1]Department of mechanical engineering, Federal University of technology, Minna, Nigeria
[2]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
Corresponding author: masin.muhammadu@futminna.edu.ng

Abstract

Preserving perishable food is one of the challenges required to overcome food security and season tomatoes and other vegetables wastage. Forced drying of agricultural products, in particular vegetable - such as tomatoes is one modern methods of perishable food drying. Solar drying uses abandoned solar energy during the day. Effective solar drying requires tracking of the sun by the drying tray. Therefore, this necessitates the development of solar dryer with tracker. Aim of this paper is to design a solar tracking for drying tomatoes. This paper however, presents Simulink design of these applications of Flywheel Energy Storage System (FESS) in power system and also analyses the design parameters in order to improve the solar energy tracker. A solar dryer with solar tracking was designed. The drying chamber has overall dimensions of 457.2 mm x 406.4 mm x 558.8 mm with three drying trays having a drying area of 0.25 m^2 each. The dryer consists of three major units namely, the drying chamber, the solar tracker and a solar powered control. The control unit has four temperature sensors, and four controlled DC fans for varying the air flow rate from the solar collector. The drying chamber is to be lagged with carbon fibre as an insulator. The solar collector made of Aluminum sheet and the glass on top. Fresh tomatoes were used for performance evaluation testing. Each drying tray was loaded with 5 kg of tomato slices of 8 mm thickness from initial moisture content of 93.3% (w.b.) and dried to a final moisture content of 12% (w.b.) in 13 hours, when operated under natural convection current. The maximum drying rate of tomato slices attained under natural convection and forced circulation were 3.1 and 2.8 kg of water per kg of dry matter-hr. For the open-air sun drying, the maximum drying rates for tomato were 1.5 kg of water per kg of dry matter-hr. The dryer was able to remove 52.8% of moisture while tracking the sun, dry basis, from 4.6 kg of product in one day of 10.00 hours drying time, which is about 0.46 kg/hr drying rate. The efficiency of the dryer was 56.25%.

Keywords: Renewable Energy, Device, Food, Moisture, Tracker, and Slices

1. Introduction

Generally, high moisture content in some agricultural produce after harvesting can facilitate the growth of microorganisms resulting in spoilage of the foodstuff. Reducing moisture content of food to between 10 and 20% prevents bacteria, yeast, mold and enzymes from spoiling it (Ahmad and Abdul 2022). Direct open sun drying is the oldest technique used for food preservation. It can reduce wastage of surplus production and also make produce lighter, smaller and easier to handle (Akani, 2009).

This value of moisture content is very much higher than the required for long preservation. Due to this moisture content bacterial and fungal growth is very fast in the crops. Bacterial and enzymes may spoil the product and reduces the nutrient content in it. The moisture content of crops to a certain level slows down the bacterial, enzymes and yeast effect. Therefore, it is necessary to reduce the moisture content in the product for its long preservation. Another case of drying is to remove the total excess water from the product. These dehydrated products regain their original conditions after re-watering whenever necessary to use (El-Sebaii and Shalaby, 2024).

A solar dryer can generate higher sensible heat than the sun-drying process. Consequently, solar-dried products tend to have better product quality and consistencies compared to sun-dried products due to their higher rate of evaporative capacity. Being enclosed in a container, products solar-dried are not exposed to contamination by insects, pests, dust, wind, rain and animal attack. The use of sunlight directly as an energy source has proved in the past to be less economical than the use of other sources of concentrated sunshine (Adeniyi and Muhammadu, 2024).

The radiant energy of the sun is the only source of energy that influences directly or indirectly processes in the atmosphere and surface layer of the earth’s crust since the sun itself is a gaseous sphere, the temperature of which varies from about `6000 °C at the radiating surface to over 1×10^6 °C at the tenuous outer atmosphere of the sun, and over 1×10^7 °C in the deep interior (Bashiru *et al.*, 2021).

The direct use of solar energy means using light, which is a form of electromagnetic radiation. About 9% of this lies in the extremely short and invisible ultraviolet region; about 40% is the visible light and the remaining 51% constitute the long waves (infrared) (Bashiru *et al.,* 2021).

El-Sebaii and Shalaby (2024) classified solar dryers into: direct dryers, indirect dryers, mixed mode dryers and hybrid dryers. He further explained that the direct solar dryer can be made from materials such as wood or metal sheet with saw dust, wood shavings or straw being used as the insulating material. The transparent material can be glass or plastic film. It is noted that for these dryers, whom operate at up to about 30 ℃ above ambient temperature, drying rates are faster compared to open air drying. In the indirect dryer, he noted that the main constraint on the use of these drying methods was inadequate airflow in the free convective mode and high cost. When a fan is used for air circulation, the design of the dryer is relatively straightforward.

Amans *et al.* (2019) stated that in general, a cabinet type of dryer reduces the drying period by one half in comparison to open sun drying and that the shorter drying period improves the quality of agricultural products.

Anugbai and Muhammadu (2019) stated that development of efficient solar drying processes would permit increased production of dried food while reducing industrial dependence on fossil fuels. They explained that technology was available for designing flat-plate solar collectors and thermal storage systems that could be used to heat air for conventional continuous food drying process.

ASHRAE (2009) reported that a continuous drying process might require storage of up to 75 percent of the daily solar energy as thermal energy to provide continuous supply of air at 50 ^{0}c - 70 ^{0}c for overnight use. They further pointed out that for high efficiency and sanitary reasons, the frame should be air tight, except for the vents, which help to direct air flow through the dryer.

Awachie (2019) stated that in developing countries the uses of solar energy technologies in agriculture are most economically viable compared to industrialized countries. The introduction of solar drying system seems to be the most promising alternative in reducing post-harvest losses and could have significant contribution to steady food supply throughout the year.

A study carried out by Ahmad and Abdul, (2022) using a flat-plate solar grain and fruit drying system showed that the cost of drying fruit and vegetable using the dryer was three times less than the cost of drying with conventional green-house type solar dryer and its dried fruit/vegetable output capacity was much higher (7 times) than the conventional system.

Akani (2009) designed and constructed direct and indirect mode type free convection solar crop dryers using mud as a construction material. Further find out found that wooden and soil black surfaces were as good as metal in terms of heat absorption.

2. Materials and Methods

The materials used in fabrication of the solar dryer are listed in Table 1.

Table 1: Materials used in fabrication of the universal solar tracker

S/No	Item	Purpose and Specification
1	Glass	Use for reflection of light
2	Wooden frame	Use for construction of solar collector
3	Absorber	Use for collecting of heat to generate hot air
4	D.C Fan	2 V, 0.5 A, for blowing hot air
5	Air Duct	Plastic Flexible pipe for conveying air
6	PV Module 80 W	80 W solar panel for powering the DC fan and tracking system
7	Angle Iron	1” Mild steel iron, use for solar panel frame
8	Square Pipe	1” Mild steel pipe, used as dryer chamber
9	Insulator	Fiber glass, use as insulator
10	Al–sheet	Use for covering the drying chamber
11	Al–foil	Use for covering inner chamber
12	Wire mesh	0.5 cm ironic rode, used as tray
13	Linear Actuator	For actuating the solar collector

2.1 Description and Working Principles

The schematic diagram of solar tomatoes dryer shown in Figure 1, is comprises of the tracker, air flow solar collector.

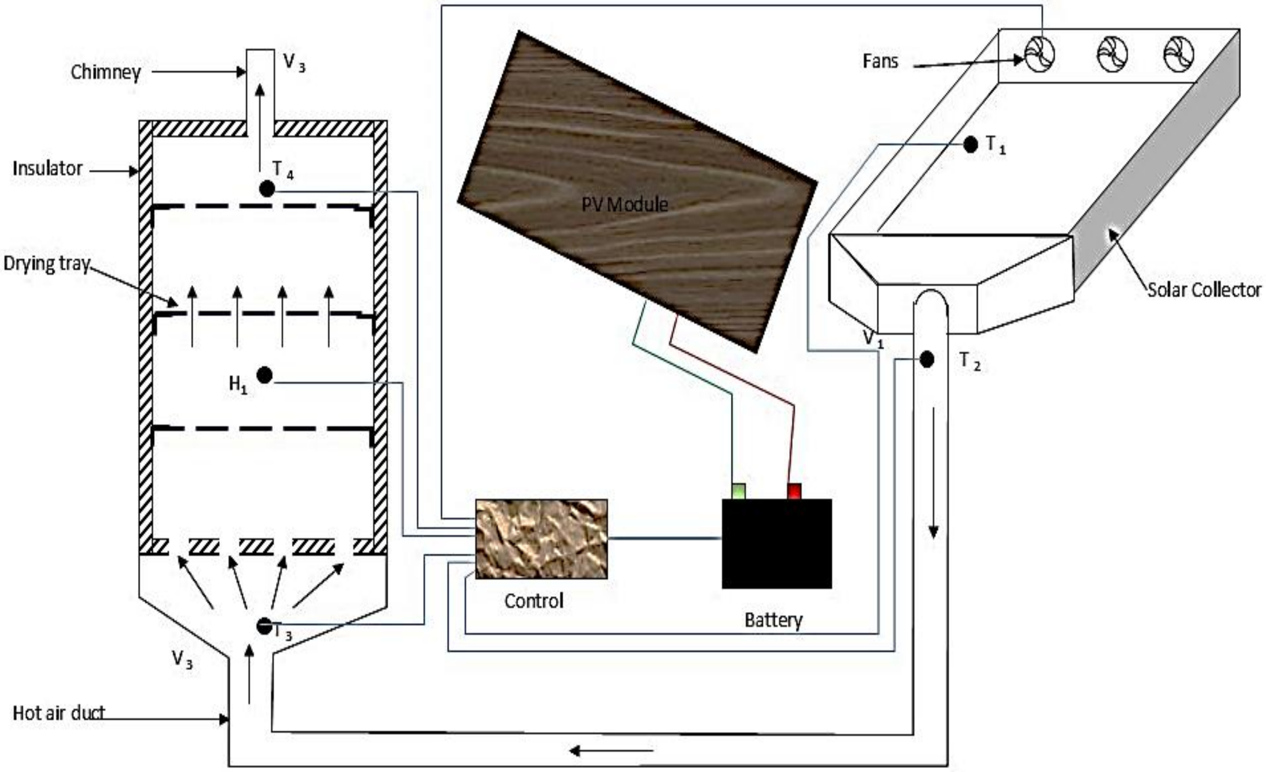

Figure 1: Schematic layout of the universal solar dryer with tracking device drying chamber section and chimney.

The solar collector was designed to track the movement of the sun when working. The solar collects the solar radiation from the sun to heat up an air extracted from the environment and blow the hot air flow through the transparent (glazing) into the tomatoes drying chamber via a mini-DC fans. The air is transported through an insulated air duct. The solar radiation is absorbed into the collector via a black body absorber. The collector is insulated using a fiberglass to minimized heat loss to the environment.

Air from the surrounding pass through an inlet pipe attached to the absorber plate with the aid of an air sucker and when the solar collector, collected the incoming solar radiation from the sun, it heats up the air from the surrounding and the hot air pass through the multiple pipes to exit at the outlet pipe the hot air enters the drying chamber under the effect of thermal force and is placed in shelves and passes through drying trays with tomatoes.

The hot air enters the tomato dryer from the bottom of the dryer and exit from the top of the dryer through a chimney. The hot air losses its temperature before exiting the dry chamber and the tomatoes gain temperature from the hot air, thereby losing its moisture content to a certain level. The entire system is monitor by a control system that is capable of measuring the temperature and humidity inside the drying chamber.

3.0 Design Analysis

The drying of vegetables is analyzed in two face or stages. The first stage is to raise the temperature of the wet materials to a level at which the moisture will be removed. Equations (1) and (2) were used to determining the amount of heat required to remove the moisture content.

$$Q_{Exp.} = M_T C_P (\Delta T) \qquad (1)$$

Where: M_T – Mass of tomatoes (kg), Cp – Specific heat capacity (kJ/Kg°C), ΔT - Change in temperature (°C), $Q_u = A_c \,.\, F_c \,.e\, .IH$, Fr = heat remitter factor (0.7 for an air collector), E = Effective transmittance (0.5 for transparent white polyether), I = Total solar radiation per unit area,

Q = 40 m x 0.7 x 0.5 x 500

=7000 W

= 7.0 kJ/s

Therefore, energy required for 1 hr (3600 S), 7.0 x 3600 = 25200 kJ/hr, and for 10 hrs, 10 hr x 25200 kJ/hr = 252000 kJ/day. Therefore, the period that will be required is

$$\frac{8k}{2k/d} = 4\ days$$

However, determination the quantity of water or moisture to be removed in drying substances is directly connected to the amount of drying space. According to ASHRAE (2009), equation (2), can be used to determine the quantity of water in a drying substance.

$$M_w = \frac{W_w\,(M_i - M_f)}{1 - M_f} \qquad (2)$$

Furthermore, the average daily solar insulation of Minna, is 12.58 MJ/m^2/day and for an ambient temperature of 33 °C and F = 500 W/m^2. The collector efficiency ranges between 30% to 40%. Other factors that influence the collector efficiency are temperature, air flow rate, isolation that of cover material use, and absorber plate, type of insulator use. An efficient of 30% was chosen and this mean that the expected energy production is can be determined by Equation (3):

$$Q_{exp.} = I \times \eta_{collect} \qquad (3)$$

$Q_{exp.} = 12.58 \times 0.38$

$Q_{exp.} = 4.7804$ MJ/m^2/day

Therefore, the collector area required is given by Equation (4)

$$A_c = \frac{Total\ drying\ energy\ required}{Solar\ energy\ product} \qquad (4)$$

$$A_c = \frac{718.200}{14.34},$$

$A_c = 5.0\ m^2$

Therefore, the total collector area required is 5.0 m^2 and considering a collector dimension ratio of 1:1:5, the collector width = 0.8 m while the length is 1.12 m was used.

In addition, recommended drying temperature for the fruits and vegetables (Tomatoes inclusive) is between 37.7 °C to 54.4 °C [Bashiru *et al*., 2021]. Any temperature below this range may not effectively dry the material and if the temperature is higher than the recommended, it may cause sugar caramelization (browning of sugar) for many fruits products.

Also, energy efficiency in drying is of obvious importance as energy consumption is such a large component of drying costs. So this adiabatic air-drying efficiency, (ŋ), can be defined by: The efficiency (ŋ) of the energy efficiency in drying was calculated using Equation (5).

$$\eta = \frac{T_1 - T_2}{T_1 - T_a}\ x\ 100 \qquad (5)$$

where: T_1 is the inlet (high) air temperature into the dryer, T_2 is the outlet air temperature from the dryer, and T_a is the ambient air temperature. The numerator, the gap between T_1 and T_2, is a major factor in the efficiency.

Then, the rate of mass transfer is proportional to the potential (pressure or concentration) difference and to the properties of the transfer system characterized by a mass-transfer coefficient, we have

$$\frac{dw}{dt} = k'_g . A . \Delta Y \qquad (6)$$

where: dw is the mass (moisture) being transferred kgs^{-1} in time dt, A is the area through which the transfer is taking place, kg' is the mass transfer coefficient in this case in units $kgm^{-2}\ s^{-1}$, and ΔY is the humidity difference in $kgkg^{-1}$

So also, air flow rate affects the performance of the dryer, therefore, determining air flow rate in the dryer is a function of the cross-sectional area of a duct and the distance the air travels with time. Then the cross-sectional area can be easily determined and the volumetric flow calculated.

$$Q = A.V \text{ (m}^3\text{/s)} \tag{7}$$

where: A = area (m^2) and V = air velocity m/s.

This comprised of the supporting frame, the jack that provides the linear motion and the mechanism for translating the linear motion into a rotary motion for the flat solar collector. Therefore, the position, velocity and torque equations of the tracking mechanism are given by Equations (8) - (10).

$$Xd = b.cos\theta + (a^2 - b^2 sin\theta)^{1/2} \tag{8}$$

$$V_d = -\left[bsin\theta + \frac{bcos\theta\ sin\theta}{a^2-b^2sin^2\theta}\right]\dot{\theta} \tag{9}$$

and $T = m_1ga \times cos\theta + m_2ga \times cos\theta \times sin\theta$ (10)

where: a – Jack length (cm), b – half of collector length (m) and c – angle that the jack makes with horizontal (degree).

Fabrication Procedure - PV Module Stand: The 80 W solar use has a side of 0.8 m x 1.2 m and there from 1” angle iron (mild steel) was cut using hacksaw and joint together with the aid of a bolt and nut to form the frame for the PV-module. The supporting stand of the PV-module was also fabricated using a 1” mild steel equal angle iron. The stand was also bolted together using a M5 bolt and nut. The PV-module frame and PV-module stand was coupled via a pivoted pin joint.

To determine the air flow rate required for drying; the useful energy has to be estimated. The volumetric flow rate of the air at the drying section is

$$V = \frac{Ma}{\rho} \tag{11}$$

3.1 Computational Fluid Dynamics (CFD) simulation components

For accurate simulation of the air flow and temperature distribution, particularly in complex dryer geometries, CFD is employed. This involves solving the fundamental conservation equations for the fluid (air) and the solid (vegetables) within the computational domain. Simulating a model on ANSYS, requires the implementation of correct governing equations and applying appropriate boundary conditions. In CFD, a finite volume method is used to resolve the governing equations of flowing fluid. This method involves dividing the flow domain into several control volumes and applying the fundamental laws of conservation on them [Iranmenesh *et a*l., 2020]. For determining the characteristic properties of the fluid domain, several conservation laws are considered. The laws involved are stated below [Demissie *at al*., 2019]:

Conservation of mass:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0 \tag{12}$$

Conservation of momentum (Navier-Stokes equations):

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot(\tau) + \rho\vec{g} + \vec{F} \tag{13}$$

Conservation of energy:

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot(\vec{v}(\rho E + p)) = \nabla\cdot\Big(-q + \sum_j h_j\vec{J}_j + (\tau_{eff}\cdot\vec{v})\Big) + S_h \tag{14}$$

where ‘ρ’ is the fluid’s density, ‘v’ is the velocity with which the fluid flows, ‘ρg’ is the gravitational force, ‘F’ being the external force applied, static pressure is represented by ‘p’ and ‘V’ is the viscosity. CFD is applied to determine the airflow and temperature variation within the solar dryer. A mathematical model is generated by providing the necessary boundary conditions, and result data and contours are obtained. The flow of the CFD simulation process is depicted in Figure 2.

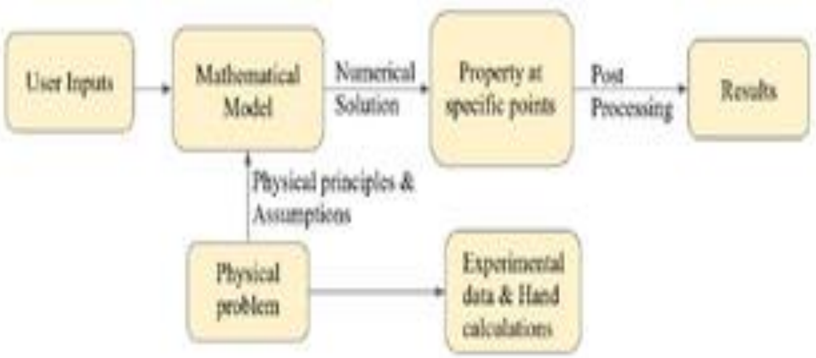

Figure 2: Flowchart representing CFD simulation process [Iranmensh *at al.*, 2020]

3.2 Meshing

Meshing was carryout for calculating the governing equations at the required points and defining the domain. To simulate the result on the analysis software, a refined tetrahedral shaped mesh with 102946 nodes as well as elements of 630116 were generated over the completely assembled solid model. Table 2 indicates boundary conditions used for simulation.

Table 2: Boundary conditions

Region	Boundary conditions	Value
Inlet	Mass flow-inlet	0.0872 kg/s
Outlet	Pressure-outlet	0 Pa
Absorber	Heat flux	992 W/m^2
Wall	No-slip, Convection	5 W/m^2
Ambient Temperature	---	27 ^{0}C

4.0 Design Analysis Results

The model equations presented here were solve numerically. The amount of heat required to remove moisture content of the tomato from 80% to 20% was computed to be 332640 Joules at a device drying efficiency of 65.52%. The drying area of the drying chamber was computer to be 0.264 m^2 with a drying space of 0.2123 m^3. The air flow rate is 0.732 m^3/s. while the mass of the water removed is 7.62 kg during the drying period, when drying tomatoes.

The results of the tracking device show a maximum velocity and acceleration of 0.2 m/s and 0.05 m^2/s which occur at an angle 5 ^{0}c while the positioner is tracking the sun. The velocity of the collector increases steadily, while the acceleration remains almost constant as indicated in Figures 3 – 5 respectively. Figure 5 show increases in the velocity up to 1.1 m/s as the time also increases up to 5 sec and the degree decreases linearly. Figure 3 indicates angular position of the Solar Collector.

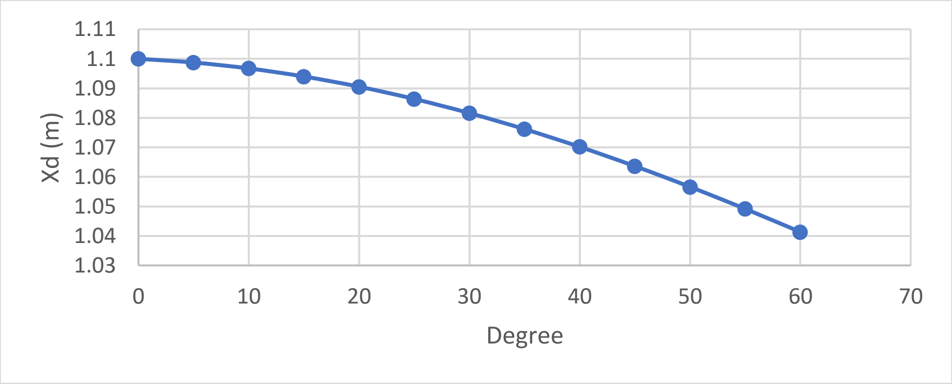

Figure 3: Angular position of the Solar Collector.

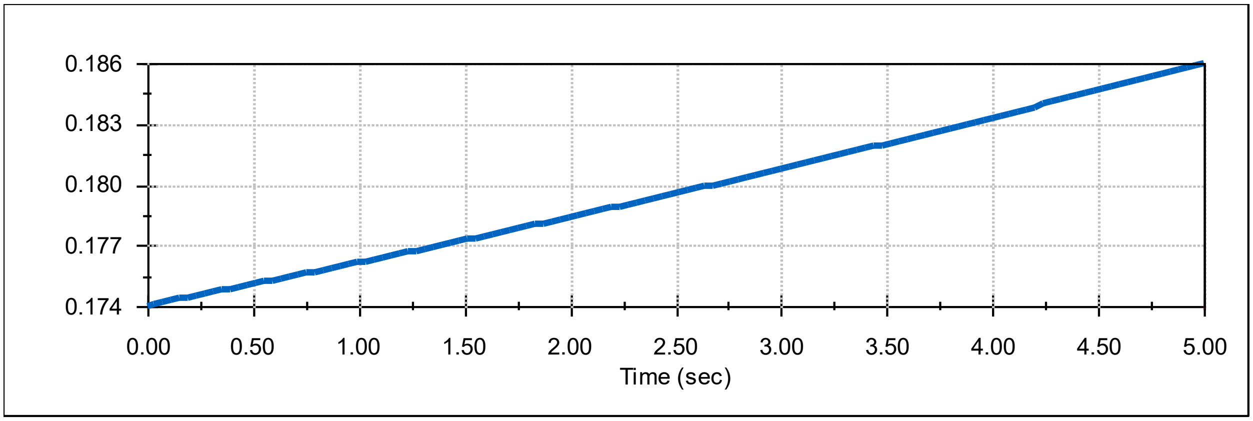

Figure 4: Velocity Profile of the Solar Collector.

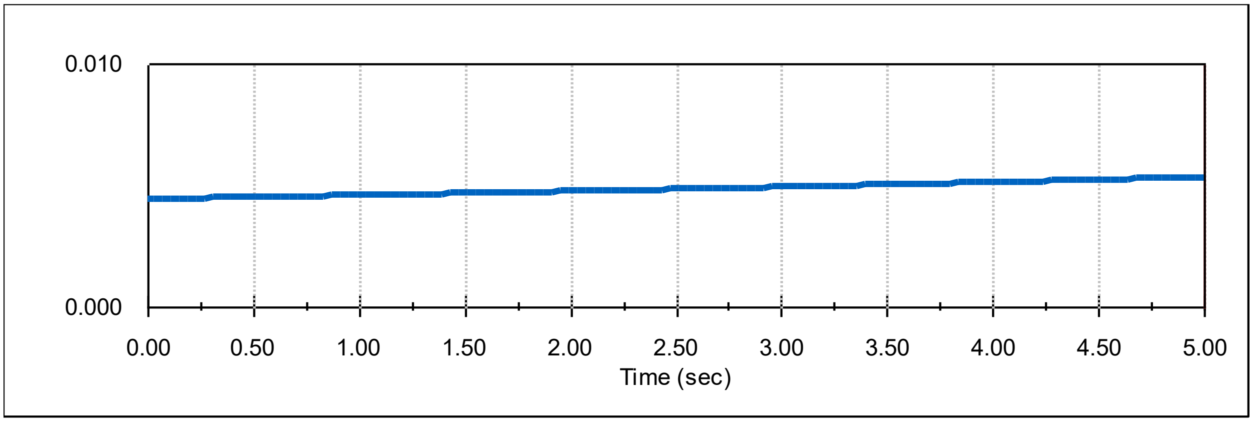

Figure 5: Acceleration Profile of the Solar Collector.

4.1. Simulation Results

The results of the simulation are presented in Figures 6 and 7. The first set of the result is a temperature colour map of the drying chamber presented in Figure 6. the highest temperature of the chamber is at the inlet of the drying chamber which is 345.37 K and 335.10 K at the outlet of the drying chamber. Tray 1, 2, 3 have an average temperature of 338.1 K, 336.8 k and 335.1 K respectively. Figure 6 shows drying chamber temperature color map.

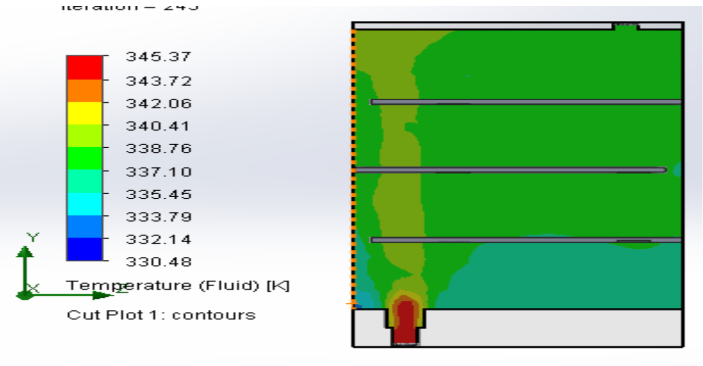

Figure 6: Drying Chamber Temperature Colour Map.

Figure 7 shows the air velocity color map, and can be seen that the air velocity is higher at the inlet and the air drop the velocity as it hits the top wall before exiting the drying chamber at about 3 m/s.

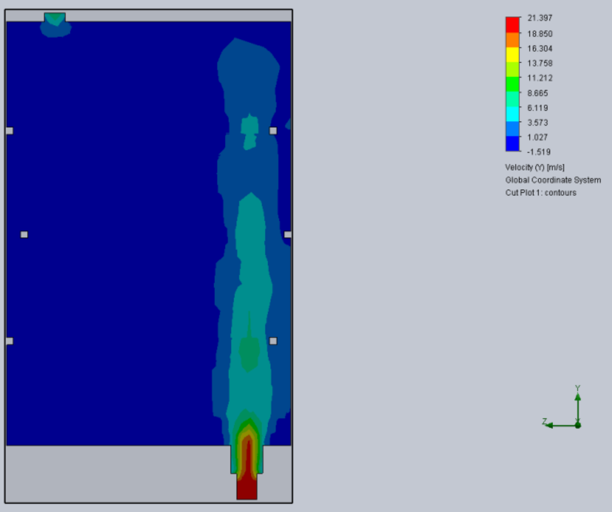

Figure 7: Drying Chamber velocity Colour Map.

The summary of the simulation results is presented in Table 3, this shows the minimum, average and maximum values of the simulation goals. Table 3 shows summary of simulation results.

Table 3: Summary of Simulation Results

Goal Name	Unit	Averaged Value	Minimum Value	Maximum Value
GG Average Temperature (Fluid) 1	[K]	335.66	334.32	336.90
GG Average Total Temperature 1	[K]	335.66	334.32	336.90
GG Average Density (Fluid) 1	[kg/m^3]	1.05	1.05	1.06
GG Mass Flow Rate 1	[kg/s]	0.00	0.00	0.00
GG Volume Flow Rate 1	[m^3/s]	0.00	0.00	0.00
GG Average Velocity 1	[m/s]	0.68	0.67	0.68
SG Inlet Mass Flow 1 Static Pressure Av	[Pa]	101407.24	101406.57	101407.59
SG Inlet Mass Flow 1 Total Pressure Av	[Pa]	101622.60	101621.92	101622.95
SG Inlet Mass Flow 1 Velocity Av	[m/s]	20.51	20.51	20.51
SG Inlet Mass Flow 1 Absolute Total Enthalpy Rate	[W]	7047.93	7047.93	7047.93

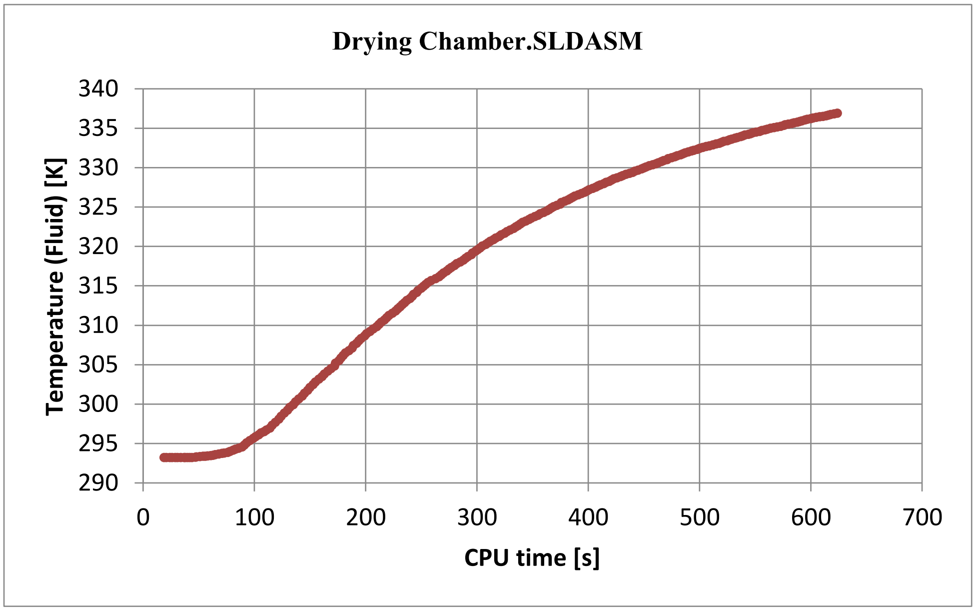

Figure 8: Temperature Profile of the drying chamber

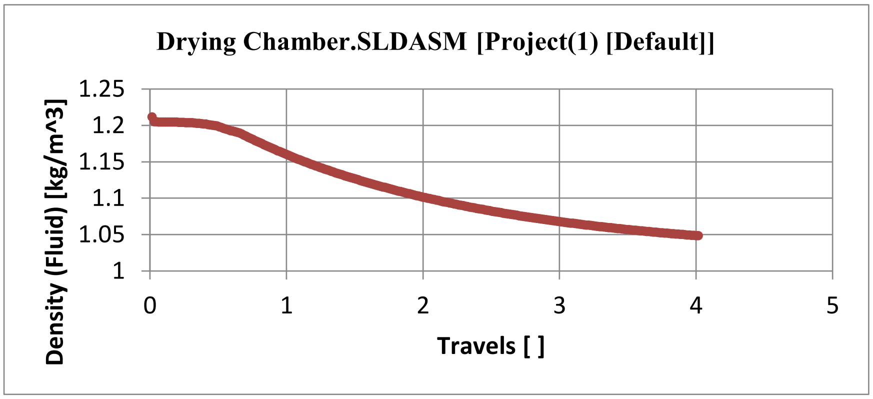

Figure 9: Air density Profile of the drying chamber

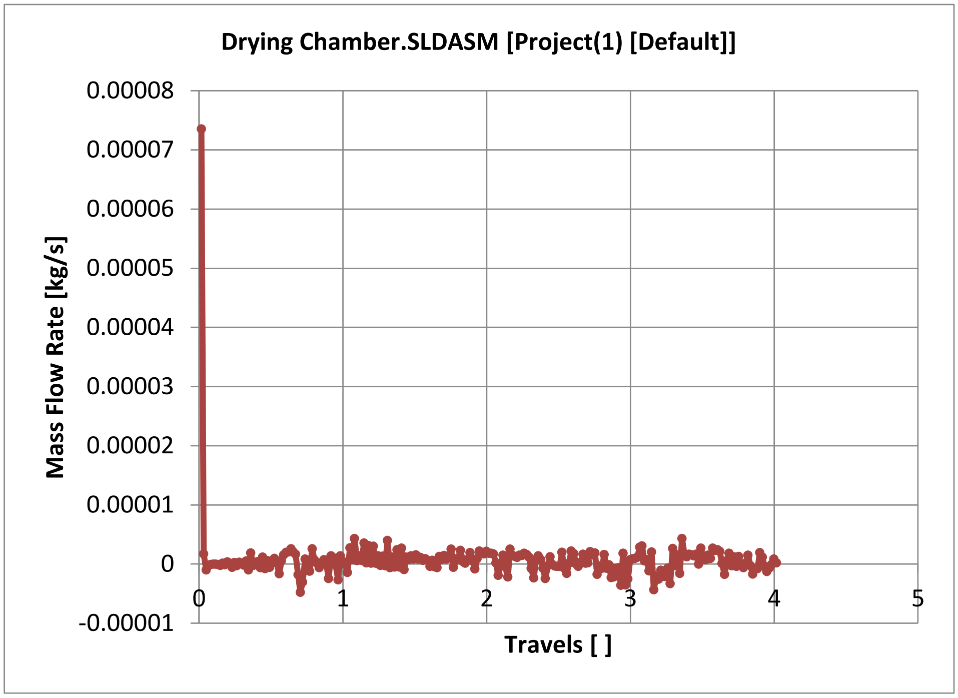

Figure 11: Mass flow rate Profile of the drying chamber

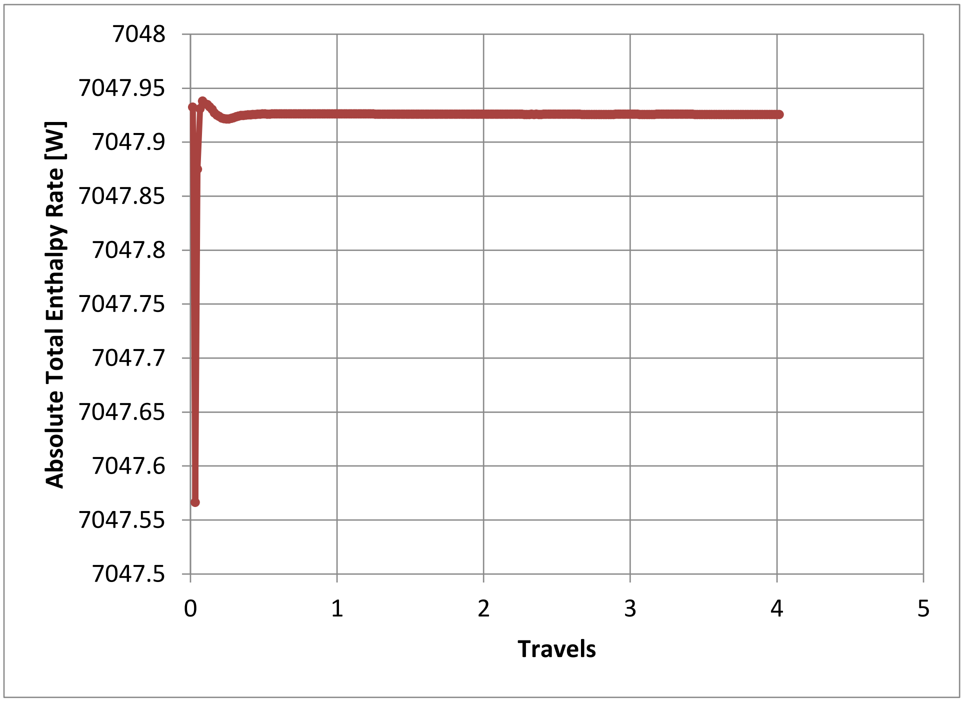

Figure 12: Total Enthalpy rate Profile of the drying chamber.

The drying curve of the product is shown in Figures 9 and 10, it was observed that the drying rate increased due to increase in temperature between 10.00h and 14.00h but decreased thereafter, which shows the earlier and faster removal of moisture from the dried item. The dryer was able to remove 52.8% of moisture, dry basis, from 4.6 kg of product in one day of 10.00 hours drying time, which is about 0.46 kg/hr drying rate. This rate compare well with the rate obtained from other dryers. Bashiru *et al*. (2021) obtained a drying rate of 0.03 kg/hr for yam chips using forced convection solar crop dryer for rural application in Nigeria. The system drying efficiency of the simple solar dryer during the test period was found to be 65.52%. Figure 12, it was obsevered that as travels increases, absolute total Enthalpy rate also increases and at 7047.94 W increases in straghtline respectively as when correlated with results ASHRAE (2009).

5. Conclusion

A solar dryer with sun solar tracker was successful design. The dryer has a three-layer drying chamber and the tracker was equipped with a Light resistance sensor to enable the device to track the sun as it changes position for a more efficient utilization of the solar energy as design. A control unit was developed to control the movement of the jack or collector actuator using the LDR sensor.

The dryer has a drying area of 0.21 m^2 the developed dryer has a thermal efficiency of 65.52% and a flow rate of 0.732 m^3/s. The hourly variation of the temperatures inside the dryer compare to the ambient temperature shows that the temperature in the dryer is always above the ambient temperature by average of 21.6 0^C (37.7 %) throughout the daylight hours. The tray temperature rise was up to 52.4 0^C for about three hours immediately after noon time (between 13.00 h and 15.00 h).

The drying rate and system efficiency were 0.46 kg/h. The dryer exhibited sufficient ability to dry food items reasonably rapidly to a safe moisture level and simultaneously it ensures a superior quality of the dried product. The results achieved are possible indications that solar dryers have a future especially in food preservation. However, a lot still has to be done to improve the performance of passive solar dryers. A possible area of improvement is on the use of solar storage systems in the dryer to store heat for use when insolation is insufficient due to adverse weather conditions and in the night when insolation is totally absent.

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