DESIGN AND DEVELOPMENT OF A HYBRID SOLAR-ELECTRIC DRYER FOR SLICED VEGETABLE CROPS

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Abstract

A hybrid cabinet dryer was designed and developed to reduce vegetable waste and improve their storage conditions. The dryer consists of three main units: drying chamber, heating unit and control unit. Design calculations were made based on some basic engineering assumptions, considerations and principles of heat and mass transfer. The dryer has a batch capacity of 25kg of fresh sliced vegetables per day. A no-load test was conducted to evaluate the thermal profile of the dryer, which involved running the dryer at five different air velocities (0.1, 0.5, 1.0, 1.5, and 2.0m/s) in order to determine the required time to reach the preset optimum drying temperatures (50, 55, 60, 65, 70^oC) for the selected sliced vegetable crops (okra, tomato, and pepper). Results obtained indicate that an average minimum dryer heat-up time of 5.2 minutes was required by the hybrid dryer at a temperature and air velocity of 70^oC and 2m/s respectively. Drying temperature and air velocity were observed to have significant influence on the dryer heat-up time and dryer tray temperatures. The performance of the dryer was attributed to the heat contribution of the solar collector which is affected by the hourly solar radiation and ambient air relative humidity as well as the heat contribution of the electric heater, making the dryer a hybrid. The hybrid energy regression equation model was developed in terms of drying time. These results were obtained for no-load condition of the designed dryer. Good prospects for future applications as well as recommendations were stated.

Keywords: *drying, vegetables, hybrid dryer, solar heat, electric heat.*

1.0 Introduction

Farmers in Nigeria have been producing large quantities of fresh agricultural output with high moisture contents which are lost annually due to decomposition by micro-organisms (Nwakuba, 2011). This results in reduction of the net agricultural output and subsequent reduction in the gross domestic product (GDP) of the nation. This is a serious concern for an agricultural country like Nigeria where approximately 91% of the rural dwellers are dependent on subsistent farming for their livelihood. Several factors contribute to this postharvest losses and some of the technological factors include faulty harvesting and handling practices, poor packing and transport systems, lack of storage facilities and poor processing techniques (Nwajinka and Onuegbu, 2014) including drying.

Drying is a major method of preserving agricultural food products especially in developing countries like Nigeria (Nwakuba *et al.,* 2016). It involves the removal of moisture present in agricultural products like vegetables to a certain limit at which all metabolic activities are hindered (Mujumdar, 2000; Montero, 2005; Montero *et al.,* 2010; Okoroigwe *et al.,* 2013; Idah *et al.,* 2014). The basic essence of drying is to reduce the amount of moisture contained in the product to a level that prevents deterioration after harvest (Mujumdar, 2000; Antwi, 2007; Okoroigwe *et al.,* 2013; Nwajinka and Onuegbu, 2014). Longer shelf-life, product diversity and substantial volume reduction are the reasons for the popularity of dried agricultural produce, including improvements in product quality, preservation of nutritive values, reduction in costs of packaging, storing, transportation and process applications (Antwi, 2007; Idah *et al.,* 2014). Such improvements could lead to an increase in the current acceptance of dehydrated foods in the market (EL-Mesery and Mwithiga, 2012).The most common method of dehydration is by open-air sun drying but this often results in food contamination, insect and bacteria infestation, nutritional deterioration, heat stress, loss of flavour, colour, taste, case-hardening, due to wetting by rain squalls (Ratti and Mujumdar, 1997; Ehiem *et al.,* 2009; Nwajinka and Onuegbu, 2014). In order to protect the products from these mentioned disadvantages and also to accelerate the time for drying, moisture reduction and hence wastage through bacterial action, different types of solar dryers have been developed. Nwajinka and Onuegbu (2014) observed that shortages of oil and natural gas, and increase in the cost and depletion of fossil fuels have stimulated efforts in the development of solar energy as a practical power source. This power source was harnessed for heating, cooling, drying, irrigation pumping, and numerous other thermal processes in food industries (Oje and Osunde, 1995; Itodo *et al.*, 2002; Madhlopa *et al.*, 2002).

Vegetables are seasonal crops characterized by their rich vitamins, high moisture (usually above 70% wet basis) and low fats contents especially at harvest. This makes its drying a highly energy intensive operation; and for this reason, large amount of energy is needed to bring down the high moisture content to a safe storage level (usually 5 – 15%) at a temperature range of 35 – 65^{o}C (Mu'azu *et al.*, 2012; Idah *et al.,* 2014). In Nigeria alone, up to 50% of fruit vegetable harvested get spoilt annually (Musa-Makama, 2006) causing seasonal shortage and fluctuations in supply and prices. Vegetables can be successfully preserved through drying by reducing their moisture content. Drying of vegetables however, is facilitated by slicing and spreading out the product to increase their surface area to hot convective air; using a reliable heat source; increasing the airflow around the product; insulating the areas that are not exposed to the same heat source to avoid heat loss; avoiding direct heating since it affects the quality and appearance of the product; and protecting the dried products against contamination, reabsorption of moisture from the environment and harmful effects of sunlight such as undermining of sensory qualities of vegetables, increased ambient air temperature etc. The process of indirect heating is achieved by heating of air in a separate solar collector and circulating same through the drying racks where it picks moisture from the crop. Owing to intermittent solar radiation throughout the day, continuous drying of agricultural products can be accomplished through a combination of solar and non-solar heating sources in a mixed mode system with biomass or electricity (Prasad and Vijay, 2005; Prasad et al., 2006). This informs the design of a hybrid dryer.

Many dryers have been developed and used to dry vegetable crops in order to improve their storage conditions using different sources of energy such as electricity, solar, liquefied petroleum gas, biomass *etc.* or a combination of solar energy and other forms of energy. The most common dryers for vegetables are continuous tunnel dryers, vacuum dryers, microwave, heat pump and solar dryers (Huber and Menners, 1996; Nwakuba et al., 2016). This wide range is as a result of different physical forms of the vegetables to be dried, desired rate of drying and quality constraints of the dried products.

In the development of solar hybrid dryers in Nigeria, Komolafe and Osunde (2005) evaluated the performance of a hybrid convective solar dryer for drying vegetables. Similarly, Oparaku *et al.* (2003) evaluated a solar cabinet dryer with auxiliary heater. Some researchers like Minka (1986), Mulhlbauer *et al.* (1996) and Berinyuy (2000) have outlined some of the major technical bottlenecks confronting the development of this dryer technology in Nigeria, which include poor design and construction of the dryers, lack of data on the effects of the various design parameters on the behaviour of the dryers, little or no mathematical modeling and poor choice of materials for construction. This has necessitated a search for suitable and efficient dryers based on local technology rather than importing dryers not suited for Nigerian conditions. Based on this, it is necessary to design and develop a hybrid vegetable dryer operating either on electricity, fossil fuel or wood/ charcoal biomass in conjunction with solar flux using local weather parameters in order to enhance the drying potential of the dryer, given the moisture-laden nature of most vegetables such as tomato, okra, onion, pepper, carrot, eggplant, *etc.* by reducing the relative humidity so as to dry the crops more efficiently. This work has the specific objective of designing and developing a hybrid crop dryer using solar heat and electricity to produce hot air for sliced vegetable drying.

2.0 Materials and Methods

2.1 Design assumptions and considerations

The following assumptions were made in order to obtain the macroscopic scale governing equations for the dryer design:

i. Air density is constant = 1.2922kg/m^3 and its velocity distribution in the dryer is uniform.
ii. Drying is considered in thin layers for the sample crops.
iii. All the crops samples are considered homogenous, which are characterized by its superficial temperature taken to be constant across the thin layers.
iv. Shrinkages of the product samples during drying process is neglected and the products can be estimated to a thin layer of water.
v. The phenomenon of water condensation on the inner walls of the drying chamber is neglected and so is the radiative transfer phenomenon inside and outside the drying chamber.
vi. Hot air is provided by two sources; the solar module and the electric heating unit, and the drying chamber is assumed to be water proof and heat losses minimal except through the air vent/chimney.
vii. Daily maximum period of drying is taken as 8 hours (i.e. between 9:00am to 5:00pm) daily, assuming no rainfall, when the solar radiation flux is optimal.

The design considers an active hybrid convective crop dryer with integral and distributed modes with outlet. It emphasizes the drying air temperature and control, air velocity, energy requirement for drying and other drying parameters such as drying rate, drying time, and drying efficiency. The following considerations were made:

i. Initial and desired final moisture contents and allowable drying temperature for the selected crop samples (okra, tomato, and pepper) are 88.7%, 10 - 15%wb, 65^{o}C; 96%wb, 5%wb, 60^{o}C; and 87%, 10%, 55^{o}Crespectively(Tiwari, 2012), as well as the specific heat capacities of the crops, which are1.85, 3.68, and 1.97kJkg^{-o}C respectively (Eke, 2014; Ekpunobi et al., 2014).

ii. Crop sample slice thicknesses of 10, 15, 20, 25, and 30mm at different drying air temperatures of 50, 55, 60, 65 and 70^{o}C, and airflow rates of 0.1, 0.5, 1.0, 1.5, and 2.0m/s would be used.

iii. The average ambient environmental conditions of Federal University of Technology (F.U.T.), Owerri between April and November is 29.6^{o}C and 77.7% for temperature and humidity respectively; total amount of solar flux available is1.02kWm^{-2} and the solar tilt angle, $\beta = 15.4^{o}$.

iv. Amount of moisture to be removed from a batch of crop sample and the amount of heat generated from each heat source for optimum drying of a given batch quantity should be about 83.1%, 94.8%, and 88.5% of any given mass of okra, tomato and pepper respectively.

v. The energy required for the drying operation should be generated from a clean naturally renewable source (such as the sun), and supplemented with a clean source of heat like electricity for further drying during inclement weather.

vi. The heat units should be sizeable enough to be able to generate the required enthalpy for drying each crop sample.

vii. The solar collector should be oriented with respect to the local latitude of Federal University of Technology (F.U.T.), Owerri, Nigeria (5.4^{o}N).

viii. The entire system is mounted on a roller rectangular base angle-iron frame for easy movement.

ix. Considerations are also made on the availability, quality, and cost of the prospective construction materials.

x. The hybrid crops dryer should be designed based on the initial and final desired moisture content of tomato, given its most moisture-laden nature when compared to the other two samples (okra and pepper).

2.2 Basic design calculations

(a) Batch capacity

There is a choice of batch capacity since the dryer is a prototype and drying is done in racks. The rack dimensions are taken based on the chamber size (400mm x 400mm x 500mm). The batch capacity varies based on the available drying space and quantity of crop produced by a farmer. An average Nigerian subsistent farmer dries between 2kg and 15kg of sliced okra and tomatoes per batch per day with open-air sun drying (Eke, 2003). Using this as a basis to develop the batch capacity of the hybrid dryer, a maximum of 25kg, 30mm thick sliced crop (sample with an average diameter of 3.5cm) arranged in single layers on drying racks is chosen.

(b) Drying chamber volume and tray size

The volume of the drying chamber V_C is expressed as equation (1):

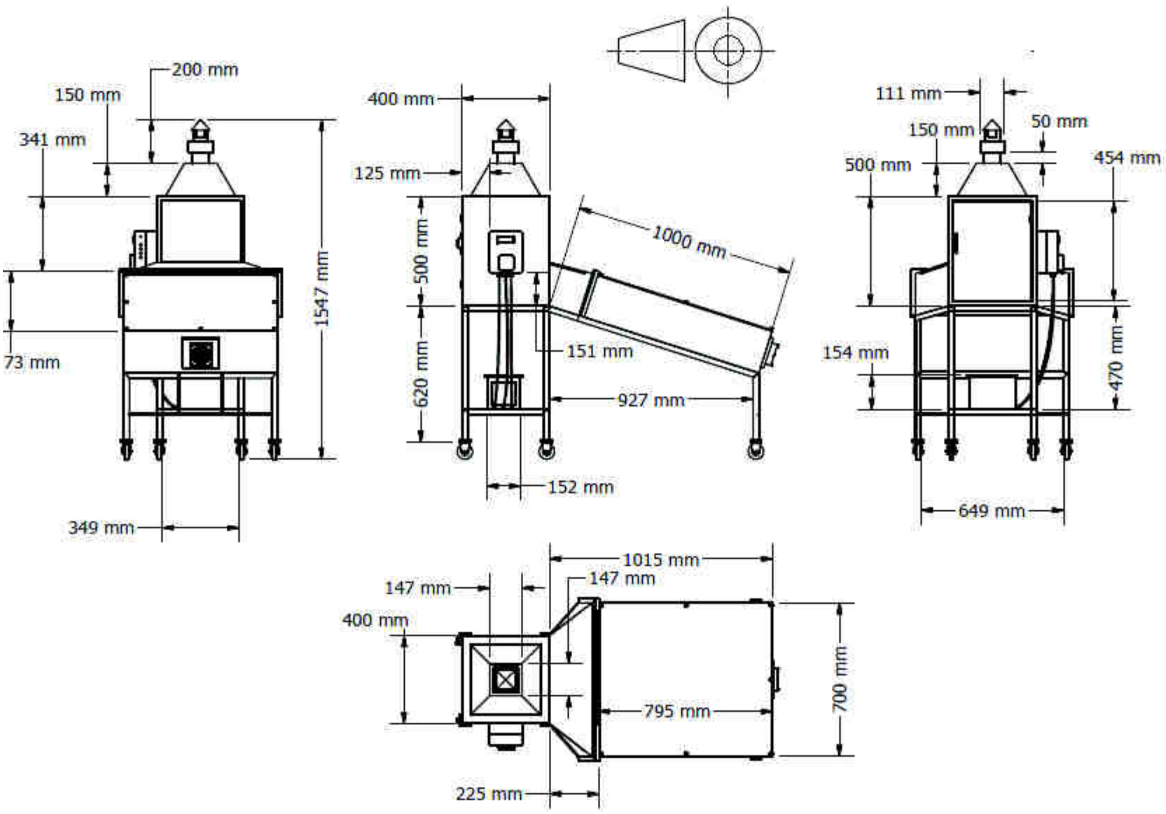
$$\mathbf{V_C = L.W.H} \qquad \mathbf{1}$$

Where: L = length of chamber (cm); W = width (cm); H = height (cm).

Since the average diameter of fresh sliced tomato with circular cross-section (most moisture-laden crop sample) is 3.5cm and drying is done in thin layers, a maximum of 125 sliced samples can be dried per batch per tray. Thus, tray length, L_T is given as:

$$L_T = \frac{125}{3.5} = 35.7\text{cm}$$

Hence, two square trays were selected with dimensions, 39cm x 39cm. one is placed 15cm from the base of the drying chamber while the other is 15cm from the chimney hood. Hence the, drying chamber dimension becomes: 40cm x 40cm x 50cm as shown in Figure 1.



(c) **Amount of moisture to be removed (M_R)**

The amount of moisture to be removed from the sliced sample, M_R is estimated from equation (2) as:

$$\mathbf{M_R = M_i \frac{(Q_1 - Q_2)}{1 - Q_2}} \qquad \text{(Ehiem } et\ al., \text{ 2009)} \qquad \mathbf{2}$$

Where: M_i = initial mass of wet sliced sample to be dried (25kg); Q_1 = initial moisture content of sample crop (% wet basis); Q_2 = desired final moisture content (%wb).

Using equation (2), the following quantities of moisture would be removed from a batch of 25kg of sliced samples for optimum storage:

Therefore, the amount of moisture to be removed (M_R) from okra, tomato and pepper becomes: M_{Rokra} = 21.86kg, $M_{Rtomato}$ =23.95kg, and $M_{Rpepper}$ = 21.39kg given their Q_1 and Q_2 as 88.7%, 15%; 95%, 5%; and 87%, 10% respectively (Tiwari, 2012).

(d) Quantity of air required for drying (Q_a) per batch

The quantity of air needed for moisture absorption in a given batch is estimated as in equation (3):

$$\mathbf{Q_a = \frac{M_R H_L}{C_a \rho_a (T_{f-} T_i)}} \quad \text{(Ehiem et al., 2009; Nwajinka and Onuegbu, 2014)} \qquad 3$$

Where: M_R = Amount of moisture to be removed (kg); H_L = latent heat of vaporization (2499.94kJ/kg); C_a = specific heat capacity of crop sample (kJ/kg^{o}c); ρ_a = density of drying air (1.2922kg/m^3); T_i and T_f = 29.6 and 65 = initial and final temperatures of the drying air before passing through the drying bed respectively (^{o}C).

The latent heat of vaporization at 65^{o}C for the highest drying temperature is given by Eke (2014) as equation (4):

$$\mathbf{H_L = 2,502,535.259 - 2,385.76424\ (T_d - 273.16)} \qquad 4$$

Where: T_d = drying air temperature = 65^{o}C; H_L = 2499.94kJ/kg; C_a for tomato = 3.68kJ/kg^{o}C; $M_{Rtomato}$ = 23.95kg.Therefore, Qa = 355.68m^3 of air.

Note: This hybrid crop dryer is designed based on the optimum drying temperature of fresh tomato (65^{o}C) - the most moisture-laden sample.

Assuming a maximum drying time of 24 hours per batch of sliced tomato sample of maximum diameter = 3.5cm, the drying rate which is the loss of moisture from the wet sample per unit time can be estimated according to Amer (1999), Nwakuba (2011), Usman and Idakwo (2011) as equation (5):

$$\boldsymbol{DR = \frac{W}{A}\left(-\frac{dx}{d\theta}\right)} \qquad 5$$

Where: DR = drying rate kg/hr.); W = weight dry sample (kg); A = surface area of sample exposed (cm^2); $-\frac{dx}{d\theta}$ = difference of humidity with regard to time. It is the differential quotient operating in constant drying condition when air conditions (temperature, humidity and velocity) are constant along time.

(e) Amount of energy required to heat drying air (H_D)

The amount of energy required to heat this volume of air to the chosen drying temperature in order to remove any given amount of water in the crop samples is given by Ehiem et al. (2009) as equation (6):

$$\mathbf{H_D = (M.H_K) + (H_L.M_R)} \qquad 6$$

Where H_K is given in equation (7).

$$\mathbf{H_K = C_T(T_2 - T_1)} \qquad \mathbf{7}$$

Where: M = Batch size (dryer capacity) = 25kg; H_L = Latent heat of vaporization at 65^0C = 2499.94kJ/kg; M_R = amount of moisture removed = 23.95kg; C_T = specific heat capacity of tomato = 3.68kJ/Kg°C; $T_2 - T_1 = (65 - 29.6)$; and H_K = 130.27kJ.

Therefore, theoretical amount of energy required for the drying process,

H_D = 63,131.06kJ = 17.54kW.

(f) Heat generated from electric heater (Q_E)

The maximum quantity of heat produced by the resistance wire per hour is given by equation (8) as:

$$Q_E = IVT \qquad \text{(Gustafon et al., 2004)} \qquad \mathbf{8}$$

Where: I = current (Amps); V = applied voltage (220Volts); T = time (hrs.); Power rating of the heater, P = 2000W.

From (8), I = 4.6Amps, Q_{Emax} = 1.012kW-hr ≡ 3.64MJ = 224.7kW.

(g) Solar collector tilt angle

For maximum solar energy received by the flat plate collector, the inclination angle of the collector to the horizontal was determined using equation (9).

$$\boldsymbol{\beta = 10 + \text{lat } \emptyset} \qquad \text{(Gbaha et al., 2007; Nwajinka and Onuegbu, 2014)} \qquad \mathbf{9}$$

Where: β = angle of tilt of the solar collector, degrees
$\emptyset$ = Latitude of collector location, the latitude of F.U.T, Owerri where the dryer was designed is 5.4°N.

Therefore, $\beta = 10 + 5.4 = 15.4^o$

(h) Solar Collector Area (A_c)

The area of the solar collector is calculated using the expression given in equation (10):

$$\boldsymbol{A_c = \frac{Q}{F_R T_{\infty\emptyset} I_H}} \qquad \text{(Komolafe and Osunde, 2005)} \qquad \mathbf{10}$$

Where: F_R =Collector heat removal factor = 0.7; I_H= average solar radiation incident on the collector = 1.02kW/m^2 (Kate, 2011); Q = collector useful heat(kW); $T_{\infty\emptyset}$ = effective transmittance-absorbance of glass = 0.79.

But the collector useful heat gain, Q required to dry a given batch of sliced crop samples is calculated using the expression given in equation (11):

$$Q = [C_P W_P (T_C - T_a) + L_V . M_R] \qquad 11$$

Where: Cp = Crop specific heat capacity (3.68KJ/Kg^{o}c); Wp= initial weight of sample before drying (25kg); Lv= latent heat of evaporation (2499.94kJ/kg).

Therefore, Q = 63, 130.36kJ ≡ 17.54kW.

Substituting for Q into equation (11) above, Area of the solar collector, Ac= 0.7m^2 ≡ (100 x 70) cm^2.

With a minimum drying time of 15hrs from 8am to 10pm (using the electrical heat) for sliced tomato in the hybrid dryer (Abano et al., 2013; Eke, 2003), the mass flow rate of air through the solar collector to the drying bed is calculated thus as in equation (12):

$$M_a = \frac{I_H A_C \eta_C}{C_{pa} \Delta T} \qquad 12$$

Where: C_{pa}= specific heat capacity of air (1.0kJ/kgK); ΔT = temperature difference: (65 – 29.6) ^{o}C; η_c = efficiency of the hybrid system computed as 78.5%.

The mass flow rate M_a = 1.58kg/sec.

(j) Thermal efficiency of heat source, η_{th}

Thermal efficiency is the ratio of the heat used to effect drying to the total heat supplied by the heat source. It is expressed as equation (13):

$$\eta_{th} = \frac{\text{Heat actually used}}{\text{Total heat supplied}} \text{ X } 100 \qquad 13$$

For electrical heater and solar collector, this efficiency is given in equations (14) and (15) (Eke, 2014):

$$\eta_{eh} = \frac{H_D}{224.7\text{kW}} \text{ X } 100 \qquad 14$$

$$\eta_{sc} = \frac{M_R L_V}{A_C T_t I_H T_r} \, X\, 100 \qquad 15$$

Where: A_C = Area of solar collector (m^2); T_r = transmissivity of glass (0.79); T_t = theoretical drying time (15hrs.).

The specific energy consumption SEC is computed as given in equation (16):

$$\text{SEC} = \frac{\text{Total hybrid energy}}{\text{Mass of water removed during drying}} \qquad 16$$

(k) Dryer insulation thickness, T_d

To maximize the energy of the solar collector unit, the base of the collector box was insulated with fibre glass (40mm thickness) while the heating and drying chambers were insulated with refractory material (kaolin – 25.4mm thickness) in order to minimize heat loss. The minimum thickness of insulation was determined by the expression given by (Papade and Boda, 2014) as equation (17):

$$\mathbf{T_d = \frac{kA_C}{F_R M_a C_{pa}}} \qquad \mathbf{17}$$

Where: K = thermal conductivity of insulation of fibre glass and kaolin (0.04W/m^{o}C and 0.023 – 2.9W/m^{o}C respectively); M_a = mass flow rate of air (kg/s); other parameters are earlier defined.

(l) Fan selection

The fan serves the purpose of transferring heated air from the heating unit to the dryer cabinet as well as expelling the exhaust air from the drying chamber to improve the drying rate. The selection was based on the characteristics of centrifugal fan performance curve based on the recommendation of Henderson and Perry (1976) reported in Ehiem *et al.* (2009) as equation (18):

Fan power, $h\mathbf{p_2} = \mathbf{hp_1} \left(\frac{\mathbf{N_2}}{\mathbf{N_1}}\right)^{\mathbf{3}}$ **18**

Where: N_1 and N_2 = rpm of electric motor and fan respectively, and their relationship given in equation (19).

And, $\mathbf{N_2 = N_1 \left[\frac{q_1^{1/2}}{H_1^{3/4}}\right]\left[\frac{H_2^{3/4}}{q_2^{1/2}}\right]}$ Ehiem et al. (2009) **19**

Where: q = volumetric flow rate of air (m^3/hr); H = static pressure (Pa). From fan chart in Henderson and Perry (1976), N_i = motor speed =1000rpm, q_1 = 225.99m^3/hr, q_2 = 195.54 m^3/hr. (calculated volumetric air flow rate), H_1 = 1.41, H_2 = 1.09 (tabulated); Then, fan speed, N_2 = 886.5rpm; hp_1 = 2.28 (from chart); hp_2 = 1.74. This means that an electric motor horsepower of 2hp can be used.

However, Okafor, O. (personal communication, February 5, 2016) recommended that a DC, 12V fan of 3 – 7Watts capacity can be used in a crop dryer for thin layer drying. Therefore, two 4W, 12V DC fans were selected for use in the inlet and exhaust points of the hybrid dryer.

2.3 Description of the hybrid sliced vegetable crop dryer

The hybrid vegetable dryer consists of two major integral components (see Figure 2) namely: the air heater unit (solar collector) and the dying chamber having two layers of drying racks made of wire mesh on which the sliced crops are placed for drying. Other components of the dryer system include: solar panel (80W, 12V), DC battery (75Amps, 12V), control unit, liquid crystal display (LCD), inverter system, inlet and exhaust fans, plain glass (4mm thick), temperature and relative humidity sensors (LM-35 transducers), weighing balances, weight sensors, heating element, frame support, and rollers.

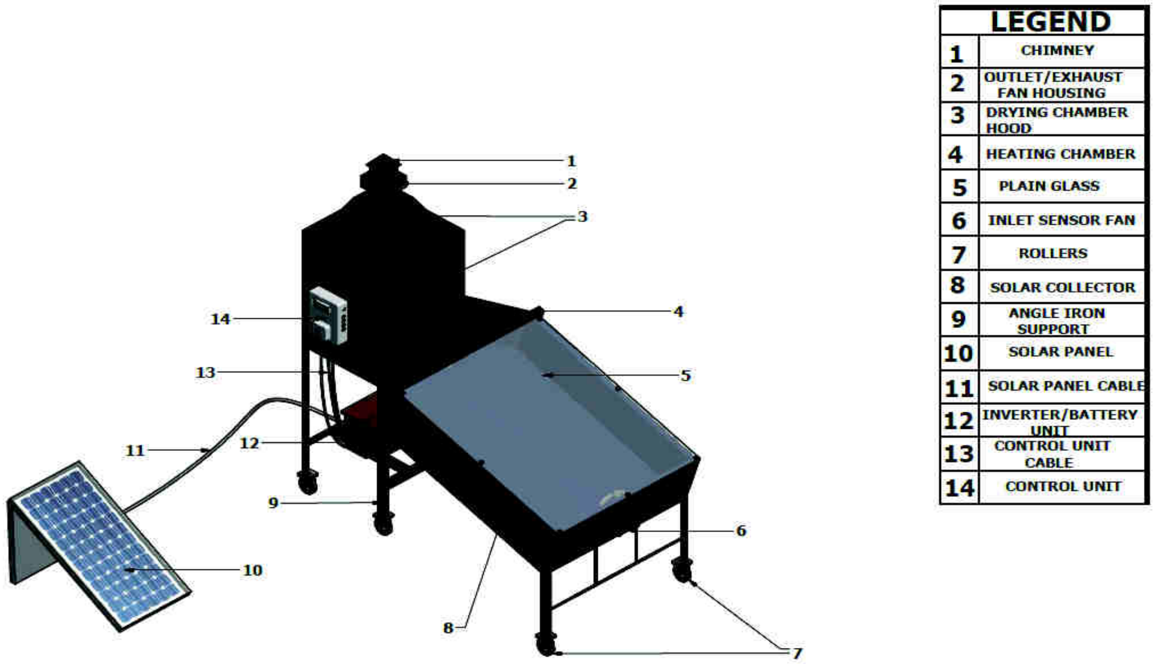


Figure 2: Isometric view of the hybrid sliced vegetable crop dryer.

The heart of the dryer comprises an Arduino microprocessor which controls the overall operation of the system and automates tasks such as temperature and humidity control, sample weight loss, and electrical energy consumption (from AC and DC sources). The system also contains a main heating element powered by alternating current (AC) from the Public Power Supply or an electricity generating set. Transducers (for recording both temperature and relative humidity) are placed at five strategic points on the hybrid dryer namely: chimney, two drying racks, solar collector, and inlet fan, where measurements are taken automatically by the microprocessor unit and displayed on the LCD as shown in Figure 3 (Legend S/N 1).

Different drying temperatures and air speeds can be selected by the use of keypad panel for input and LCD for displaying the current state of the system. In the drying chamber, the drying racks are suspended rigidly by a weighing balance that records the sample weight loss through the use of a weight sensor attached to it. A 1000W resistance wire supplies electrical heat to the drying chamber at preset temperature. The control unit and its accessories as well as other instrumentations are powered by a -75Amp accumulator, which is simultaneously charged by an-80W solar panel; whilst the resistance wire is powered by a public power supply or an electric generator. The energy consumption from the accumulator and AC are measured and recorded by the control unit. When the control unit is connected to the computer, a specialized software called SCADA (Supervisory Control and Data Acquisition) is used to log the readings at 30 minutes interval and the results, stored in a database for immediate or future analyses. This SCADA software is connected to the Arduino microprocessor via a USB cable. The SCADA also conducts analysis using models and performs a regression analysis to the same effect. The results of this analysis (graphs, figures, notes, etc.) are stored in the micro-computer for future reference and documentation purposes, thus the system is fully automated. Through the use of a universal serial board (USB) cable, stored data are transferred to a computer for further analysis.

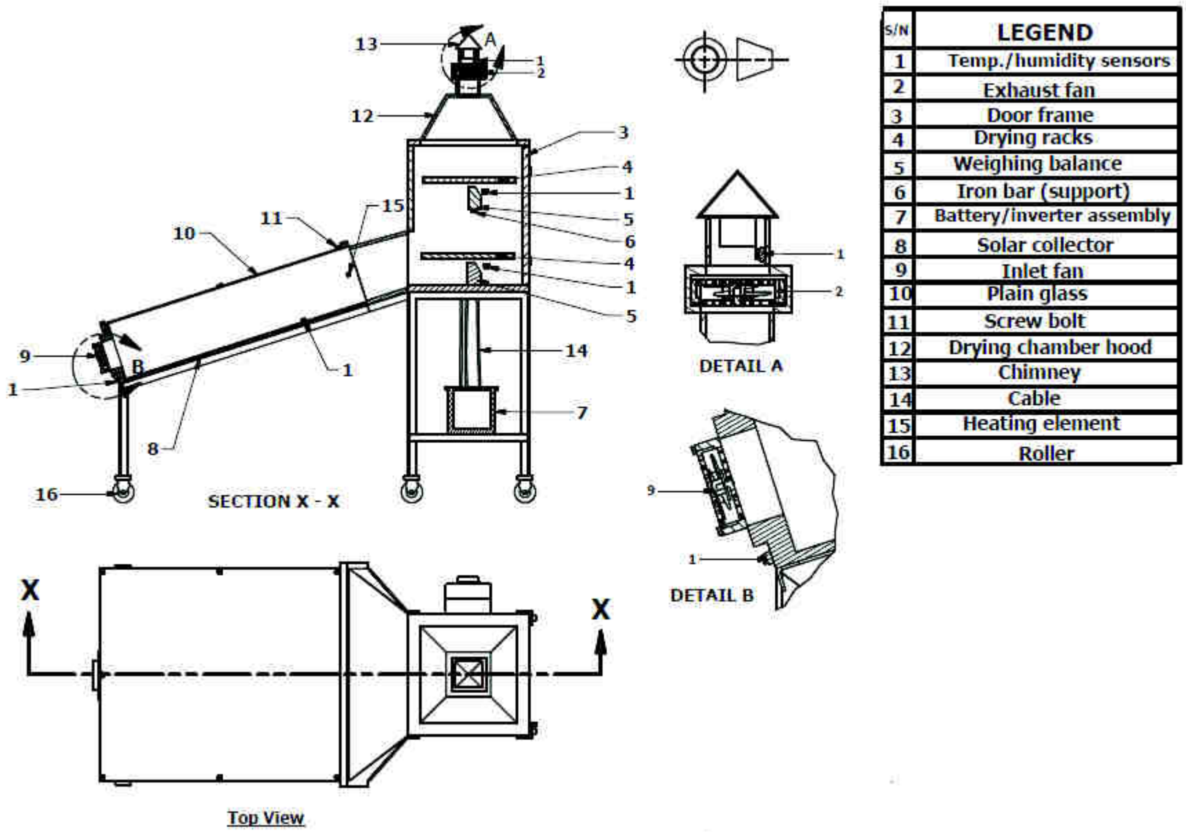


Figure3: Sectional view of the hybrid dryer.

2.4 *Experimental procedure*

The preliminary experiment (no-load test) was conducted at the Federal University of Technology, Owerri (F.U.T.O), Nigeria located at longitude 7.03^{o}N and latitude 5.48^{o}E between 22ndMay and 14th of June 2016, in order to evaluate the thermal profile of the hybrid dryer heat sources. The dryer was positioned in the open, a far distance from the shadows of trees and buildings, and the solar collector faced towards the North-South axis for maximum solar flux collection. The test which lasted between 9am and 4pm was conducted by first selecting the fan speed using the 4 x 4 matrix keypad of the control unit to initiate the required air velocity. Solar radiation was trapped by the solar collector and the heat forced in with use of a suction fan. The incident solar flux on the solar collector was measured with a pyranometer (Apogee MP-200) at 30 minutes interval. The electrical heating unit was switched on to operate at five different preset air temperatures of 50, 55, 60, 65 and 70^{o}C at five varying air velocities (0.1, 0.5, 1.0, 1.5, 2.0m/s). The time taken for the dryer to be heated up to each preset temperature was recorded for each air velocity. When the optimum temperature was attained, the Arduino microprocessor automatically switches off the heating element, and turns it on again when the drying chamber temperature falls one degree below the preset temperature. The dryer was operated in three replications on no-load for a total of 15 days (between 8am to 4pm), and the average results of the drying chamber temperature, relative humidity, time as well as ambient air temperature and relative humidity were measured and recorded by the transducer sensors placed at five different points on the dryer (i.e. outside the solar collector, inside of the solar collector box, by the sides of each of the drying racks, and in the chimney). These readings were transferred and displayed on the LCD of the control unit. The incident solar flux on the solar collector was measured with a pyranometer (Apogee MP-200) at 30 minutes interval.

3. Results and Discussion

The temperature profile of the hybrid dryer was obtained under no-load condition by measuring the temperature inside the drying chamber and the hourly ambient air between 9am and 4pm (local time). The technical performance of the hybrid system of the dryer is as presented in Table 1. Tray 1 receives the highest convective heat due to its closeness to the heat source than tray 2. This is as a result of the increased difference in the quantity of heat produced by the hybrid heat source as evidenced in the Table 1. The hybrid dryer chamber temperature is always higher than the ambient temperature - an indication of greater prospects of the hybrid system. This, therefore signifies that the hybrid dryer system is functional.

Table 1: Technical performance of the hybrid dryer

Local time (mins.)	Avg. ambient condition		Avg. drying chamber condition (hybrid heat)			
	Temp (^oC)	Rh (%)	Tray 1 temp (^oC)	Rh (%)	Tray 2 temp (^oC)	Rh (%)
0	26.2	86.6	34.9	71.0	34.8	71.6
30	27.1	81.4	45.8	68.3	39.8	70.0
60	28.6	77.6	68.9	59.4	62.6	59.8
90	29.7	73.8	71.7	33.4	68.9	52.4
120	30.4	71.7	74.9	31.5	69.5	47.8
150	34.9	69.1	79.6	30.6	73.7	35.2
180	36.5	68.8	85.7	25.4	79.9	31.9
210	39.6	67.6	88.5	23.2	81.3	28.1

The time taken by the hybrid dryer to be heated up to the different preset temperatures at different air velocities were recorded as shown in Figure 4. At constant temperature and varying air velocities, the hybrid system shows a consistently lowered dryer heat-up time. However, drying temperature and air velocity have important roles to play on the total dryer heat-up time as well as the dryer energy consumption. More energy (in form of convective heat) is transferred to the drying chamber as the temperature and air velocity increase for each of the heat sources. For each parameter regime in Figure 4, the hybrid dryer heat-up was found to be reduced with increased air velocity, hence less energy requirement for the dryer heat-up. The hybrid dryer heat-up time decreases as drying air temperature decreases with constant air velocity. At low air velocity (0.1m/s) and temperature (50^{o}C), the dryer heat-up time was observed to be 54.6 minutes. Whilst for a higher air velocity (2m/s) and temperature (70^{o}C), the dryer heat-up time was significantly reduced by 85%. This implies that higher air velocity at constant temperature increases the heat-up time, which would considerably reduce the drying rate.

At higher fan speed, more volume of dry air is forced into the drying chamber and less heat-up time is achieved which results in increase in the energy requirement of the dryer. Generally, a maximum and minimum average dryer heat-up times of 8.5 and 2.5 minutes respectively were taken by the hybrid system at each treatment combination. This significant time lag accounts for economy in terms of time savings, higher rate of moisture transport, and less dryer energy consumption, which are good prospects of hybrid crop dryers. This implies that at higher temperatures, drying time decreases due to increasing thermal gradient inside the drying chamber and consequently increasing the drying rate. Drying time also decreases with increasing air velocity due to decreased vapour pressure with increasing air velocity; thus, the product moisture would encounter less resistance on its way out and exits at a higher rate. These observations were similar to the results reported by Idah et al. (2014); Motevali et al. (2011); Nwajinka and Onuegbu (2014), and Nwakuba et al. (2016).

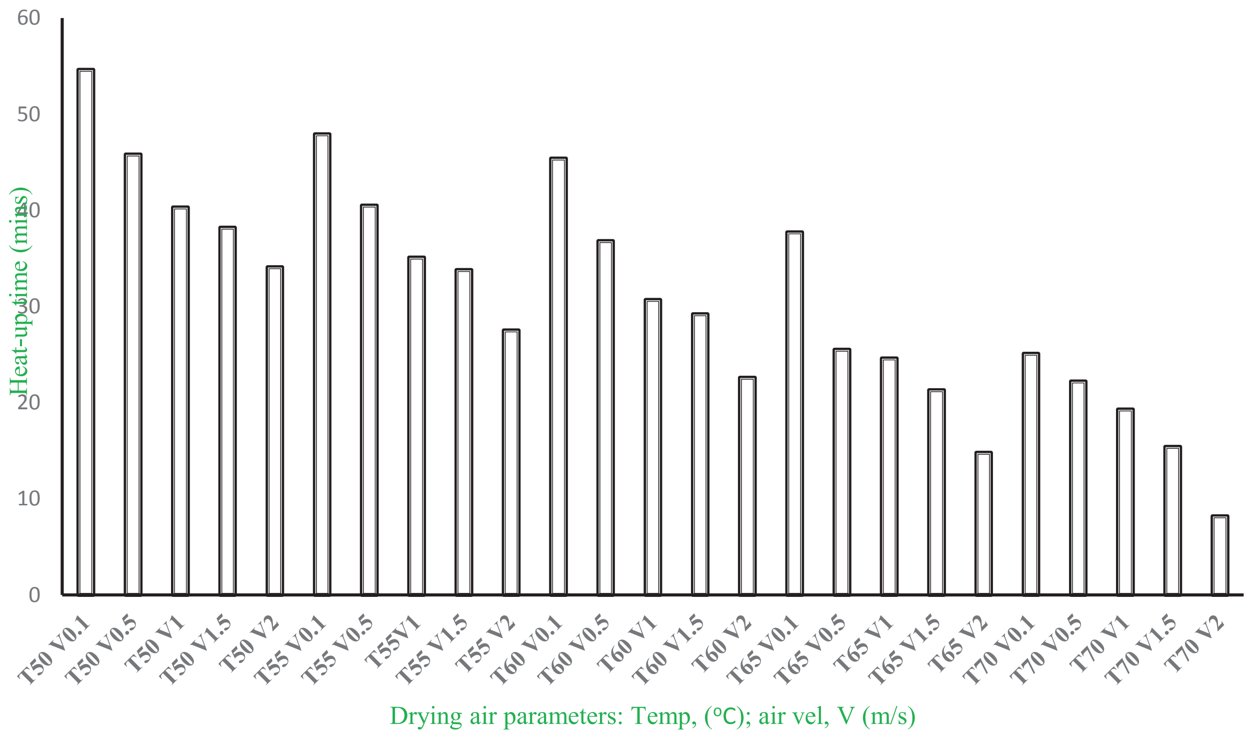


Figure 4: Effect of drying parameters on hybrid dryer heat-up

The amount of energy developed by the dryer heating units under no-load condition has been observed to be dependent on time as presented in Figure 5. As time increases, more energy is developed to heat-up the drying chamber to the desired (preset) temperature level for drying. The hybrid system sums the energy from solar and electricity units and thus develops higher energy in a lesser time (as earlier described in Figure 4). As the drying time increases, more energy is developed by the hybrid unit due to increase in the solar collector heat contribution as a result of increased solar flux in the afternoon. However, about 375 to 400kWhr of energy was developed at 9:00am, whilst 1774 to 1906kW was developed by the hybrid unit between 14:00 to 15:00 local time. These amounts of energy according to Abdulla *et al.* (2011), Motevali *et al.* (2011) and Afolabi *et al.* (2014) are adequate for both initial surface evaporation and moisture migration of sliced moisture-laden crops respectively. The hybrid energy is presented in Equation (20).

$$E_h = -30.894T^2 + 989.55T - 6037.5 \qquad (R^2 = 0.9932) \qquad 20$$

Where: E_h = hybrid energy (kWh), T = drying time (minutes).

This energy model is described by a polynomial function of the 2nd order with R^2-value of 0.993. The energy consumption increases polynomially with drying time. This behavior is majorly due to variation in hourly solar heat trapped by the solar component of the hybrid system. The peak hybrid energy of about 1946kWhr was observed at 4pm and begins to decrease with time (as the sun goes down), while the minimum energy of 372kWhr was developed at 9am. This trend, together with the high R^2-value show very close correlation with dryer energy parameters (such as voltage, current, solar intensity, and time) with respect to the drying time.

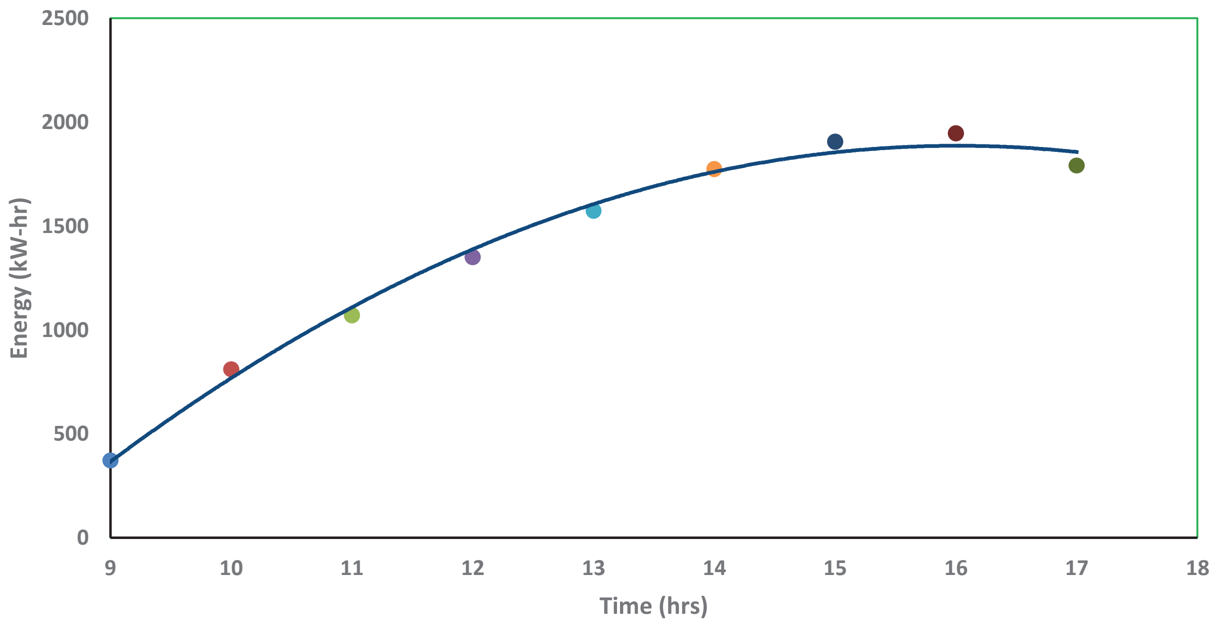


Figure 5: Effect of drying time on dryer energy consumption.

4. Conclusion

A hybrid solar-electric sliced crop dryer has been successfully designed and developed for drying sliced vegetable crops. The dryer was designed for a maximum temperature of $70^{o}C$ (given the optimum drying temperatures of the crops to be handled) with a maximum batch size of 25kg of fresh sliced vegetables. Results of no-load tests obtained show that the dryer demonstrated high heat generation in the hybrid mode given the moisture-laden nature of crops to be handled. The hybrid heat source performed very well in terms of energy development and drying chamber heat-up time. A minimum heat-up time of 5.2 minutes was required by the hybrid heat source at a temperature and air velocity of $70^{o}C$ and 2m/s respectively. Both the drying temperature and air velocity were found to have significant influence on the dryer heat-up time and drying tray temperatures. Drying time had significant effect on the energy consumption of the dryer mainly due to variation in hourly solar heat. The peak energy consumption was observed at 4pm, a time corresponding to about optimum solar heat flux. From the results obtained, the hybrid dryer has prospects of drying a wide range of freshly harvested vegetables, roots and tubers, as well as fish products and other crops to any desired final moisture level given its high heat generation and efficient temperature control. In order to minimize the energy consumption of the hybrid dryer, a constant optimum drying temperature at a fairly high air velocity greater than or equal to $2ms^{-1}$ should be maintained.

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