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DESIGN, CONSTRUCTION AND PERFORMANCE ASSESSMENT OF A HYBRID SOLAR DRYER USING FORCED CONVECTION PRINCIPLE

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Abstract

In developing countries like Nigeria, local farmers are always facing challenges on drying and preservation of the agricultural products after harvesting due to losses in quality and quantity of the products by using local drying method, to address the problem, solar drying system is used. This study presented design, construction and performance assessment of a hybrid solar dryer using forced convection principle for drying of tomato slices. The system consists of solar collector, drying chamber with four drying trays, solar photovoltaic for powering fans and adding more heating in the evening and/or cloudy hours and chimney. The result revealed that for all the testing days, the air temperatures at the drying chamber were greater than that at ambient, solar collector and chimney outlet. It was also found that the solar dryer has a drying rate of 0.274kg/hr while the dryer efficiency and collector's efficiency were 50.2% and 43.03% respectively. It was recommended that the solar drying system should be used to dry and preserve the agricultural products without losses in quality and quantity of the products.

Key words: *Air Temperature, Chimney, Drying Chamber, Relative Humidity, Solar Collector*

1. Introduction

Nowadays, in order to maintain the quality of most agricultural products (Cereals, Fruits, Vegetables) after harvesting, they need to be dried and preserved. Therefore, drying has become very important in the agricultural sector.

It was found that when the temperature of the agricultural products (Cereals, Fruits and Vegetables) reaches 271°K, the contaminated micro-organism were killed away from the products, this will prevent about 10% and 20% bacteria, yeast, moulds and enzymes of agricultural products from spoiling by reducing the moisture content of the products [1]. Traditionally, farmers used some food preservation techniques such as drying, refrigeration, freezing, salting (curing), sugaring, smoking, pickling, canning and bottling. The traditional drying is known as direct (open) sun drying and it is common and widely used method for drying agricultural products, although it is simplest and cheapest method but it includes contaminations, losses, damage by birds or insects and slow drying [2-5]. Lack of foodstuffs in developing countries like Nigeria is links to this local drying method that cause significant losses with is estimated as 40% [6, 7].

Solar thermal technology as one of the wider applicable solar energy technologies, it is also playing vital role in agricultural application due to it nature of abundantly, non-polluting and inexhaustible [8-11]. In tropic areas, where there is at least six (6) hours of sunshine, solar dryer is higher important for the farmers to dry the moisture contents of the agricultural products [12]. Solar drying has many advantages such as time saving, free, low cost of maintenance, improvement of the product quality, environmental protection, and control of required air condition [13-20].

Solar dryer is basically divided into two types namely passive (Natural Convection) solar dryer and active (Forced Convection) solar dryer. Passive solar dryer is also sub-divided into direct, indirect and mixed-mode passive solar dryer while active solar dryer is divided into direct, indirect and hybrid active solar dryer [21, 22].

In indirect dryers, solar energy collected by the solar collector is passing to the drying chamber where the drying products are sprayed on the trays, and the mixed-mode type of dryer has the same operations with the indirect solar dryer but the different is that the wall or roofing of the dryer are made up of transparent materials with high absorbance of solar energy. Whereas direct solar dryers, the drying products are arranged on the plate tray inside the solar collector with the transparent cover through which the solar energy is passed by radiation and the heat is absorbed by the drying products by means of conduction [23].

Hot air is circulating to the drying chamber using fans in forced convection dryers, while in natural convection dryer fan is not used to circulate the hot air. Forced convection dryer is more efficient than the natural convection dryer since the hot air is circulating to the drying chamber, this will yield high rate of drying of the agricultural products [15, 24].

One of the limitations of forced convection dryer, it may not be applicable in rural areas since it required fan and a source of electricity is required to drive the fan [25]. Hybrid solar dryer is a dryer that has a combination of two or more energy sources. It makes use of solar energy during the day and an alternate energy source at night. The alternate source of energy could be electricity, diesel, biomass or solar PV which is used to powered the fan in forced convection solar dryer [26].

2. Materials and Method

2.1. System's Description

The hybrid dryer consists of four components namely; solar collector, drying chamber, solar photovoltaic and chimney. The solar collector is used to absorb solar radiation and convert it to heat energy, this energy is then passed to the drying chamber where the drying products are arranged on the trays of the drying chamber. The solar collector used in this study is double passed air collector in order to increase the amount of air entering to the solar collector opened at one end to allow atmospheric air enters into it while another end was connected to the drying chamber. The solar dryer is using forced convection principle; therefore, the fan was placed at the air inlet of the drying chamber, this fan pushes the air into the drying chamber in the morning and it used to circulate the inside air at night.

The drying chamber contains four (4) trays which is made up of wire mesh on which the agricultural products spread on. The chimney was provided on top of the drying chamber to decrease the relative humidity of the air around the drying chamber, facilitate and control the convective flow of air through the drying chamber and the chimney has cover to prevent water or rain from entering the drying chamber. The two opposite sides of the drying chamber were glazed to collect additional solar radiation. A side door was provided for ease access with trays when loading and offloading of the drying products. The thermal storage material was sprayed on the bottom of the drying chamber which heat the air in the drying chamber, and it will reduce its moisture content because the storage material has adsorptive characteristic. The solar photovoltaic was used to generate electricity which will then be used to power the fan.

2.2. Materials Selection

Materials used for construction of the system was selected based on cost, reliability, functionality and processability of the materials.

Table 1 shows the components of the system, materials used and reason(s) for selections:

Table 1: Materials Selected for Construction of the System

Components		Materials Selected	Reason(s)
Solar Collector	Absorber Plate	Galvanized Iron Sheet	High solar radiation absorption, thermal emissivity, corrosion resistance and strong [27]
	Glazing	Perspex glass	Cheap, ease to processing and strong [28]
	Insulation	Sawdust	Cheap and availability
	Frame Cover	Plywood	Cheap, ease to process and strong [28]
	Black Pebbles	Rocks	Cheap, ease to process and strong [28]
Drying Chamber`	Chamber Cover	Plywood/Silica Glass	Availability, reliability and ease processing [28]
	Tray	Wire mesh	Maintainability, strong and cheap
	Chimney	Mild steel	Low cost and ease processing [27]
	Thermal Storage material	Gravels	High insolation and absorption characteristics
Solar Photovoltaic		Polycrystalline Silicon	High solar radiation absorption
Supporting Stand		Mild steel	Cheap, ease to process and strong [28]

2.3. Design Considerations and Assumptions

The following were considered or/and assumed in designing of forced convection hybrid solar dryer:

i. The effect of dust on the solar collector and solar photovoltaic are negligible.
ii. The solar collector operates under steady state conditions.
iii. The amount of solar irradiance falling on the collector and photovoltaic to be available.
iv. The amount of moisture from the fresh agricultural products to be removed.

2.4. System's Components Desisgn

The components of the solar dryer were designed based on the materials selected as follows:

2.4.1 Design of the Solar Collector

a. Energy Balance for Solar Collector

For the solar collector to be properly designed, the heat gained by the collector must be equal to the heat lost by the collector [8].

$$Heat\ Energy\ Gained = Heat\ Energy\ Lost$$

$$I_T A_c = Q_u + Q_l + Q_p \tag{1}$$

But $Q_u = \alpha\tau I_T A_c - Q_l$, $Q_l = Q_{Cond} + Q_{Conv} + Q_R$ and $Q_p = \rho\tau I_T A_c$

Where:

I_T = total amount of solar irradiance harnessed by the absorber's surface (Wm^{-2});

A_c = area of the collector (m^2);

Q_u = rate of useful energy collected by the air (W);

Q_{cond} = amount of conduction losses from the absorber (W);

Q_{conv} = amount of convective losses from the absorber (W);

Q_R = amount of long wave re-radiation from the absorber (W);

Q_ρ = amount of reflection losses from the absorber (W);

τ = transmittance of the top glazing(dimensionless);

ρ= coefficient of reflection of the absorber and

α = solar absorptance (dimensionless)

If τ is the transmittance of the top glazing and I_T is the total solar radiation incident on the top surface, therefore, $I_T A_c = \tau I_T A_c$ and $Q_l = U_l A_c (T_c - T_a)$

Where: U_L = overall heat transfer coefficient of the absorber ($\mathrm{Wm}^{-2}\ \mathrm{K}^{-1}$); T_c = temperature of the collector's absorber (K) and T_a = ambient air temperature (K).

Therefore, the useful energy gained by the collector is expressed as:

$$Q_u = \alpha\tau I_T A_c - U_l A_c (T_c - T_a) \tag{2}$$

Finally, the energy absorbed per unit area (q_u) by the collector will become:

$$q_u = \alpha\tau I_T - U_l (T_c - T_a) \tag{3}$$

The heat gained by air (Q_g) is given as [29]:

$$Q_g = \dot{m}_a C_{pa} (T_c - T_a) \tag{4}$$

Where $\dot{m}_a$ is mass flow rate of air through the dryer per unit time (kg/s) and C_{pa} is the specific heat capacity of air (kJ/kg K).

The heat removal factor (F_R) in the collector can be calculated using expression given by [30]:

$$F_R = \frac{Q_g}{Q_u} = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{\alpha\tau I_T A_c - U_l A_c (T_c - T_a)} \tag{5}$$

b. Sizing of Solar Collector

Sizing of solar collector is based on meteorological and crop parameters. The required area of the collector for solar dryer is given by [31].

$$A_c = \frac{Q_{load}}{\eta I_T t_d} \tag{6}$$

Where:

Q_{load} is the drying head load (W);

t_d is a drying time (hours) and

η is an efficiency of the collector (%).

The area of the absorber A_{ab} is approximately equal to the area of the collector, A_c; this is related to the length, L_c and width, W of the solar collector as follows:

$$A_{ab} = A_c = L_c \times W \tag{7}$$

2.4.2 Design of Drying Chamber

A. Amount of Moisture to be Removed

The total amount of moisture to be removed (Mw) from the agricultural product is given by [5] as:

$$M_w = W_w \left(\frac{M_i - M_f}{1 - M_f}\right) \tag{8}$$

Where

M_w = amount of moisture removed

W_w = total weight of the products before drying;

M_i = initial moisture content on wet basis and

M_f = final moisture content on wet basis;

B. Energy Balance for Drying Chamber

The amount of heat energy (Q_m) needed to remove moisture from the agricultural product was obtained through the relation [32]:

$$Q_m = M_p C_p \Delta T + M_w L \tag{9}$$

Where:

M_p is the mass of the product to be dried (kg);

Mw is the mass of water removed (kg),

ΔT is the change in temperature in °C and

L is the latent heat of vaporisation of water.

The quantity of heat stored (Q_{hs}) by the heat storage media can be obtained by using the equation [33]:

$$Q_{hs} = M_{hs} C_{hs} \Delta T \tag{10}$$

Where:

M_{hs} is the mass of heat storage medium (kg); and

C_{hs} is the specific heat of the heat storage medium ($kJkgK^{-1}$).

C. Sizing of Drying Chamber

The breadth of the drying chamber, B, is usually equal to the width (W) of the solar collector. Thus, the length of the drying chamber, L_{dc}, is determined from the relation:

$$L_{dc} = \frac{A_{dc}}{W} \tag{11}$$

Where: A_{dc} is the area of drying chamber

2.5. Construction of System's Components and Assembly of the Solar Dryer

The system's components were constructed using the selected materials and available tools. The Tools used in the construction are hammer, handsaw, paint brush, chisel, measuring tape, screw driver, square/straight edges, rolling machine, grinding machine.

2.5.1 Solar Collector

The solar collector sized (1100 x 600 mm) was constructed. The solar collector consists of transparent cover, absorber plate and insulation. Galvanized iron sheet of 2 mm thickness was used for absorber plates and the absorber plates were painted black to increase its solar radiation absorption, the transparent cover is made from 4 mm thickness of Perspex glass. The collector frame was made from plywood and covered it is one end with galvanized wire mesh and a sliding door was attached to control the air flow into the dryer. At outlet of solar collector, a fan was mounted provide the forced convection to the drying chamber. To minimize heat loss from the absorber plate, black pebbles (Rocks) were spreads below the first absorber plate.

2.5.2 Drying Chamber

The drying chamber consist of four (4) trays made up from galvanized wire mesh which is riveted on the wooden frame, to regulate the temperature of the chamber, four (4) thermostats were installed under each tray. The trays are designed to be removable for easier cleaning and loading potential. The two opposite sides of the drying chamber were made from silica glass to increase the amount solar irradiance absorbed. This further increases the convective air flow and additional heating necessary for drying. Access door to the drying chamber was constructed using plywood which is painted black to enhance elevated temperature within the chamber.

A mild steel of 2 mm thickness painted black was used to form a chimney to control the flow of air through the drying chamber. A metallic cup was provided at the top of the chimney to prevent rain, insect and wind from entering the drying chamber. Gravels were spreads at the bottom of the drying chamber as a thermal storage material to absorb heat during the day hours and subsequently dissipate heat at night or during cloud cover.

2.5.3 Solar PV system

The solar photovoltaic module made from polycrystalline silicon rated 200 W was placed on the roof of the drying chamber, a charge controller, an inverter and 150A battery to provide the power for the fan.

The solar collector was oriented facing south and both the solar collector and the roof of the drying chamber tilted at 22.2° to the horizontal. This is 10° more than the local geographical latitude of Kano a location in Nigeria, (12.2° N) [34].

3. Performance Evaluation of Hybrid Solar Dryer

3.1. Experimental Set-up

The hybrid solar dryer was tested to evaluate the performance of the system, the tests were done March, 2020. The tests were conducted for four (4) days, the first day test was done under offload condition (without tomato slices loaded) and the subsequent days under load condition (with tomato slices loaded) starting by 9:00 am with intervals of one (1) hour. The measurement variables included air temperature (ambient, collector, drying chamber and chimney outlet), relative humidity (ambient, drying chamber and chimney outlet), solar radiation intensity, mass of drying tomato slices and wind speed drying air.

After taking reading of the measuring variables under offload condition, the tomato slices were arranged on the dryer tray and the door was closed then the measuring variables were read and recorded with one (1) hour interval starting by 9:00 am for each testing days.

In the evening and/or during cloud days, the door, cover of chimney and sliding door of the inlet of the solar collector were closed in order to maintain the heating condition of the drying chamber, in this case the storage material is giving out the heat storage and used to dry the products.

The temperatures of the hot air were measured using thermocouple device and wire while psychrometer was used to measure the relative humidity of the variables. The anemometer was used to measure the wind speed and amount solar irradiance harnessed by the collector using solarimeter.

3.2. Drying Rate

For the solar dryer to work efficiently, the rate at which the drying products are drying should be known. The drying rate is given by [35] as:

$$R_d = \frac{M_w}{t_d} \qquad (12)$$

Where:

R_d is the drying rate (kg/hr), and

M_w is the mass of evaporated water (kg)

3.3. Percentage of Moisture Loss

The percentage of moisture removed from the agricultural products (on wet and dry basis) can be expressed as given by [36] as:

$$MC = \frac{M_1 - M_2}{M_1} \times 100\%\ wet\ basis \tag{13}$$

Where:

MC is the percentage of moisture loss (% wb) and

M_1 and M_2 are the initial and final masses of the drying products respectively (kg).

3.4. Dryer Efficiency

The efficiency of the solar dryer can be found using the relation given by [37] as expressed:

$$\eta_{dryer} = \frac{M_w L}{A_c I_T t_d} \tag{14}$$

3.5. Solar Collector Efficiency

The solar collector efficiency used for solar drying system is related in the expression given by [38] as:

$$\eta_c = \frac{\rho_a v_a c_p \Delta T}{I_T A_c} \tag{15}$$

Where:

V_a is the volumetric flow rate of air (m^3/s), and ρ_a is the density of air.

4. Results and Discussion

Amount of solar irradiance incident on the solar collector for four (4) days of conducting experiments were shown in figure 1.

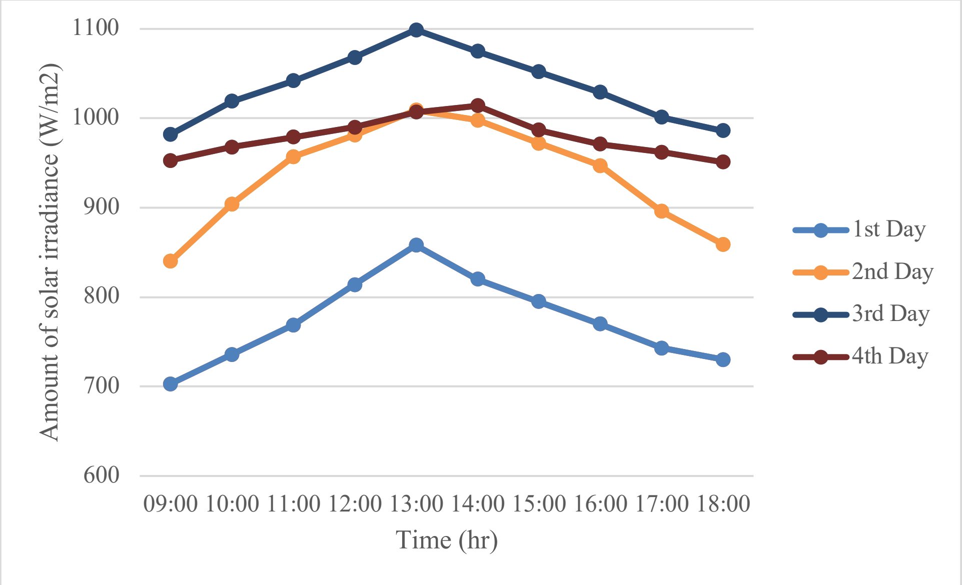

Figure 1. Amount of Solar Irradiance against time for four (4) days

It was observed that the amount of solar irradiance attains it is maximum values between 12:00 to 14:00 for all the testing days and in the third (3rd) day, the solar collector absorbed more solar irradiance. The average solar irradiance harnessed by the collector for the testing days were 773.8W/m^2, 936.3W/m^2, 1035.3W/m^2 and 978.2W/m^2 respectively.

Figure 2 presents the air temperature (ambient, collector, drying chamber and chimney) against time for 24 hours testing when the solar drying chamber was under offloading condition.

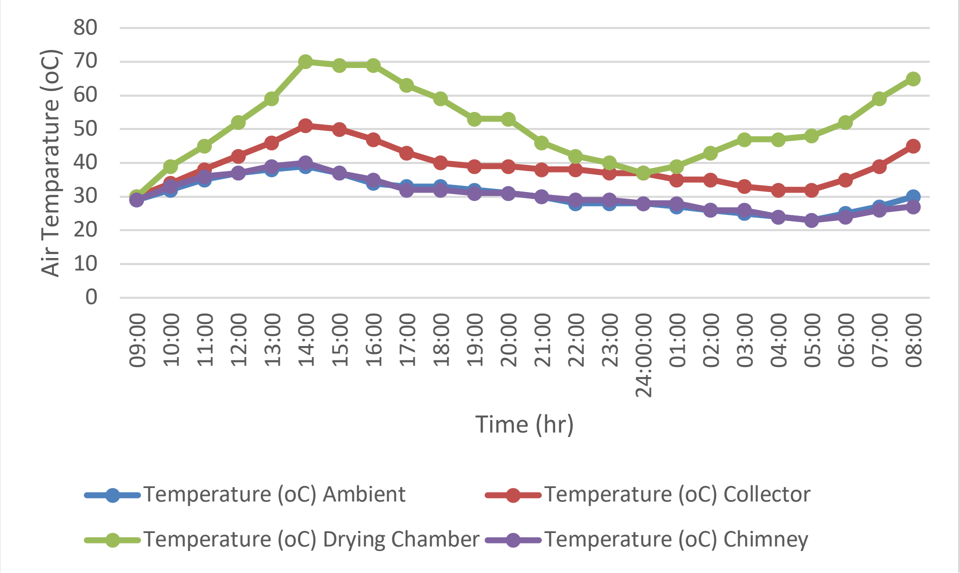

Figure 2. Air Temperature against Time for offloading Condition

From figure 2, the air temperature of all the measuring variables were increasing from 9:00 and reaches their maximum values between 12:00 to 14:00, and then retarded between 15:00 to 20:00. But for drying chamber, the temperature kept increasing between 23:00 to 8:00 this is due to the thermal storage materials that is given out heat stored in the evening or during cloudy hours.

It was also found that the temperature for drying chamber was always higher with an average of 51.08°C and it has peak value of 70°C at 14:00 when the ambient temperature was 39°C, the average ambient temperature was 30.46°C, which is 20.62°C less than that of drying chamber, a similar result was reported by [5].

Figure 3 shows the relative humidity with respect to time for offloading condition.

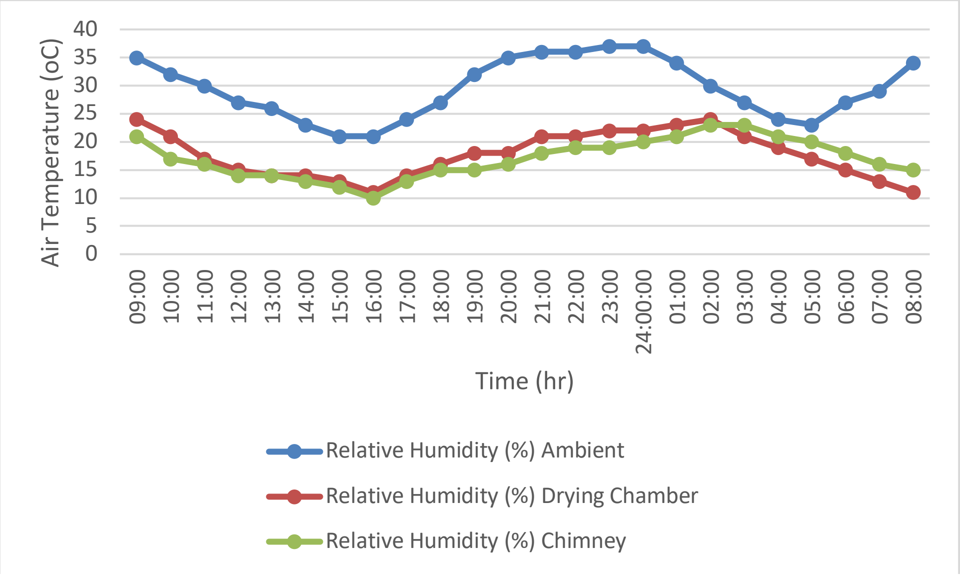

Figure 3. Relative Humidity versus Time for Offloading Condition

It was found that the relative humidity for ambient, drying chamber and chimney outlet were decreasing as the sun rise as shown in figure 3. It was observed that the relative humidity at ambient was higher than at any point of measurements (Drying chamber and chimney outlet) and it was decreased from 35% at 09:00 hour to 21% at 15:00 and 16:00 hours respectively. The average relative humidity at ambient, drying chamber and chimney outlet were recorded as 29.46%, 17.67% and 17.04% respectively.

For loading conditions of the solar drying chamber, the air temperature and relative humidity at all measuring points with respective to time were presented in figure 4 and figure 5 respectively.

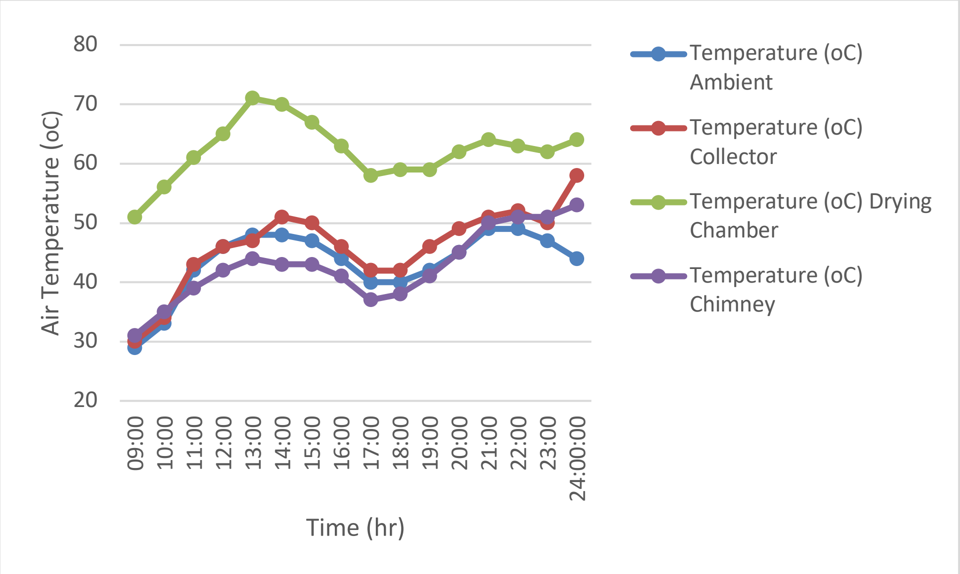

Figure 4. Air Temperature against Time for loading Condition

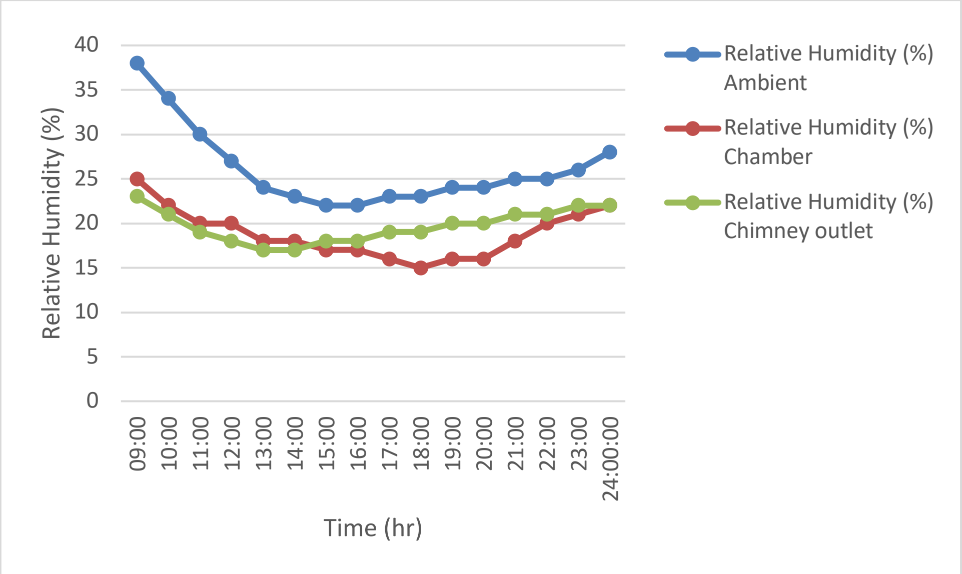

Figure 5. Relative Humidity versus Time for Loading Condition

It was observed that the temperature at drying chamber is higher than that at ambient, collector and chimney, where it attains peak value of 71°C at 13:00 hour as shown in figure 4, which is closed to the maximum allowable temperature for drying tomatoes (70°C). The average air temperature at ambient, collector, drying chamber and chimney outlet for loading condition were 43.31°C, 46.06°C, 62.19°C and 42.75°C respectively. There is significant variation between the air temperatures at drying chamber and ambient, which is 18.88°C which is within the report of [5].

As shown in figure 5, the relative humidity at drying chamber varied between 15% and 25% at 18:00 hour and 09:00 hour respectively. It was noticed that the relative humidity at all the measuring points were decreasing up to midday and being stable within 13:00 hour to 16:00 hour. This shows that high amount of the moisture from the tomato slices had already been removed, this is supporting the finding of the study conducted by Ezekoye and Enebe [39].

The average wind air at ambient, collector and chimney outlet were 0.32m/s, 0.06m/s and 0.28m/s respectively. The average drying rate of tomato slices was 0.274kg/hr and the quantity of moisture content removed from tomato slices was 58.5% (w.b). The efficiencies of solar dryer and solar collector were found to be 50.2% and 43.03% respectively, for the solar dryer, a similar result was obtained by [40] where they found the efficiency of solar dryer as 56.78%, so also for the efficiency of the solar collector, Struckmann [41] obtained it between 25% to 45%.

5. Conclusion

A hybrid solar dryer was designed and constructed using available materials for drying tomato slices, the performance of the dryer was carried out at Kano, Nigeria with latitude of 12.2° from March

9th to 12nd 2020. The performance of the solar dryer was conducted under two conditions namely: offloading condition and loading condition.

The temperature of hot air measured at the solar collector outlet is always higher than the ambient temperature throughout the testing days for both condition and the temperature inside solar chamber was greater than that at both the ambient temperature and collector, this yield a suitable condition for drying. The drying rate, efficiency of solar collector and drying efficiency were obtained 0.274kg/hr, 43.03% and 50.2%, respectively.

It was found that the solar dryer can dry high initial moisture content agricultural products to the recommended value of moisture content for safe storage within two to three days. The presence of thermal storage material (gravel), therefore, this hybrid solar dryer can be used both day and night/cloudy days.

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