Design, Fabrication and Performance Evaluation of Hybrid Solar Dryer

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Abstract: **In this paper, a hybrid solar panel integrated dryer using both solar energy as well as electrical energy has been designed, constructed and tested at the faculty of Science, The Polytechnic, Ibadan, Oyo state, Nigeria. The system designed consists of solar collector, drying chamber as well as three trays of dimension 1.30 x 1.40 m. It also consists of four photovoltaic cell (PVC) modules which power the heating element and charging 200 AH Tubular battery as well as for the operation of DC fan. The system designed was made to operate as both solar energy dryer and hybrid dryer. The performance of the dryer constructed was assessed with 10.5 kg of fresh yam slices and compared its drying ability with direct open sun drying under the same atmospheric weather conditions. The results revealed that, at around 2pm, the ambient temperature recorded was 36.5^{o}C while the solar collector and chamber temperatures recorded were 64.5^{o}C and 51^{o}C respectively. It was also noted that the moisture content of the fresh yam slices reduced from 89% to 33% in ten hours at drying rate of 0.8776 Kg/hour for direct open drying. For the solar drying, the moisture content reduces from 89% to 20% in ten hours at drying rate of 0.9056 Kg/hour while the moisture content for hybrid drying was found to reduce from 89% to 7% in ten hours at drying rate of 0.9258 Kg/hour. This implies that solar hybrid drying method was faster than other two techniques. It overall efficiency of system constructed was found to be 66.7%**

***Key words*: Hybrid dryer, moisture content, PVC, solar dryer, yam slices**

I. INTRODUCTION

The purpose of drying is to remove moisture from the agricultural product so that it can be refined and stored for a long periods of time. Solar drying of food products can be most successfully used as a cost effective drying method. Although, open sun drying of crops under direct sunlight is economical, but the product obtained by it is of lower quality due to contamination by dust, insects, birds, pets and rain. Also, loss of vitamins, nutrients and unacceptable colour changes due to direct exposure to ultraviolet rays, and it take long time to dry. Solar dryers are specialized devices that control the drying process and protect agricultural product from damages by insect pest, dust and rain. Comparison between sun drying and solar drying revealed that, solar dryers generate higher temperatures, lower relative humidity, and lower product moisture content and reduced spoilage during the drying process than sun drying. Hence, solar drying technique is preferred to other alternative sources of energy such as wind and shale, because it is abundant, inexhaustible, and non-polluting, readily available at no cost and can be tapped in the site itself [1, 2, 3, 4]. However, one major disadvantage of solar-energy dryer is that it can only be used during the daytime when there is sufficient solar radiation for conversion to heat. Solar dryers are constructed normally with no any form of back-up heating systems [5] and makes it burdensome to use them for drying at nights or during the rainy season. For commercial processors, this factor restricts their capacity to dry an agricultural products at night when there is no sunshine; this restriction usually leads to long periods of drying because drying can only takes place when there is sunshine. This problem does not only reduce the productivity but leads to inferior drying quality. Hence, there is need to proffer solution to this problem, that is, for a solar dryer to operate during day time and at night even during the rainy season. Several hybrid dryers were designed and constructed to control the drying air conditions throughout the drying time independent of sun-shine especially at night or poor weather when it is not possible to use the solar energy, using alternative heating sources such as sawdust burner [6]; kerosene stove [7] or by using a biomass stove [8]; electric heater [9]. But the food materials and agricultural products are more sensitive to all these drying techniques most especially, the smoke developed in using sawdust burner may degrade the drying products. Hence, in this work, a new innovation called hybrid solar dryer has been designed, constructed and tested for drying yam slices. The drying results obtained are compared with the result of direct sun-dried product.

II. EXPERIMENTAL CAMPAIGN AND METHODOLOGY

The experimental studies was carried out at The Polytechnic, Ibadan with Latitude of 7.4296^{0}N and Longitude of 3.8919^{0}E, Faculty of Science,Physics with electronics. The study was conducted with a view to obtain the moisture content for solar drying and sun drying of tubers of yam.

2.1 Material used and designed

The type of metal used, the thickness and the dimension of the construction is shown in table 1

Table 1: Parameters of metal used

s/n	Metal	Dimension	Thicknes
1)	Iron metal	3¼ inches and 1 inches	0.85 m
2)	Aluminum	2¼ inches by 2 inches	Gauge 0.8 m
3)	Galvanized sheet	2 inches	3.0 m

2.2 Design considerations

(i) Angle of tilt of solar collector

The tilt angle (β) of the solar heater at a latitude φ of the collector is obtained using [10]. The value of latitude in Ibadan where the dryer was designed $7.4296°N$

$$\beta = 10° + \; lat\; \varphi \quad (1)$$

$$\therefore \beta = 17.4296°$$

(ii) Isolation on the collector surface area

The average daily radiation (isolation), H, on the horizontal surface as well as the average effective ratio of solar energy on tilted surface to the horizontal (R) in this region of study, Ibadan south western, Nigeria are 978.21 and 1.0036 respectively. Thus, the isolation on the collector surface is obtained using equation (2)

$$I_C = HT = HR \quad (2)$$

$$I_C = 978.21 \times 1.0036$$

$$\therefore I_C = 981.731\; Wm^{-2}$$

(iii) Collector area

A solar collector is a device that collects and concentrates solar radiation from the sun which is used for active solar heating. The volumetric flow rate, $V_a{}'$, of air was determine using (3)

$$V_a{}' = V_a \times a_h \times C_w \quad (3)$$

whereV_a is the mass flow of air = 0.21 m/s, the air gap a_h= 0.052 m and the width of the collection = 0.6 m.

$$V_a{}' = 0.21 \times 0.052 \times 0.6$$

$$\therefore V_a{}' = 0.00655\; m^3/s$$

Thus, the mass flow rate of air with density of air, ρ, taken as 1.28 kg/m^3 is given as

$$M_a = V_a{}'\rho_a \quad (4)$$

$$M_a = 0.00655 \times 1.28$$

$$\therefore M_a = 0.00838\; kgs^{-1}$$

Area of the collector, A_c is given as

$$A_c = \frac{M_a}{C_w \times I_c} \quad (5)$$

$$A_c = \frac{0.00838 \times 1005 \times 30}{0.6 \times 981.731}$$

$$\therefore A_c = 0.429\; m^2$$

The length, L, of the solar collector is given as [11]

$$L = \frac{A_c}{B} \quad (6)$$

$$L = \frac{0.429}{0.6}$$

$$\therefore L = 0.715\; m$$

$$The\; collector\; area\; = \; L\; \times B = 0.715 \times 0.6$$

$$\therefore A = 0.43\; m^2$$

(iv) Base insulator thickness for the collector

For this work, the thickness of the insulator was taken as 7 cm. and the side of the collector is made up of wood. The dimension of the drying chamber has a volume of 0.5 m^3.

(v) Power rated of the dryer

The power of the dryer is given as

$$P = \frac{Q_Y}{t_Y} \quad (7)$$

(vi) Fan blower design

The mass flow rate of air is given as [11]

$$M_a = \frac{Q_a}{C_{pa}\Delta T t_d} \quad (8)$$

whereQ_a is the quantity of heat required, C_{pa} is the specific heat capacity of air (1.095 kJkg^{-1}K^{-1}) and t_d is the taken taken for drying (8 hours).

(vii) Absolute energy needed

The initial energy needed for drying is given as [12],

$$E = M_a(H2 - H1) \quad (9)$$

where H2 is the heat content of warm air and H1 is the heat content of ambient air. The heat content is given as [12]

$$H = 1.006.9T + H_r(2512131) + 1552.4T \quad (10)$$

H_r is the humidity ratio and T is the air temperature (^{o}C)

(viii) Estimation of total power consumption by the system

Since the solar panels system can generate electrical energy to compensate the energy consumption. The configuration of the solar panel designed was optimized so as to match the energy produced. The power rating of the dryer of the dryer designed was 400 W and the daily operational time was 8 Hours.

$$Energy\; required, E = Pt = 450 \times 8$$

$$\therefore E = 3{,}600\; Wh$$

(ix) Number of solar panels required

To determine the correct size of solar panels required, the total energy produced has to be known. Since the peak wattage produced by solar panels depends on the size and the climate of the experimental campaign/location. Also, the power generation factor which is also location dependent need to be known. The maximum power of the solar panels P_{max} needed is given as,

$$P_{max} = \frac{Total\ energy\ required}{Power\ generation\ factor}$$

$$P_{max} = \frac{3600}{3.75}$$

$$\therefore P_{max} = 960\ Wh/day$$

$$The\ number\ of\ PVC\ modules\ needed\ = \frac{960}{250} = 3.84$$

$$\cong 4\ modules$$

Hence, in this work, four PVC modules of 250 W were used with 200 AH Tubular battery for energy back-up.

2.3 Construction

The dimensions and thickness of the metal used is shown in table 1. The aluminum used is of thickness 0.85 mm and it was cut to the size of 120x60 cm in order to reduce the top heat loss. The aluminum sheet together with an insulator of thickness 4 mm was placed in the solar collector. Three trays of size 1.3 x 1.4 m were used and the trays were made of iron net so as to allow free flow of air within the drying chamber. The gap between the trays from lower, middle to upper level is 4.5 inches.

Materials used for the air inlet and outlet are; fan outlet and trasparernt polythene. The polytene allows hot temperature to pass into the dryer chaber to dry the food substance

The air tight chamber was achieved by adding rubber wihch helps to trap the heat so as not to escape out from the chamber.

Figure 1: Side view of hybrid solar dryer under construction

Figure 2: Drying chamber with three trays

Figure 3: Voltage and Temperature output display unit

Figure 4: Constructed hybrid dryer

2.4 Working principle and testing.

Figure 4: The constructed hybrid solar dryer

The hybrid dryer was place in an open place throughout the day and night of operation. Since, two independent sources are embedded and can be used for drying, which are; solar collector and the heating coil element. During the day, the solar irradiance from the sun falling on the dryer is absorbed by the collector plate which in turns transmitted into the drying chamber via the inlet opening by forced convection system and the moisture is removed by the process. Conversely, when the ambient temperature is low (early in the morning) or when it rained, the thermostat switched ON the heating element in order to continue or complete the drying process of the product. The solar panels convert the solar irradiance to electric current which is stored in the battery as back-up to power the heating coil, fans and the control system.

Various experimental tests were carried out in the last week of the month of March to first week of August in the year 2019 (rainy season) for checking the performance of the solar collector and the behavior of the system as a whole. Yam slices was selected for drying in the constructed hybrid dryer. The initial water content of the 10 kg slice yam was determined by oven dry technique. The same quantity of yam was arranged on the three trays in dryer chamber. Experimental data is recorded from morning 8.00am to evening 4.00 pm. Drying chamber temperature, collector temperature and ambient temperature as well as relative humidity were measured concurrently. The entire procedure was repeated with another 10 kg yam slices in open sun drying and the data were compared with solar hybrid drying method.

2.5 Performance evaluation

The performance of solar dryer system was determined using the following; solar collector efficiency, drying rate, moisture loss and drying efficiency.

The efficiency of solar collector is given as [13]

$$\eta_c = \frac{M_a C_p (T_o - T_a)}{A_c I_T} \quad (11)$$

The Overall Efficiency of the dryer is defined as the amount of heat utilized by the dryer to evaporate the moisture from yam slice to the amount of heat fallowing on the collector surface or heat supplied by solar radiation [14],

$$\eta_d = \frac{M_w L_v}{A_c I_T t} \quad (12)$$

where M_w is the amount of water evaporated (kg), L_v is the specific latent heat of vaporization of steam (2320 Kj/kg), t is the drying time (hours), A_c is the collector area (m^2), T_a is the ambient temperature, I_T is the total irradiance and T_o is the temperature of outgoing air from the collector

The moisture loss, M_L, and moisture content on wet basis$M_C$are determined using equations (13) and (14) respectively.

$$M_L = M_i - M_f \quad (13)$$

$$M_C = \frac{M_i - M_f}{M_i} \times 100\% \quad (14)$$

The water content for dry basis is given as

$$M_w = M_{we}\left(\frac{M_i - M_f}{1 - M_f}\right) \quad (15)$$

whereM_i is the percentage initial mass of the yam slice and M_f is the percentage final mass of the yam slice, M_w is the mass of water evaporated from yam slices in kg and M_{we} is the initial water content in the yam slice in kilogram.

The average drying rate which is the quantity of moisture removed from the yam slice over the dying time is given as [15]

$$M_{dr} = \frac{M_w}{t_d} \quad (16)$$

where M_w is the mass of water evaporated and t_d is the time of the day.

III. RESULTS AND DISCUSSION

Figure 5 depicts the hourly variation of the temperatures in the solar collector and the drying chamber compared to the ambient temperature. The trend of the graph shows that the temperature starts to increase from morning (8am) and reaches its peak value in the afternoon (2pm) when the solar irradiance is highest, and starts to descend. After putting the ambient temperature, drying chamber temperature and the collector temperature with respect to time it is observed that at 2.00 pm the temperature and solar radiation both are high and after few hours they get slow down and goes back to normal temperature. The temperatures inside the drying chamber and the solar collector were much greater than the ambient temperature throughout the period of study.It was noted that at 2.00 pm when the maximum average ambient temperature for the day was 36.5^{o}C, the temperature of the solar collector was 64.5^{o}C and the drying chamber temperature was 51^{o}C. Thereafter, the collector, drying chamber and ambient temperatures started decreasing with time of the day. It was also noted that, between 12.00 hour and 3.00 pm the ambient temperature, drying chamber and collector temperatures ranges from 34 to 33^{o}C, 46 to 44^{o}C and 53.5 to 52^{o}C. This result shows that the dryer is hottest within these range of temperatures and it indicates prospect for better performance than open-air sun drying

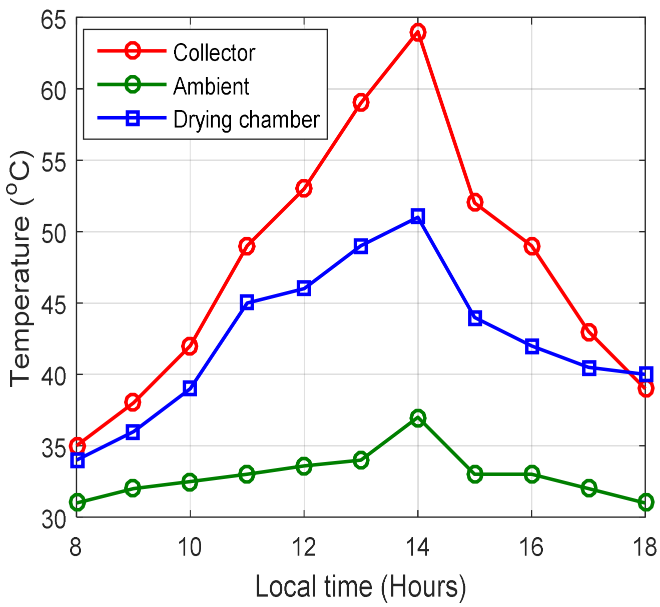

Figure 5:Day results of the variation of temperatures in the solar dryer.

Figure 6 shows the variation of the relative humidity of the ambient air, solar drying chamber and hybrid chamber. It was noted that the relative humidity of ambient air ranges from 75 to 83% while that of solar drying and hybrid drying chambers ranges from 39 to 75% and 32 to 72% respectively. From the figures 5 and 6, it can be deduced that, generally, the drying processes were enhanced by the heated air at very low humidity.

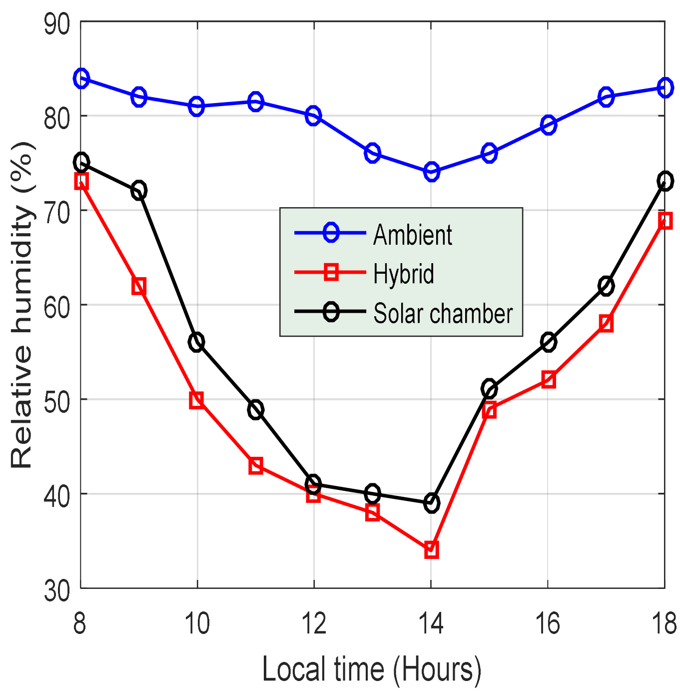

Figure 6: Variation of relative humidity with local time

Figure 7 shows the performance of hybrid drying, solar drying and sun drying under loaded condition. The initial moisture content of the yam slice was determined in the laboratory using [16] the AOAC (2000) air oven method and 94.22% wet basis moisture content was obtained. It was observed generally that, the moisture content in the yam slice decreases with increasing drying time. It was also noted that, the moisture content of the fresh yam slices reduced from 89% to 33% in ten hours at drying rate 0.8776 Kg/hour. For the solar drying, the moisture content reduces from 89% to 20% in ten hours at drying rate 0.9056 Kg/hour while the moisture content for hybrid drying was found to reduce from 89% to 7% in ten hours at drying rate 0.9258 Kg/hour. The percentage of moisture content remained in the yam slice after drying for 10 hours for all the three methods is shown in figure 7 while table 2 shows the computed drying rates and the mass of water evaporated from the yam slices for the three modes of drying considered.The hybrid solar dryer had a faster rate of drying than the yam slices in the solar drying and open sun drying method. This indicates that the hybrid dryer exhibits sufficient ability to dry yam slices at a reasonably rapid rate. The overall efficiency of the hybrid solar dryer during the test period was found to be 66.7%

Table 2: Computation of drying rates and mass of moisture content

Drying method	Data obtained	Computations/ remarks
Hybrid solar drying	$M_{we} = 10.5\ kg$ $M_f = 7\%$ $M_i = 89\%$	$M_w = M_{we}\left(\frac{M_i - M_f}{1 - M_f}\right)$ $= 10.5\left(\frac{0.89 - 0.07}{1 - 0.07}\right)$ $\therefore M_w = 9.258kg$ The average drying rate was obtained by using (16) $M_{dr} = \frac{9.258}{10}$ $\therefore M_{dr} = 0.9258\ kg/hour$
Solar drying	$M_{we} = 10.5\ kg$ $M_f = 20\%$ $M_i = 89\%$	$M_w = 10.5\left(\frac{0.89 - 0.2}{1 - 0.2}\right)$ $\therefore M_w = 9.056kg$ $M_{dr} = \frac{9.056}{10}$ $\therefore M_{dr} = 0.9056\ kg/hour$
Open sun drying	$M_{we} = 10.5\ kg$ $M_f = 33\%$ $M_i = 89\%$	$M_w = 10.5\left(\frac{0.89 - 0.33}{1 - 0.33}\right)$ $\therefore M_w = 8.776kg$ $M_{dr} = \frac{8.776}{10}$ $\therefore M_{dr} = 0.8776\ kg/hour$

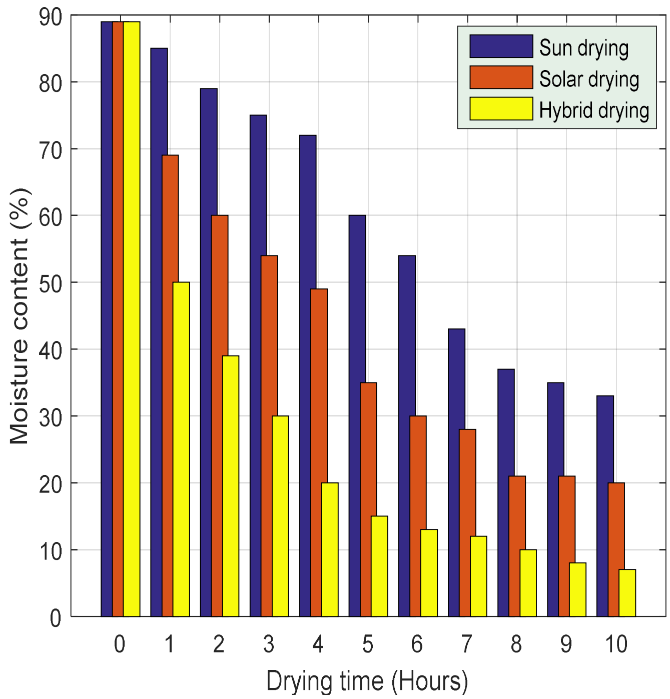

Figure 7: Graphical representation of moisture content against drying time.

IV. CONCLUSION

In this work, a hybrid solar dryer has been designed and constructed using a cheap locally made materials which make it available and affordable to all and especially for farmers. From the performance evaluation of the dryer constructed, the hourly variation of the temperatures inside the solar collector and the drying chamber are much higher than the ambient temperature during the experimental period. At 2pm when the maximum average ambient temperature for the day was 36.5°C, the temperature of the solar collector was 64.5°C and the drying chamber temperature was 51°C. Hence, the solar dryer raised the ambient air temperature to a considerable high value for increasing the drying rate of yam slices. It was also deduced that, generally, the drying processes were enhanced by the heated air at very low humidity. The hybrid solar dryer had a faster rate of drying (0.9258 Kg/hour) than the yam slices in the solar drying with drying rate (0.9056 Kg/hour) while open sun drying method had a low drying rate of ($0.8776\ kg/hour$). This indicates that the hybrid dryer exhibits sufficient ability to dry yam slices at a reasonably rapid rate. The overall efficiency of the hybrid solar dryer during the test period was found to be 66.7%, this made the hybrid dryer fabricated to dry food items quickly to a safe moisture level and it also ensures a better quality of the dried product

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