Design and Implementation of an Automatic Indirect Hybrid Solar Dryer for Households and Small Industries

L. Akana Nguimdo*‡, V. A. Kembou Noumegnie*

* Department of Electrical and Electronic Engineering, Faculty of Engineering and Technology, PO Box 63 Buea, Cameroon

(languimdo@yahoo.fr, valdoaubin@gmail.com)

‡ Corresponding Author; L. Akana Nguimdo, PO Box 63 Buea, Tel: +237677975262, languimdo@yahoo.fr

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Abstract- The agricultural sector in most developing nations is negatively affected by post-harvest losses, emanating mainly from the use of inappropriate drying and storage facilities. With respect to these limitations, this work discusses the design, the construction and test of an automatic indirect hybrid solar dryer for home and small industries applications. The dryer consists of a solar collector, drying chamber, axial fans, photovoltaic solar panels, battery and automatic control devices. The dryer performance was tested using sliced tomatoes under two drying modes i.e. the solar and the automatic hybrid solar drying modes. A maximum chamber temperature of 46°C was recorded in the hybrid mode under an average insolation of 318.74W/m^2 while 39.9°C was registered in the solar mode with an average insolation condition of 303.7W/m^2. The average drying rate in hybrid mode was computed as 19.7g/h with 6.83% efficiency whereas 10.5g/h was obtained in solar mode with 4.8% efficiency. On the basis of moisture content, the drying test revealed that the quality of the product dried using the automatic hybrid dryer was superior compared to that dried with simple solar dryer. Hence proving that this new technology is a viable alternative to open sun drying as well as solar drying methods. This is because the incorporation of a backup heater does not only shorten the retention time, but also allows for a continuous drying process during poor weather conditions and at night.

Keywords: Hybrid solar dryer, automatic control, rehydration, moisture content, drying rate, photovoltaic solar system.

1. Introduction

Agriculture remains one of Africa's most important economic sectors, accounting for over 15% of the continent's gross domestic product and providing employment to more than two-third of the population working in small-scale plantations [1]. Cameroon for example, produces several agricultural commodities for export and domestic consumption [2]. This sector however faces certain basic impediments including high post-harvest losses as a result of poor post-harvest management which needs to be addressed with due diligence. Over the years, a number of food conservation techniques like cold storage, open air drying and smoking were developed to tackle this setback as well as seasonal fluctuation in food products availability. Nonetheless, the major constraint in most developing countries remains the quasi inexistence or unreliable nature of grid-connected networks in remote areas and the high cost associated.

Since pre-historic times, open sun drying has been practised in most African communities as a primary food preservation technique because of the abundance of solar radiation, its free nature and constant availability throughout the year. Nonetheless there are some adverse effects related to this practice which have been ignored by users. These effects are the partial or full deterioration of the nutrients in the crop due to contamination, enzymatic reactions, infection by micro-organisms and fungal growth as a result of intermittent drying. Added to these, the drying approach is labour and time intensive as the crops have to be spread and covered during harsh weather and at night.

Solar drying seems to be a more suitable alternative to properly address issues raised by open sun drying. This technology offers a more hygienic and sanitary manner of handling the crops since they are enclosed in a cabinet. It offers a higher drying rate as a result of the concentration of sun irradiation on the solar collector for its transfer to the crops in the cabinet. It also requires less human intervention in the drying process. Despite all the aforementioned qualities of this technology, a critical question remains unanswered: How to regulate the drying temperature and prevent the crops rehydration at night given that the system is entirely sun dependent? Li et al [3] designed an indirect forced convection solar dryer with auxiliary heating device for drying mango. The system consisted of an auxiliary heating device (backup), a drying chamber, the evacuated tube solar air collector, a three phase inverter fan (acting as thermal regulators), an automatic control system, pipes, and measuring equipments. However, the three phase inverter fan and the auxiliary heating device were electrically powered thus limiting the use of this dryer to grid connected zones. Aduewa et al. [4] proposed a dual operation mechanism Hot-Air Supplemented Solar Dryer with the aim of enabling the drying process to run even at night, thus preventing the sample from rehydrating. However, this dryer relies on a manually controlled air vent at the back of the drying cabinet in order to prevent moisture accumulation thus requiring human intervention. Mendez et al. [5] constructed a hybrid solar-gas dryer with the principal aim of enabling its operation at night or under other non-ideal irradiance conditions and evaluating its performance. Despite their significant efforts to improve the temperature in the drying chamber, it is important to note that the dryer uses LPG (liquid propane gas) that is not only a non-renewable energy resource but is also costly. In this context, the dryer may not be highly solicited in remote areas where this gas facilities are absent. Nevertheless, heat performance, end-product quality, economic aspect and dryer size [6] are key parameters for solar dryer evaluation. It is therefore a necessity to monitor the factors influencing drying process such as solar irradiance, drying airflow rate, ambient temperature, wind velocity, relative air humidity etc. [7] for efficient and timely process.

This work aims at the design and implementation of an automatic indirect hybrid solar dryer essentially equipped with axial fans for humidity and temperature regulation as well as a uniform heat flow in the dryer, microcontroller for automatic control of the drying process, data logger, LCD and a keypad to ease user's interaction with the dryer. The system is also equipped with a photovoltaic solar system consisting mainly of solar panels and a battery bank to run the system components and a resistive element serving as backup heating source. The dryer's particularity is its ability to operate with less or no human intervention in an uninterruptible manner regardless of the weather conditions. Therefore, reducing consistently the drying time and improving the products quality for preservation. It is then a green system operating uniquely on solar energy and capable of auto regulating its temperature to match a set of drying conditions for preserving a variety of food products.

2. Materials and Methods

The indirect hybrid type solar dryer is basically composed of a preheating unit, a drying unit, a control unit and a photovoltaic solar system unit.

2.1. Design Procedure

The automatic hybrid solar dryer was designed based on the procedures described by Tonui et al. [8] for grain drying and Tiruwork [9] for fruit drying. The design takes into consideration different criteria and parameters such as environmental conditions of the test location, drying temperature, amount of moisture to be expelled, heat energy requirement and airflow requirement as well, since they drastically affect the performance of the dryer. The performance of the dryer was evaluated for Buea station (4°9′34"N, 9°14′12"E) in Cameroon. With data obtained from Weatherbase [10] Meteorological Services website, the average daily solar irradiation for Buea was computed to be 344 W/m^2. The wind speed, ambient temperature, and relative humidity for the test location are 64km/h [11], 22.5°C and 72 % respectively [12].

2.1.1. Tilt Angle (β) and Insolation on the Collector Surface Area

The performance of a PV module as well as the solar collector is affected by its tilt angle with the horizontal plane because the tilt angle changes the amount of solar energy received by the surface of the modules [13]. The optimum tilt angle of 16 degrees for the solar collector at the test location to receive maximum solar radiations was determined according to the procedure described by Akana and Kum [14], and Bouabdallah et al [15]. The corresponding total irradiance (I_T) on the inclined surface was therefore given as

$$I_T = R_T I = 1.0172 \times 344 = 349.9312 W/m^2 \quad (1)$$

Where R_T is the radiation conversion factor and I the total solar irradiance on horizontal surface.

2.1.2. Drying temperature and expelled moisture quantity

Linda [16] in her dehydrator blog website recommends that tomato be dried at 47°C. Higher temperatures may cause sugar caramelization of many fruit products during the drying process. An average temperature of 47°C was hence considered for designing the dryer.

For the design purpose, a sample of 2kg of fresh tomatoes was used. The total amount of moisture (M_w) to be removed is given by Sharma et al. [17] as

$$M_w = \frac{W_w[M_{i\,wb} - M_{f\,wb}]}{(1 - M_{f\,wb})} \quad (2)$$

Where:

W_w is the initial mass of product (2 kg),

$M_{f\,wb}$ and $M_{i\,wb}$ are the wet basis final and initial moisture contents. Their values are 10% and 93% respectively

$$M_w = \frac{2kg[93\% - 10\%]}{(1 - 10\%)} = 1.844kg$$

2.1.3. Quantity of air needed for drying

The average values of air temperature and relative humidity (RH) in Buea are 22.5°C (dry bulb) and 72% respectively [12] [18]. Taking these values as inputs, the psychrometric chart [8] gives a humidity ratio (HR) of 0.013 kg water / kg dry air. When the solar collector heats air to an optimum drying temperature of 50°C, the humidity ratio remains constant. Sorption isotherms equations as given below are used to compute the equilibrium relative humidity (H) or final relative humidity in the drying chamber.

$$H = 100\, a_w \tag{3}$$

$$a_w = 1 - \exp[-\exp(0.914 + 0.5639 \ln M)] \tag{4}$$

$$M = M_{f\,db} = \left(\frac{1}{1 - M_{f\,wb}}\right) - 1 \tag{5}$$

Where: a_w is the water activity and M (kg_w/kg_s) the moisture content dry basis.

The computations yield $a_w = 0.5103$ and H = 51.03%. If on passing through the product the air absorbs moisture until its relative humidity equals 51.03%, the psychrometric chart shows the Humidity Ratio (HR) to be 0.0185kg water/kg dry air corresponding to 35°C. Therefore the change in humidity ratio is 0.0055 kg water/kg dry air. By substituting this value in gas the equation

$$PV = M_A RT \tag{6}$$

Where:

P = atmospheric pressure

V = volume of air in m^3

M_A = mass of air (kg)

T = absolute temperature (K)

R = gas constant

The total volume of air to expel 1.844kg of water from 2kg of tomato amounts to 296.642m^3. The volume flow rate ($\dot{V}$) can therefore be obtained as

$$\dot{V} = \frac{V}{t_d} = \frac{294.642}{14 \times 3600s} = 0.00589\ m^3/s \tag{7}$$

Where:

t_d = Total drying time = 14 hours

The mass flow rate can also be deduced as

$$\dot{m}_a = \rho_a \dot{V} = \left(\frac{1.2kg}{m^3}\right)\left(0.00589\ \frac{m^3}{s}\right) = 0.00706kg/s \tag{8}$$

Where:

ρ_a= density of drying air (Kg/m^3) = 1.2kg/m^3

2.1.4. *Heat energy required for drying*

The heat required to remove water from the produce was calculated using the formula provided by Mercer [19]. It considers drying as a two stages-process where the first is raising the temperature of the wet material to a desired level at which the moisture will be removed. The energy needed for this process is given by

$$Q_1 = W_w C_p (T_d - T_a) = 2kg \times \left(\frac{3.98KJ}{kg\,°C}\right)(50°C - 22.5°C) \tag{9}$$

$$= 219.45KJ$$

Where:

C_p= 3.98KJ/kg°C is the specific heat capacity of the produce [19]

The second stage is evaporating the moisture from the produce. The values for h_g (enthalpy of water as a vapour) and h_f (enthalpy of water as a liquid) at the drying temperature are obtained from steam tables. As water starts to evaporate after the produce is warmed up to the drying temperature, heat required to evaporate it is given by:

$$Q_2 = M_w L_v = M_w (h_g - h_f) \tag{10}$$

$$= 1.844 \times (2591.3 - 209.3)KJ/kg$$
$$= 4392.41KJ$$

The heat energy required is finally given by

$$Q_u = Q_1 + Q_2 = 219.45KJ + 4392.41KJ = 4611.86KJ$$

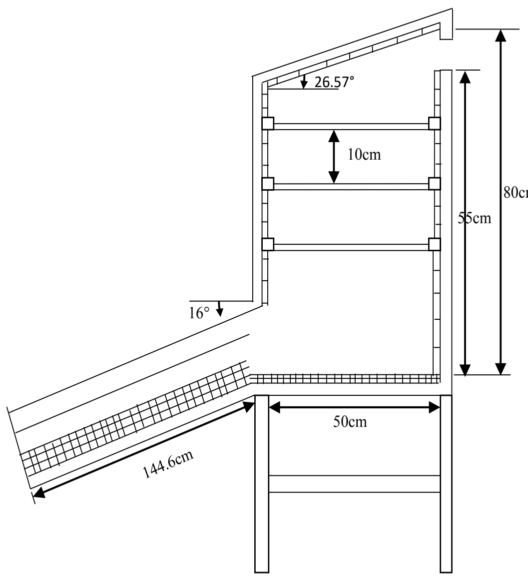
2.1.5. *Total solar collector Area (A_C) and Prototype*

The average solar power incident on the inclined surface is 349.9312W/m^2 and the collector receives this for 10 hours daily. Struckmann [20] gives a typical flat-plate collector efficiency (at ambient temperature of 25°C and I = 400 W/m^2) to be between 25% and 45%. So to achieve an optimal design, an average value of collector efficiency of 35% was considered as a design parameter.

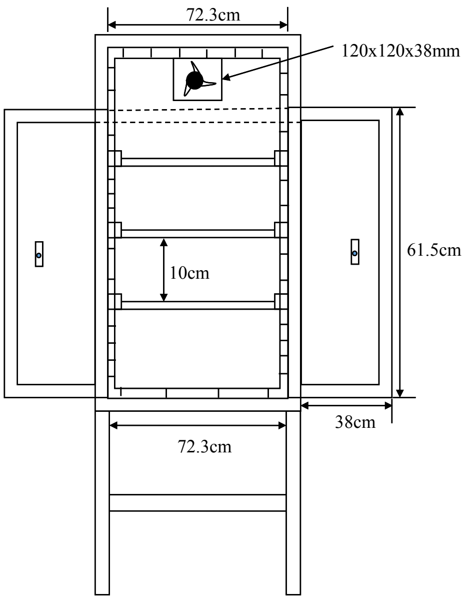
$$A_C I_T \eta = Q_u \Rightarrow A_C = \frac{Q_u}{I_T \eta} \tag{11}$$

$$Ac = \frac{1281.07Wh}{0.35 \times 3499.312Wh/m^2} = 1.046m^2$$

Fig. 1 shows the prototype of the dryer that combines all the features described above.



a)



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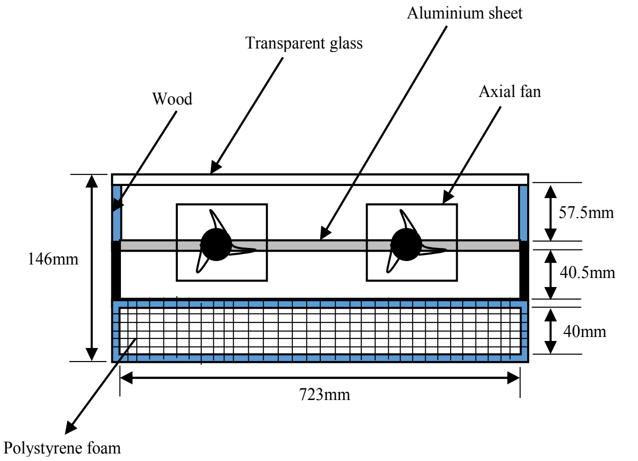


c)

Fig. 1. Design shape, dimensions and interior arrangement of the dryer. a) Cross sectional view b) Back view c) Cross sectional view of the collector

2.1.6. Calculating the airflow required for the solar dryer fans

In this study, the air velocity range applied is 0.41 m/s as Sevik [21] reported that air velocities above 0.42 m/s have no influence on drying rates.

$$\text{Airflow rate} = 0.36\text{m}^2 \times 0.41\text{m/s} = 0.148\text{m}^3/\text{s} = 313.599\ \text{CFM}$$

For a suitable airflow pressure (P_s) across the packed bed of agricultural produce, an axial fan with 1.6 inch of water static pressure [4] was chosen. From these values, the fan power (P_f) may be obtained from the equation below as suggested by Wilcke and Morey [22].

$$P_f = \frac{\dot{V} \times P_s}{3814} = \frac{313.599 \times 1.6}{3814} = 0.13156\text{Hp} = 98\text{W} \qquad (12)$$

2.1.7. Sizing the resistive element and power consumption demand

The electric heater power rating (P_{EH}) is evaluated as follows

$$\mathbf{P_{EH}} = \frac{\textbf{Quantity of heat}(\mathbf{Q_U})}{\textbf{time}} = \frac{\textbf{4611.86 KJ}}{\textbf{48×3600s}} = \mathbf{26.69 \approx 30W} \qquad (13)$$

The primary design elements to consider in sizing the Photovoltaic solar system are the solar modules, the charge controller, and the battery [23]. In determining the power demand, due consideration of wiring connection losses (5%), microcontroller losses (5%), charge controller losses (5%) and battery losses (15%) is done [24] . Hence, total energy of 2377.18Wh/day to be supplied by the solar modules is required by the appliances. The power demand of the system is illustrated in table 1.

Table 1. Power consumption of the electrical components

Electrical Load	N° of Units	Operating hours per day	Active Power (W)	Daily consumption (Wh)
Fan	5	10	105. 2	1051
Microcontroller	1	24	2.4	57.6
Heating Element	1	24	30	720
Total				**1828.6**

2.1.8. Sizing the Battery Bank and the Photovoltaic solar system Network

The battery capacity (B_C) needed for a solar installation is given as

$$B_C = \frac{\text{Total watt hour per day used by appliances}}{0.85 \times 0.8 \times \text{nominal batte]ry voltage}} \times \text{Days of Autonomy} \qquad (14)$$

Where 0.85 is the battery efficiency and 0.8 is the depth of discharge of the battery.

With a nominal battery voltage of 24V and one day of autonomy, the battery capacity used for the project was 146Ah. The system would therefore use a 150Ah /24V readily available battery.

The PV modules Peak power (W_{peak}) required to supply the system is found by dividing the daily energy demand by the panel generating factor (PFG). PFG takes into consideration the correction factor for a solar PV module that is given as 15% for temperature above 25 °C, 5% for losses due to sunlight not striking the panel straight on, 10% for losses due to not receiving energy at the maximum power point, 5% allowance for dirt and 10% allowance for the panel being below specification and for ageing [24].

$$\text{PGF} = \text{Solar irradiation} \times \text{Total correction factor on the solar panels} \qquad (15)$$

With reference to the solar climate of Buea, the daily average solar irradiation is $4.3KWh/m^2$. Therefore, the panel generating factor (PGF) equals 2.97 and the system's peak power given as

$$W_{peak} = \frac{\text{Total PV watt hour per day}}{\text{Panel generating factor}} = \frac{2377.18\text{Wh/day}}{2.97} = 800.4\text{W} \quad (16)$$

A combination of two 500Watt /24V monocrystalline solar panel connected in parallel will suitably cover the system power demand. The present system uses Risen Energy solar panels RSM150-8-500M model readily available at local market.

2.1.9. Sizing the Charge Controller

Solar charge controllers are typically rated against amperage and voltage capacities. The Solar charge controller is selected to match the voltage of PV arrays and batteries. With respect to standard practice, the sizing of solar charge controllers is to take the short circuit current (Isc) of the PV array to which a safety factor of 1.25 is applied. From data sheet specifications of the solar panel selected, short circuit current (Isc) is 13.33A. Therefore,

$$\text{Solar charge controller rating} = 13.33\text{A} \times 2 \times 1.25 = 33.33\text{A} \approx 34\text{A}$$

Hence for 1828.6Wh/day solar system load demand, the system will use an MPPT solar controller with a minimum rating of 34A/816W. Fig. 2 presents the design procedure flowchart.

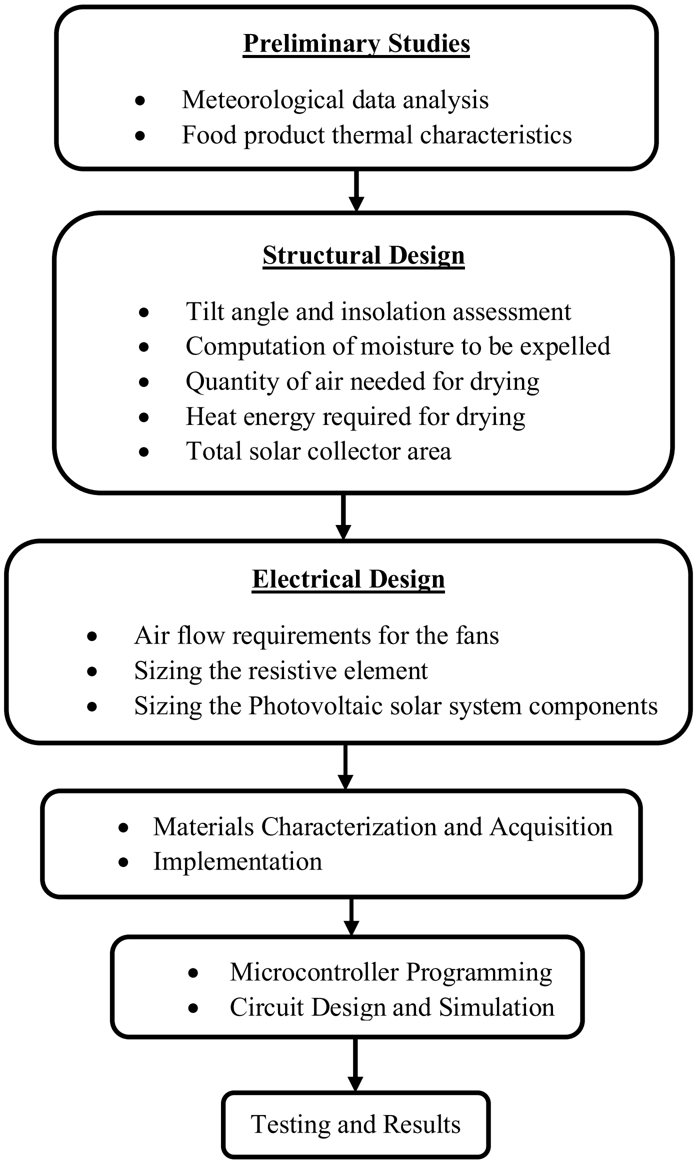


Fig. 2. Design procedure flowchart

2.2. Components of the Automatic Hybrid Dryer and Material

The dryer is made in two separate units (drying chamber and solar heater) to facilitate its mobility. The drying chamber is a trapezoidal shape frame made of well-polished camwood (Fig. 3) of 13mm thickness and $80\text{cm} \times 72\text{cm} \times 50\text{cm}$ dimension as computed previously. Two access doors are fitted at the back of the frame and an opening made above the door where the humidity fan is installed. The interior part of the dryer is covered entirely with 2mm thick polystyrene foam on which lies a layer of aluminium sheet serving as a heat insulator and heat conserver respectively. The chamber is equipped with three drying trays of $72\text{cm} \times 50\text{cm}$ designed to hold the products and separated from each other by 10cm. The chamber is equally equipped with a DHT 22 (humidity sensor) at the top, a resistive wire and two LM 35 temperature sensors placed at the centre and the inlet of the chamber respectively.

Photovoltaic thermal collectors can be categorized based on the thermal fluid (air or liquid) and also the geometry (flat-plate and concentrating) [25]. The solar collector used here as shown in Fig. 4 is a double channel heater of 120cm×50cm×14cm made of camwood and covered at the top with glass (transitivity 0.85). An aluminium sheet serving as the absorber plate is nailed in the air gap between the transparent glass and plywood beneath which a 4mm thick layer of polystyrene foam acting as a thermal insulator is mounted. In order to conserve the heat transmitted into the collector by the glass, the interior surface of the collector was painted black. Two LM 35 temperature sensors were installed below the control panel and at the interior of the solar collector in order to monitor the ambient and collector temperatures respectively.

2.2.1. *Principle of Operation*

This system consists of a controller, heating unit, renewable energy source, fans and sensors (Fig.3). At the start of the drying process, the user is invited to select what product to dry via the LCD using a keypad. The system then readjusts to set the drying conditions (drying temperature and required humidity level) of the chosen crop to be dehydrated based on the data base provided. Once the operation is started, the sensors monitor the temperature and humidity inside the drying cabinet and send the data to the controller which performs automations on the heater and the fans with respect to the drying conditions. Fig.3 presents the principle of operation block diagram. The temperature and humidity inside the drying cabinet as well as in the collector are measured and displayed on the LCD. The measured values are then compared to the drying set values of the specified product. If the temperature is less than the set value, the inlet fans are switched OFF and the heating element is switched ON to maintain a minimum temperature and prevent rehydration of the crops. If both the collector and chamber temperatures are higher than the set value, the fans are switched ON and made to rotate in the reverse direction in order to reject the excess heat, thereby preventing damage to the crops; otherwise nothing is done. Next, the Humidity level in the drying cabinet is measured and compared to the set value.

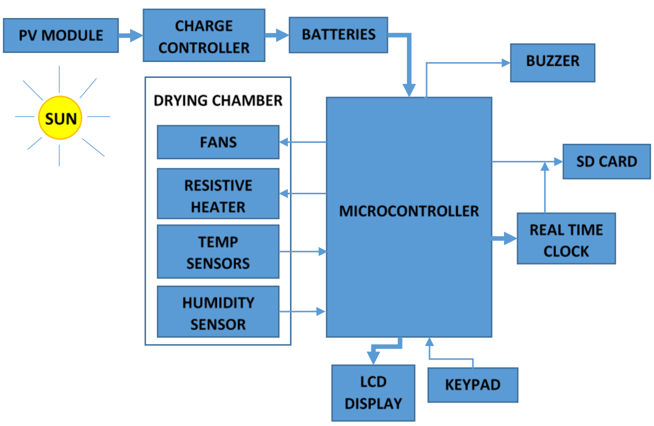


Fig. 3. Principle of operation block diagram

If the humidity level in the cabinet is more than the set value, the humidity control fans are switched ON and if the level is low, the fans are switched OFF or nothing is done otherwise.

Both working in the background, the real time clock module and the SD module log in the sensors measurements into the SD card provided for the circumstance every 30 minutes interval in order to keep track and records of the system changes. The recorded data will subsequently be exploited to determine the dryer performance. As soon as the drying process comes to an end, the microcontroller halts the inlet and outlet fans if some conditions are verified, to prevent further drying. Then, it sounds an alarm using the buzzer and goes ahead to maintain a constant temperature in the drying chamber to avoid rehydration of the dried produce. Finally the microcontroller prompts the user via the LCD display to offload the drying chamber.

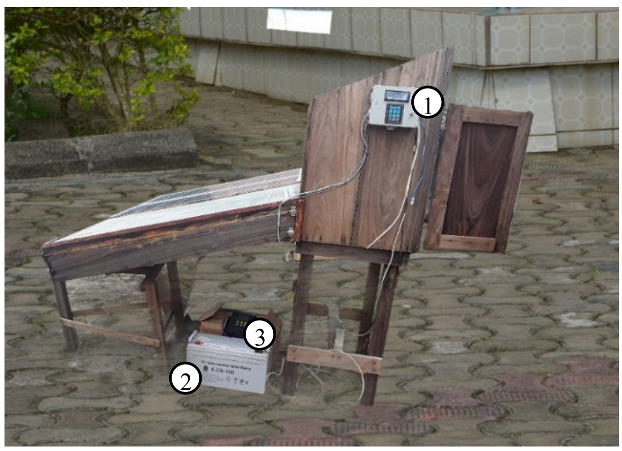
2.2.2. *Drying and experimental procedure*

Fresh tomatoes were obtained from the local market in Buea. Perishable ones were sorted out and good ones washed and sliced to an approximate thickness of 5 mm [19]. Slices are then arranged onto the movable perforated base of the drying chamber in a single layer to avoid moisture being trapped in the lower tray. After this, the trays loaded with the slices of the produce are fitted into the tray racks in the drying chamber for drying to start. For every loaded tests (i.e. with and without backup resistive element) performed, the initial and final weight of tomatoes was recorded in order to evaluate its moisture level later on. Moreover, ambient temperature, chamber humidity, chamber temperature and collector output temperature were automatically recorded every 30 minute-interval by the microcontroller as well as the insolation.

3. Result and Discussion

3.1. Dryer Evaluation Test

The automatic hybrid solar-energy dryer was designed and constructed using readily available local materials. Fig. 4 shows its essential features consisting of the solar collector, the drying cabinet, solar panels, solar battery and charge controller.



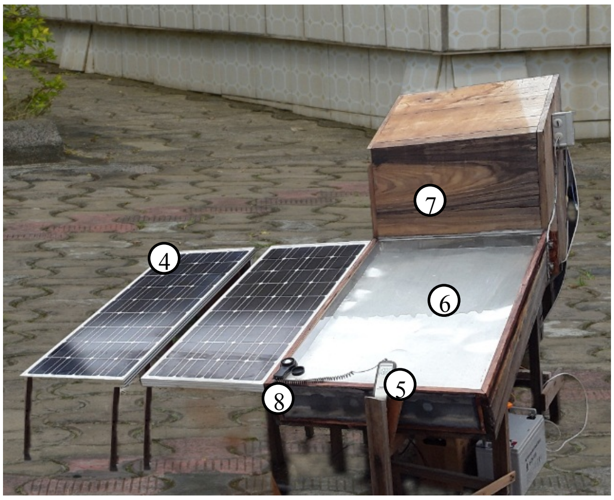


Fig. 4. Constructed automatic hybrid solar dryer

1. Control panel
2. Battery
3. Charge control
4. Solar panel
5. Solar meter
6. Solar collector
7. Drying chamber
8. Axial fans

3.1.1. Testing under unloaded condition (No Load)

The No load tests were conducted for two days to know the maximum possible rise in temperature of the drying chamber as compared to that of the ambient. On day one of the experimentation (Thursday 23/01/2020), only sun was used as the heating source from 8:00am to 18:00pm. Meanwhile on day two (Friday 24/01/2020), all the components of the solar dryer were allowed to operate fulltime from 8:00am to 21:00pm.

During the experiment, variation in solar irradiance, ambient air temperature, the temperature of air in the collector and the drying chamber were observed and plotted as shown in Fig. 5. The average solar radiation was obtained as 598.37 W/m^2. It was observed that at 12:30pm the maximum average ambient temperature was 32.69ºC, the temperature in the collector was 55.18ºC and the drying chamber temperature was 47.10ºC. Later on, the temperatures in the drying chamber as well as the ambient temperature progressively dropped to 28.6ºC and 26.29ºC at 18:00pm respectively. This result shows that the dryer is hottest at mid-day when the sun is habitually overhead, which is supported by results reported by Aduewa et al. [4] for a hot air supplemented air dryer for white yam.

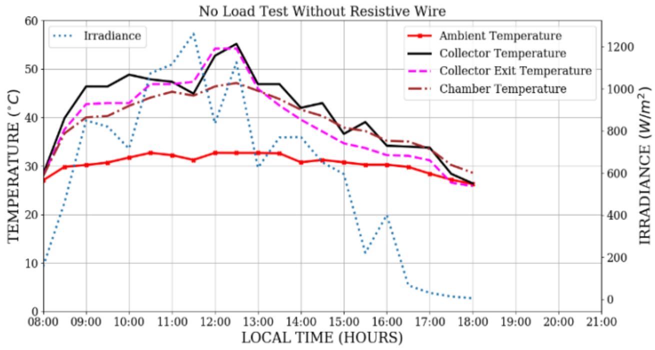


Fig. 5. Solar radiation and thermal profile inside the dryer under no load condition during experimental day 1

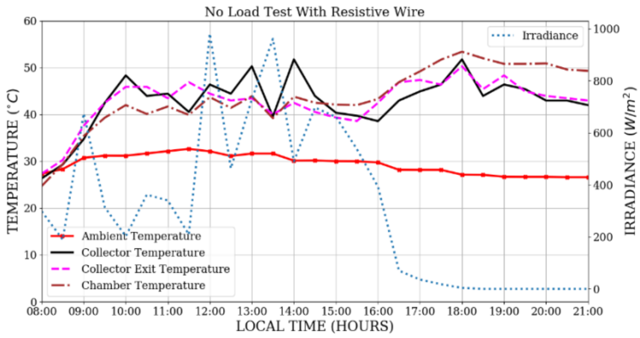


Fig. 6. Solar radiation and thermal profile inside the dryer under no load condition with resistive element (experimental day 2)

The total average insolation recorded during day 2 of the experimentation was 319.54W/m^2 which was very low compared to 598.37W/m^2 of day 1. Nonetheless as shown in Fig. 6, a maximum of 53.40°C was attained in the drying chamber during the night. This temperature was much greater than the ambient temperature with 20.76°C. From this result, the first fruit of the resistive element could be noticed. It consistently improved the chamber temperature to a value that will keep the cabinet enclosure safe from rehydration irrespective of the solar irradiation.

3.1.2. Testing under loaded condition

Two different tests were performed under loaded condition for tomatoes i.e. solar drying test and solar drying test with backup resistive wire heater. These tests were carried out to determine the technical viability of the dryer.

The solar drying test was conducted for two days on Saturday 27/01/2020 and Sunday 28/01/20. During the drying period as illustrated by Fig. 7, the maximum temperature attained in the drying chamber was 39.9°C on day two and this temperature dropped gradually from 13:30pm in the afternoon to attain a value of 24.1°C at 21:00pm. It was noted that the chamber temperature as from 18:00 at sunset to 21:00 was below ambient temperature. This is as a result of the considerable solar radiation during the day to heat it up and the absence of the backup heating source at night. Obviously at low temperatures below 30°C (as it is the case for the major experimental period) in the drying chamber at night, tomato with a high water level is prompt to spoilage.

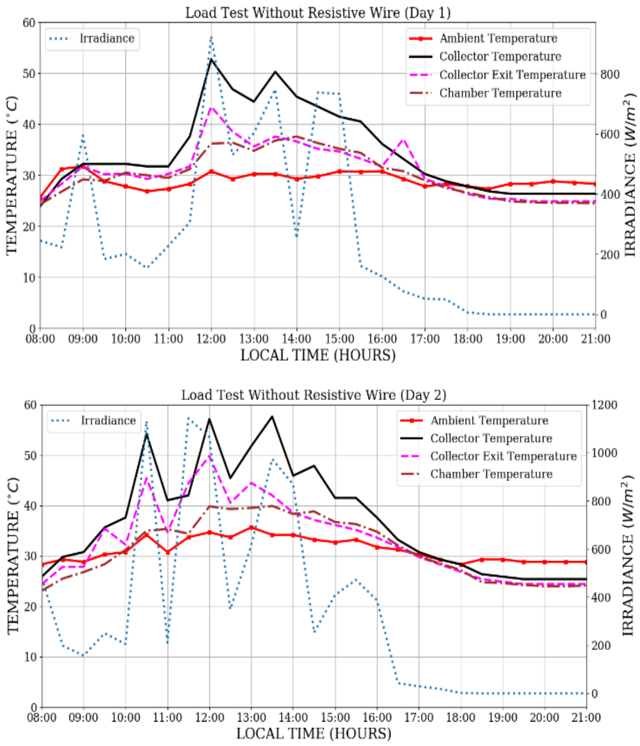


Fig. 7. Solar radiation and thermal profile inside the dryer under load condition on day 1 and day 2

The graph in Fig. 8 for day one of the loaded test with backup resistive wire clearly illustrates the tremendous consequence of incorporating the resistive element as backup in the drying process. As early as 8:00am the chamber temperature is at 42.9°C which is higher than the 27.67°C of the surroundings, despite a very low average solar irradiance of 257.77W/m^2 throughout the day. The chamber temperature then progressively drops through 37.2°C at 15:00pm to 31.6 °C at 21:00 during the night. This dropping temperature profile in the chamber is as a result of the wet tomato slices absorbing heat from the surrounding in order to evaporate the water. However, the system is capable of maintaining the chamber temperature above 30°C throughout the experiment, preventing the rehydration of the crop.

On day two of the loaded test condition with backup resistive wire as portrayed in Fig. 8 (day2), there was a slight unstable chamber temperature curve constantly rising and falling between 10:30 am to 17:00 pm. This phenomenon ensues due to the sporadic activation of the humidity control fan helping to keep the drying cabinet free from humid air.

The general observation that can be made after this experimental process is that in hybrid mode, a maximum chamber temperature of 46°C was recorded under an average insolation of 318.74W/m^2 meanwhile 39.9°C was attained in solar mode with an average insolation condition of 303.7W/m^2 suggesting a better performance in the hybrid mode. Also in the absence of the resistive element during the loaded test, day 2 recorded a maximum average chamber temperature of 25.09°C at night which is not enough to prevent the crop from getting bad. Meanwhile on the other hand, the load test conducted with the resistive element as backup on day 2 yielded a maximum average chamber temperature of 41.03°C at night suitable to keep the quality of the crops.

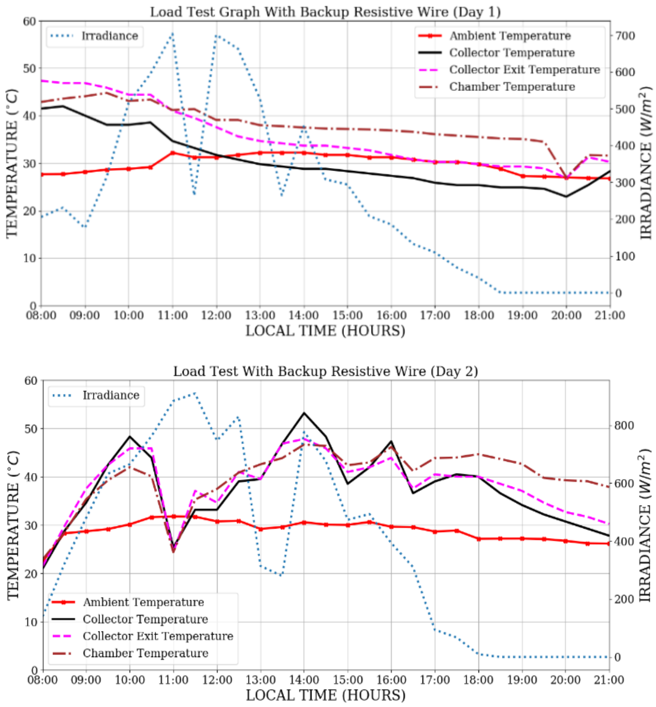


Fig. 8. Temperature variations in the dryer for load test condition with backup resistive wire for the two days

From the preceding remarks, it can be noted that the automatic hybrid solar dryer offers a smooth continuous drying process at night with temperatures sometimes reaching 41.03°C. This value is enough to preserve the food product from rehydration and hence assures its quality. Besides, the reliance of this dryer on renewable source of energy constitutes an asset to homes and small industries. In fact, the assurance of continuous supply spares them from unpleasant power outages that may occur and greatly compromise the food product quality. Furthermore, it is essential to mention that once set, the automatic hybrid dryer necessitates little or no human intervention thereby reducing the risk of spoilage due to intermittent manipulations.

3.2. Efficiency

The efficiency of solar drying system can be evaluated either based on the thermal performance of the two units or drying rate of the products [26].

3.2.1. Collector efficiency

Collector efficiency measures the thermal performance of the collector. It is defined as the useful energy gain of the collector and is computed as follows:

$$\eta_c = \frac{\rho \dot{V} C_p \Delta T}{I_c A_c} \quad (17)$$

Where: $\dot{v}$, C_p and ρ are the air volumetric flow rate (m^3/s), specific heat capacity (J/kg K) and density (kg/m^3) respectively.

ΔT, I_c and A_c are the temperature change (°C), insolation on collector surface (W/m^2) and collector area (m^2) respectively.

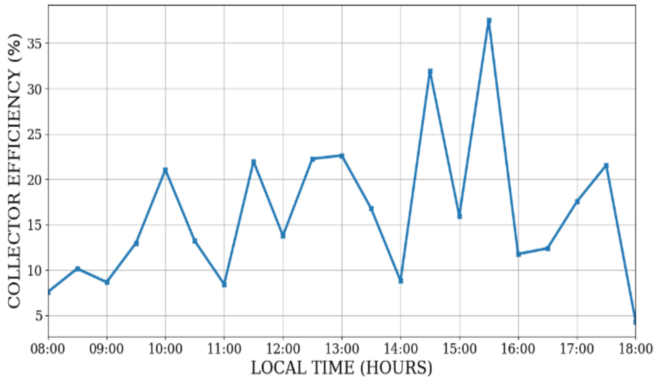


Fig. 9. Air collector efficiency testing curve

The performance of the solar collector was evaluated separately for no-load and load conditions, all without the resistive element. The two no-load tests yielded 19.24% and 28.02% respectively and the loaded test showed 8.46%. The no load efficiencies values are in accordance with Alfegi et al. [27] who indicated that a typical collector efficiency falls within the range 17% to 26.43%. The poor performance of the dryer under load condition may be explained by additional humidity in the dryer due to the load and that affects the temperature gradient. However, further investigations must be done to assess the influence of the load on the collector's performance. Putting the 3 cases all together, an average profile as shown in Fig. 9 was derived with a global mean of 18.57%. This value is still reasonable since it falls within Alfegi et al. [27] range though Tiruwork [9] reported higher values of collector efficiency. In general, we notice from Fig. 9 that despite regular variations in the profile of average efficiency that can be attributed to the fluctuations of the irradiance during experimentation, there is a global tendency to an increase over the course of the day. This trend culminates late in the afternoon by 15:30 pm, the time where solar irradiance declines in the majority of cases. This increase can therefore be conceived as the result of the heat accumulated inside the dryer since sunrise.

3.2.2. *Drying Efficiency*

Drying efficiency η_d is the ratio of the energy needed to evaporate moisture from the material to the heat supplied to the dryer. This term is used to measure the overall effectiveness of a drying system [28].

$$\eta_d = \frac{W_w C_p (T_d - T_a) + M_w L_v}{I A_c t + Q_h} \tag{18}$$

Where:

W_w is the product weight

C_p is the specific heat capacity of product

M_w is the quantity of water to be expelled

L_v is latent heat of vaporisation

I is the irradiance

A_c is the collector area

T is the drying time

Q_h the resistive wire heat

T_d, T_a are dryer and ambient temperatures respectively.

The drying efficiency of the dryer was found to be 4.8% for the loaded test with solar drying alone and 6.83% with backup heater used. It is clear that the dryer efficiency with backup heater is greater than solar drying alone. Tiruwork [9] reported an almost similar result for average drying efficiency of 8.7 % when the backup heating was used by burning charcoal throughout the drying time. However further work is needed to be done on chamber's isolation in order to improve this efficiency.

3.2.3. *Drying Rate*

Drying rate (DR) is the amount of evaporated moisture over time and is given by;

$$DR = \frac{M_i - M_d}{t} \tag{19}$$

Where:

M_i is the initial product weight

M_d is the final product weight and t the drying time

The drying rate obtained in the case of loaded test with solar energy as unique heating source was10.5g/h meanwhile 19.7g/h was recorded for the loaded test associated with the backup resistive wire. It can be observed that the process was 46.7% faster than simple solar drying.

4. Conclusion

In this work, an automatic indirect hybrid solar dryer was designed, constructed and evaluated. This dryer is essentially composed of a solar collector, axial fans, drying chamber, microcontroller and a backup heating source. It is equally equipped with photovoltaic solar system components which act as the unique power supply to the entire electronic and electric devices. Furthermore it has a capacity of 2 kg capable of drying both in the day and at night. From the tests carried out, the following conclusions were made. The solar dryer was able to raise the average air temperature from 29.36°C to a maximum of 46.7°C in the drying chamber under very low average insolation conditions of 318.74W/m^2 during loaded test experiments. This considerable high value of temperature complemented by the backup heater contributed in increasing the drying rate of the agricultural crop from 10.5g/h to 19.7g/h and moisture loss from 50.5% to 94.74% in comparison with the solar dryer without backup. The product inside the dryer requires less attention, like attack of the product by rain or pest (both human and animals), compared to those in the open sun drying. Although the dryer was used to dry tomatoes, it can be used to dry other crops like yams, cassava, maize, cocoa, coffee, vegetable etc. There is ease in monitoring when compared to the natural sun drying technique. Also the dryer was built with locally available material and the drying process was rendered autonomous by using a microcontroller to perform all the control functions. Thus making the entire system self-sustainable.

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