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Design and fabrication of a forced convection solar dryer integrated with heat storage materials

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ABSTRACT. *The purpose of this study was to designed and fabricated a 10 kg capacity forced convection solar dryer integrated with thermal energy storage materials, TSMA and TSMB, using locally sourced and low-cost materials for drying agricultural products. The dryer consists mainly of a well-insulated solar collector, drying chamber and photovoltaic components. The maximum collector and drying chamber temperatures obtained from three experiments at no-load conditions with two different thermal and without thermal energy storage materials were 86.2, 91.3 and 80.3 °C; and 67.8, 70.8 and 54 °C respectively, at the corresponding maximum solar radiations of 716.5, 810 and 724.7 W/m^2. The recorded minimum drying chamber relative humidity of the solar dryer with TSMA, TSMB and without was 27, 24 and 23% respectively, and the corresponding ambient humidity was 70.8, 56.8 and 56.2%. A full load drying process using cocoa beans with TSMA took two full days, 10 hrs (58 hrs) to reduce initial moisture content of cocoa beans from 0.6 to 0.034 g water/g w.b. The maximum drying temperature and thermal efficiency obtained were 54 oC and 48.8% respectively. The dryer was thus viable for drying products within short time with little temperature control mechanism.*

RÉSUMÉ. *Le but de cette étude était de concevoir et de fabriquer un séchoir solaire à convection forcée d'une capacité de 10 kg qui intègre aux matériaux de stockage thermique, TSMA et TSMB, en utilisant des matériaux locaux et à faible coût pour le séchage des produits agricoles. Le séchoir comprend principalement un capteur solaire bien isolé, une chambre de séchage et des composants photovoltaïques. Les températures maximales des capteurs et de la chambre de séchage sont obtenues de trois tests en conditions sans charge avec deux matériaux de stockage thermique différents et sans stockage thermique étaient de 86,2, 91,3 et 80,3 °C; et qui sont respectivement à 67,8, 70,8 et 54 °C aux radiations solaires maximales correspondantes de 716,5, 810 et 724,7 W / m^2. L'humidité relative minimale enregistrée de la chambre de séchage du séchoir solaire avec TSMA, TSMB et celle sans eux était respectivement de 27, 24 et 23%, et l'humidité ambiante correspondante était de 70,8, 56,8 et 56,2%. Un processus de séchage à pleine charge des grains de cacao avec du TSMA a pris deux jours complets, 10 heures (58 heures) pour réduire la teneur en humidité initiale des grains de cacao* *de 0,6 à 0,034 g d'eau par gramme de poids corporel. La température maximale de séchage et l'efficacité thermique obtenues étaient respectivement de 54 °C et 48,8%. Le séchoir était viable pour sécher les produits en peu de temps avec peu de mécanisme de contrôle de la température.*

KEYWORDS: *drying, Solar dryer, Forced convection, Cocoa beans, Heat storage materials.*

MOTS-CLÉS: *séchage, séchoir solaire, convection forcée, grains de cacao, matériaux de stockage thermique.*

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1. Introduction

Reduction of post-harvest losses in developing countries can significantly contribute to availability of food. Estimation of these losses is generally cited to be of order of 4% but can under very adverse conditions, be nearly 100% (Michael, 1991). Drying is one of the most important postharvest treatments being adopted worldwide to reduce spoilage and increase the shelf life of agricultural products. The drying technique is probably the oldest and the most important method of food preservation practiced by humans. The removal of moisture prevents the growth and production of micro-organisms which causes decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizes packaging, storage and transportation costs and enables storability of the product under ambient temperatures (Akpinar *et al.*, 2006; Demir *et al*., 2010).

Traditionally, drying of agricultural products is done by open sun with the consequent postharvest losses and damage to the products. Shortcomings of open sun drying of agricultural products have been reported. The disadvantages of this method include exposure of the products to rain and dust, uncontrolled drying; exposure to direct sunlight which is undesirable for some foodstuffs; infestation by insect; attack by animal, etc. (Komolafe *et al*., 2014).

In respect to better quality product, several authors have recommended solar drying as an alternative to sun drying. However, the intermittent effects and weather dependency nature of solar dryer have been major barriers to the effective use of solar energy. Consequently, different configurations of solar drying systems integrated with thermal storage materials to eliminate the reabsorption of moisture have been proposed by several researchers. Excess heat energy can be stored in fluids and solids as a change in internal energy of a material as sensible, latent and thermo-chemical heat or combination of these (Bal *et al*., 2010; Bal *et al*., 2011; Sharma *et al*., 2009).

Different thermal storage materials have been used to dry food materials and other agricultural products. Sensible heat storage materials including water, rock (granite), sand, and bricks had been used to store thermal energy in the drying of banana slices, cocoa beans, food crops (cassava leaves, cassava chips, pepper, fish, coconut, unshelled fresh groundnut and chilli) (Amer *et al*., 2010; Fagunwa *et al*., 2009; Ayensu et Asiedu-Bondzie,1986; Ayyappan et Mayilsamy, 2010; Taigan et Tekasakul, 2005); phase change material (PCM) such as seeded grape (Çakmak *et al*., 2011) and thermo-chemical storage materials (desiccants) for cocoa beans, peas and pineapple slices (Dina *et al*., 2015; Shanmugan et Natarajan, 2013).

The present study focused on the design, fabrication and thermal profiles of a solar drying system integrated either with or without thermal energy storage materials (bricks) using locally available and environmentally friendly materials. Investigating the thermal profile of the drying system is an important procedure to establish the operation strategies that will optimize the process. There are limited reports on solar dryer integrated with thermal energy storage materials for agricultural products. Study on the drying of agricultural products using solar dryer integrated with brick materials as thermal storage material, to the best of the knowledge of the authors, has not been reported.

2. Materials and methods

2.1. Design of the solar dryer

A simple cost effective solar dryer of 10 kg capacity was designed for the drying of agricultural products. Basic parameters considered for the design of the dryer were based on the design considerations, preliminary investigations, assumptions and analysis of information on different agricultural products. The environmentally friendly materials including plywood, corrugated aluminium sheet, copper pipes, angle iron, Perspex glass, mild steel, stainless steel and an axial fan used for the construction were locally sourced. The following factors were considered in the design of the solar dryer:

(i) The amount of water needed to be removed from the agricultural products
(ii) The size of the of the produce to be dried at a time
(iii) Construction materials for the drying chamber and tray
(iv) Method of loading and unloading the material.
(v) Daily solar radiation to determine energy received by the dryer per day.
(vi) The quantity of air needed for drying.

2.2. Basic theory

The dimensions of the dryer were determined by evaluating the quantity of heat required to remove the moisture from the given quantity of wet produce to final moisture content for the safe keeping of the produce.

The mass of water, mw to be removed during drying process is determined by using the following expression (Pardhi et Bhagoria, 2013; Akoy *et al*., 2012):

$$M_w = \frac{M_c\left(m_i - m_f\right)}{\left(100 - m_f\right)} \qquad (1)$$

where M_p, mass of the produce to be dried (kg), and m_i and m_f, the initial and desired final moisture content (wb).

The heat energy (Q_m) required to evaporate moisture from the product was obtained through the relation (Karlekar, 1982):

$$Q_m = M_p C_p dT + M_w L \tag{2}$$

where M_p is the mass of the product to be dried (kg); C_p is its specific heat; M_w, mass of water removed (kg), dT, change in temperature in ºC; L=2256 kJ/kg, the latent heat of vaporisation of water (Liley, 1997).

The quantity of heat stored (kJ), $Q_{hs,}$ by the heat storage media can be calculated by using the relation (Bal *et al.*, 2011; Lane, 1983; Sreekumar, 2007):

$$Q_{hs} = M_{hs} C_{hs} dT \tag{3}$$

where M_{hs} is mass of heat storage medium (kg); C_{hs}, specific heat of the heat storage medium kJ/kgK; and dT the difference in temperature level between which the storage operates.

The angle of inclination (β) of the collector to the horizontal for maximum solar energy is given as (Gbaha, 2007):

$$\left(\phi - 10^o\right) \le \beta \le \left(\phi + 10^o\right) \tag{4}$$

where ϕ is the latitude of the collector location (8.1 °N)

The energy gained by the collector can be calculated by using the following relation (Gatea, 2010; Akinola et Fapetu, 2006; Gupta et Kaushik, 2008):

$$Q_U = \alpha\tau I A_c - U_L A_c \left(T_c - T_a\right) \tag{5}$$

where A_c is the solar collector area (m^2), I the incident insolation (W/m^2), U_L the overall heat loss by the collector (W/K), α the Solar absorptance, τ transmittance of absorber plate, T_c the collector temperature (K), and T_a the ambient air temperature (K).

The heat gained by air (Q_g) (Bolaji, 2011; Sevik, 2014) is given by:

$$Q_g = \dot{m}_a C_{pa} \left(T_c - T_a\right) \tag{6}$$

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

The collector heat removal factor (F_R) is (Bolaji, 2011; Alta *et al.*, 2010):

$$F_R = \frac{Q_g}{Q_U} = \frac{\dot{m}_a C_{pa}\left(T_c - T_a\right)}{I_c A_c} \quad (7)$$

The collector efficiency (ɳ) is expressed as (Sevik, 2014; Montero *et al*., 2010; Al-Juamily *et al*., 2007):

$$\eta = \frac{m_a C_{pa}\left(T_c - T_a\right)}{I_c A_c} \quad (8)$$

2.3. Experimental set up

The designed and fabricated 10 kg capacity forced convection solar dryer shown in Figure 1 consists majorly of three units namely; the solar collector box, solar PV system (which also consists of a solar panel or cell, charge controller, inverter, and battery) and drying chamber. All contacts between these units were firmly closed to minimize infiltration losses.

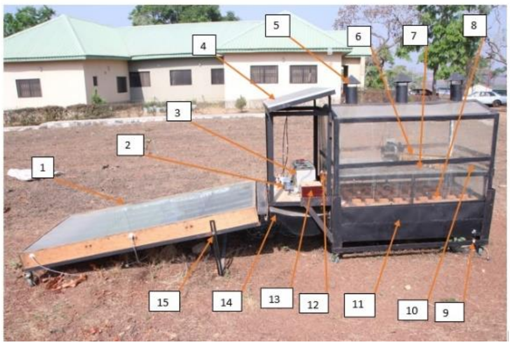

Figure 1. Picture of the fabricated solar dryer

(*1. Solar collector box; 2. Charge controller; 3. Battery; 4. Solar cell; 5. Chimney; 6. Stirrer; 7. Drying tray; 8. Thermal storage material; 9. Supporting frame; 10. Drying chamber; 11. Plenum chamber; 12. Thermostat; 13. Stirrer control box; 14. Air duct with blower; 15. Collector box supporting hanger*)

Solar collector

The solar collector was a top-open wooden box of size 2100 x 1100 x 120 mm made from 20 mm thick plywood. The box covered with 4 mm thick glass was inclined at about 15o to the horizontal. A 2000 x 1000 mm black painted corrugated aluminium sheet placed on top of the air inlet copper pipes was insulated with 50 mm thick rock wool to prevent heat loss in the box. Further design specifications of the dryer are presented in Table 1.

Solar PV system

The solar PV system consists of one 200 W solar panel, a charge controller, an inverter and 200 Amp battery. The PV system was in place to operate 30 W capacity axial fan (located in front of the air duct to suck in hot air from the solar collector and circulate within the drying chamber), a thermostat and the stirrer.

Drying chamber

The drying chamber comprised a Perspex glass cover with overall dimension of 1348 x 748 x 1239 mm, riveted to angle iron structural frame and having within it two compartments, one for loading tray and the other for heat storage material. In the loading area, there was a drying tray (1300 x 700 x 30) mm in dimension located directly above the heat storage material area. This drying tray was fabricated from a stainless steel plate. The diameter of the hole perforated on it was 6 mm and the distance between the holes was 6 mm to allow drying air to pass through the products. A thermostat was installed under the tray to regulate the drying chamber temperature during drying process. Two types of thermal energy storage materials (TSM) made of bricks coated black, of dimension 70 x 50 x 35 mm, were produced from termite mound and labelled as TSMA and river bank clay, labelled as TSMB. The TSM were placed at the top of a platform made from mild steel with 10 mm diameter holes drilled on it at 10 mm apart. The platform was placed on the top of the plenum chamber which was located under the drying chamber. The bricks were positioned in such a way that the free flow of convective heat to the product in the drying chamber was not hindered.

Table 1. Specification of the dryer

Location	Omu-Aran
Experimental period	Nov., 2016
Overall Length	3.91 m
Overall Height	1.43 m
Absorber plate dimension	2 x 1 m
Insulation Thickness (Bottom)	0.1 m
Insulation Thickness (Side)	0.05 m
Gap between the absorber plate and glass cover	0.04 m
Number of tray	1
Tray dimension	1.3 x 0.7 m
Collector tilt angle	15^{o}
Number of solar panel	1
Number of battery	1

2.4. Performance evaluation of the dryer at no-load condition

The no load tests using the developed solar dryer were conducted at the Teaching and Research Farm, Landmark University, Omu-Aran, Nigeria which is located at latitude 8o 8′N, longitude 5o 5′ E. During the no-load experiments, the thermostat was disconnected from the system in order to determine the highest temperature that could be obtained by the dryer. The experiments were conducted for a total of three days. In the first two days, the experiments were conducted with TSMA and TSMB, while the third experiment was carried out on the third day without the thermal storage material. The experiments were carried out in the last week of November from 9:00 to 18:00 hr on each day to determine the critical parameters of the drying process including temperature, relative humidity and air speed at different locations within the dryer based on the available solar radiation at the experimentation site. During the tests, it was assumed that the available energy was equal to the useful energy because no product was dried and no control experiment was set up.

2.5. Data measurements

Temperature and humidity of air were measured at different locations within the dryer as shown in Figures 2 using sensors DS18B20 capable of measuring temperature from –55 to +125°C (±0.5°C accuracy) and DHT22 for 0-100% humidity readings. The sensors were connected to a data logger made up of Atmel ATmega 328P type micro-controller which acts as the brain of the system, SD Card Module for mounting the memory card, a real time clock module for taking note of time and date of the day and a power bank unit which is powered by a 4400 mAH. It was configured and programmed to take readings at interval of thirty minutes (30 min). Air velocities were measured using digital anemometer (Thermo-anemometer Lutron AM4201A) and Kestrel weather meter). Data of other vital parameters such as ambient air and solar radiation were gathered from the Campbell weather station beside the experimental rig.

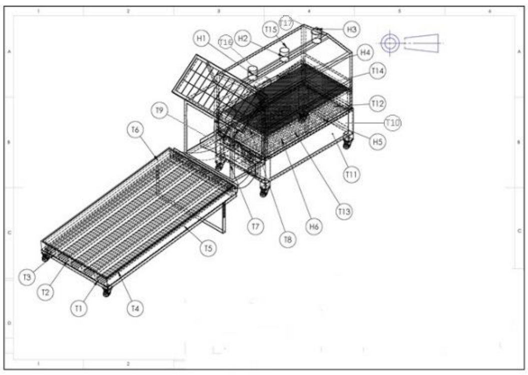

Figure 2. Schematic diagram of the solar dryer indicating the position of the sensors for temperature (T_1–T_{17}) and relative humidity (H_1- H_6)

2.6. Test with load

A full load test with TSMA was conducted using fermented cocoa beans having studied the temperature profile of the designed dryer. The incorporated thermostat was pre-set at the recommended maximum drying temperature of 60 oC (Hii *et al.*, 2008).

3. Results and discussions

Figure 3 shows the variation of the temperature of the collector, ambient, plenum chamber, drying chamber and outlet, and the solar radiation with the drying time for black coated thermal storage material (TSMA). It can be seen from the figure that towards the noontime, the temperatures and the solar radiation increased with time while they decreased from the afternoon towards evening time. The temperature profile follows the same trend with the solar radiation profile. The measured maximum solar collector, ambient, plenum chamber, drying chamber and outlet temperatures attained at 11:30 hr were 86.2, 26.1, 40.3, 67.8 and 53 ºC, respectively, at the solar radiation of 700 W/m^2. The solar radiation attained its peak value of 716.5 W/m^2 at 12:00 hr. It was also observed that at 18:00 hr, the intensity of solar radiation had reduced to 183.2 W/m^2 while the temperatures had dropped to values between 30.4 to 35.3 ºC. During night period, the solar radiation ranged between 0 and 36.9 W/m^2, and temperature between 22.3 and 33 ºC.

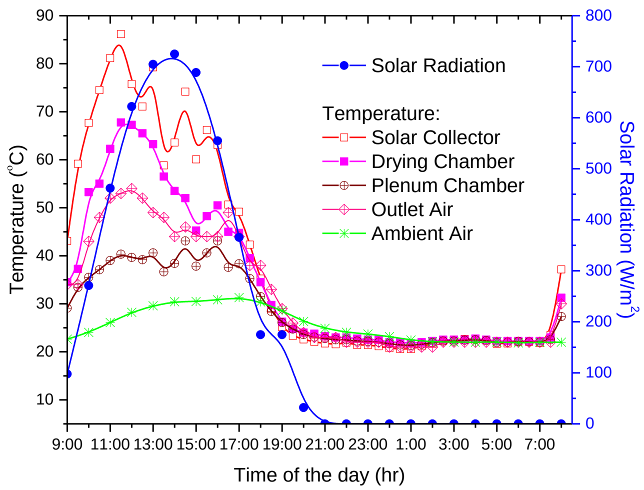

Figure 3. Variation of solar radiation and the temperature of the solar collector, drying and plenum chamber, dryer outlet and ambient air with time at no-load with TSMA

The collector, ambient, plenum chamber, drying chamber and outlet temperatures, and the solar radiation were plotted over the drying time in Figure 4 with black coated thermal storage material (TSMB). Similar to the profiles presented in Figure 3, the temperatures and the solar radiation increased with time towards the noontime and reduced thereafter towards the evening period. During the day time, it can be seen that the maximum temperature monitored in the solar collector and drying chamber were 91.3 and 70.8 °C respectively at 13:00 hr while other temperatures (ambient, plenum chamber and outlet) attained maximum values of 29.9, 44.6, and 55 °C respectively at 12:00 hr. The intensity of solar radiation was 810 W/m^2 at 12:00 pm. It can be seen from the figure that at 18:00 hr, the intensity of solar radiation reduced to 207.2 W/m^2, while the sectional or components temperatures fell to between 29.0 and 32.4 °C. The values of the solar radiation ranged between 0 and 24.1 W/m^2 during the night time (19:00 to 8:00 hr the next day), while the values of temperature ranged between 29.9 and 48.3 °C.

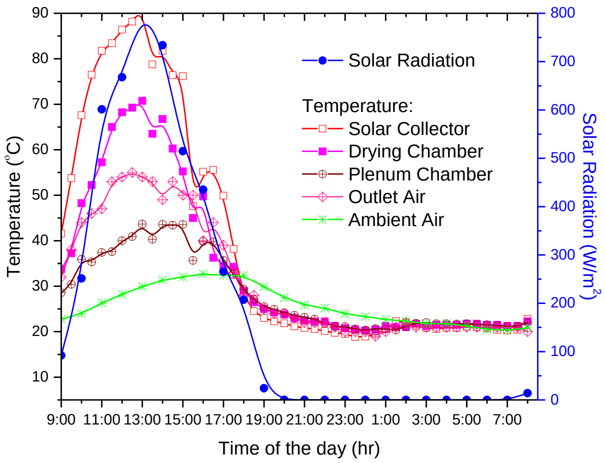

Figure 4. Variation of solar radiation and the temperature of the solar collector, drying and plenum chamber, dryer outlet and ambient air with time at no-load with TSMB

Comparison of the results from Figures 3 and 4 showed that the maximum drying chamber temperatures (67.8 and 70.8 °C) obtained will be capable of handling the drying process of any agricultural product following the recommendation of Hii *et al.* 2008 on the drying temperature of 60 °C some agricultural products. The highest temperature attained in the drying chamber for the set-up without TSM was 54 °C despite high solar radiation of 724.7 W/m^2 as compared for instance with the set-up with TSMA in which the highest temperature and solar radiation were 67.8 °C and 716.5 W/m^2 respectively. The higher temperatures measured in the set-up with TSM may be attributed to the resultant effect of thermal energy storage materials which helped to maintain the temperature to some reasonable extent within the drying chamber.

The plot of the collector, ambient, plenum chamber, drying chamber, and outlet temperatures and solar radiation against the drying time is presented in Figure 5 for solar dryer without thermal storage material. The maximum solar radiation and the temperatures of the solar collector, ambient, plenum chamber, drying chamber and outlet were 724.7 W/m^2 and 80.3, 30, 42.2, 54 and 42 °C respectively. The temperature in the drying chamber peaked in afternoon hours at 54 °C. The intensity of solar radiation reduced to 174.8 W/m^2 at 18:00 hr, while the sectional temperatures ranged between 29 and 37.5 °C thereafter.

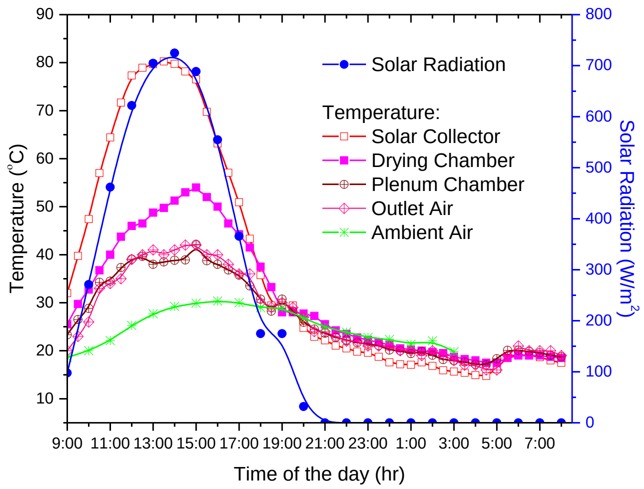

Figure 5. Variation of solar radiation and the temperature of the solar collector, drying and plenum chamber, dryer outlet and ambient air with time at no-load without TSM

The plot of the relative humidity of the ambient, exit and in the drying chamber of the dryer with black coated thermal storage material (TSMA) versus time is illustrated in Figure 6. The ambient, drying chamber and exit temperatures were also plotted over time in the figure to reflect their effects on the relative humidity. The figure shows that the relative humidity of the ambient, drying chamber and exit decreased with time from the morning hour as their corresponding temperatures increased. The relative humidity in the drying chamber was lower than those of the exit and ambient during the day time. A minimum value of 27% relative humidity was measured in the drying chamber at 11:30 hr, while the corresponding ambient and exit humidity were 70.8 and 22% respectively. The relative humidities remained fairly constant till 17.00 hour when they increased monotonically until the maximum value of 99.9% was attained in the night to morning hours.

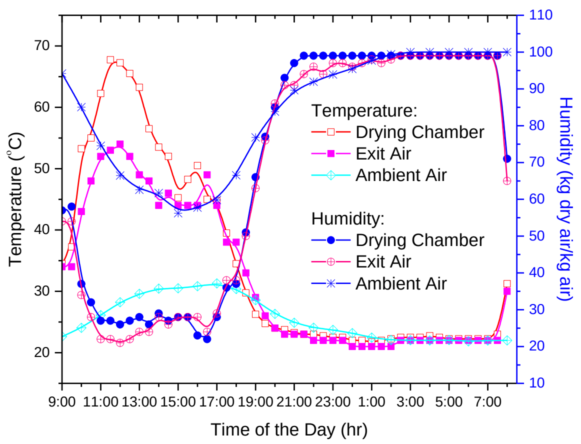

Figure 6. Variation of drying chamber, exit and ambient air temperature and relative humidity with time at no-load with TSMA

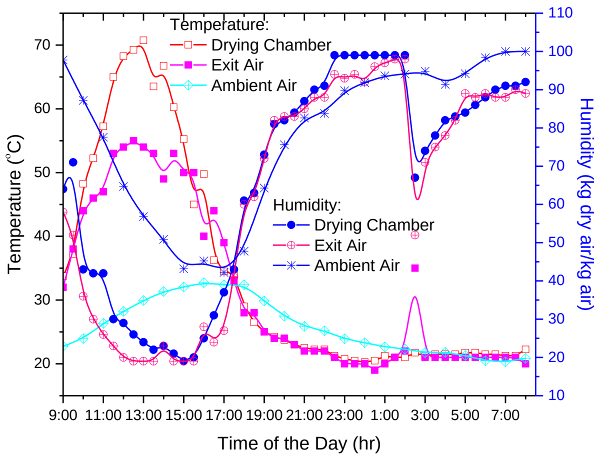

Figure 7. Variation of drying chamber, exit and ambient air temperature and relative humidity with time at no-load with TSMB

The variations of the relative humidity with time for the drying system using TSMB were plotted in Figure 7. The minimum humidity of 24% was measured in the drying chamber by 13.00 hour, while the corresponding ambient and exit humidity was 56.8 and 19% respectively. Figure 8 shows that the minimum humidity of 23% was attained in the drying chamber for the system without TSM by 15.00 hour, and the corresponding ambient and exit humidity was 56.2 and 38% respectively. The sharp difference between the ambient and drying chamber humidity is a reflection of the drying propensity of the dryer.

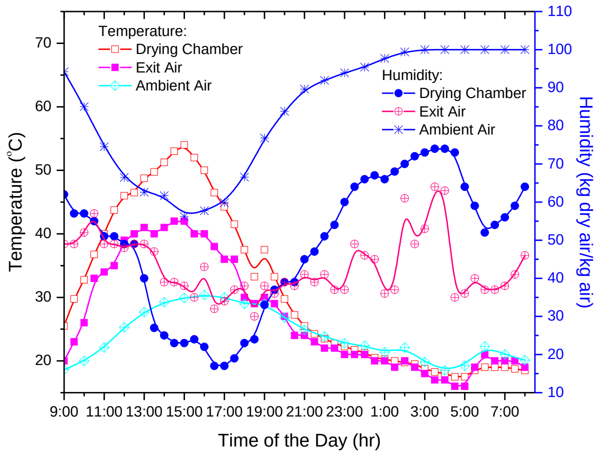

Figure 8. Variation of drying chamber, exit and ambient air temperature and relative humidity with time at no-load without TSM

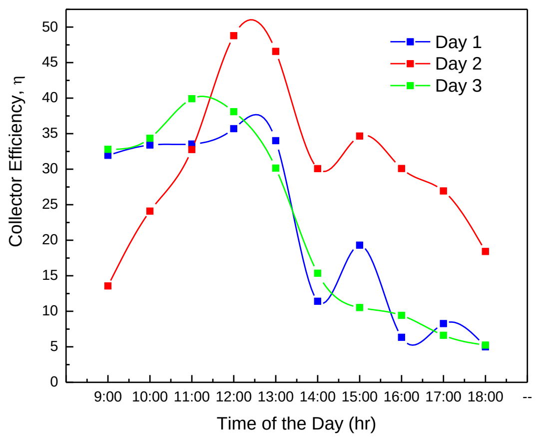

Figure 9. Thermal efficiency of the solar collector at different hour of day

The thermal efficiency of the solar collector was plotted over time in Figure 9 for measurement taken during three day time periods. The figure shows that due to the variation of the solar radiation the efficiency varies with day and increases from the morning hour obviously with the increase in insolation and attains maximum value at about 12.00 hour of the day before it starts to reduce. The daily maximum and average thermal efficiencies obtained for day one, two and three were 35.7, 48.8 and 39.9%; and 21.9, 30.6 and 22.2%, respectively. The daily maximum thermal efficiencies fall favourably within the range of 30-50% and 32.12-35.34% reported respectively by Sodha *et al*. 1987 and Bala *et al.* 2009 for solar collector. Lingayat *et al*. reported maximum efficiency of 31.5% for solar drying of banana, which is lower than the least maximum daily efficiency of 35.7% obtained in this work. Also, the average thermal efficiency values of 22.2 and 30.6% obtained are very close to 28 and 31.5% reported by Fudholi *et al.* 2014 and Lingayat *et al.*

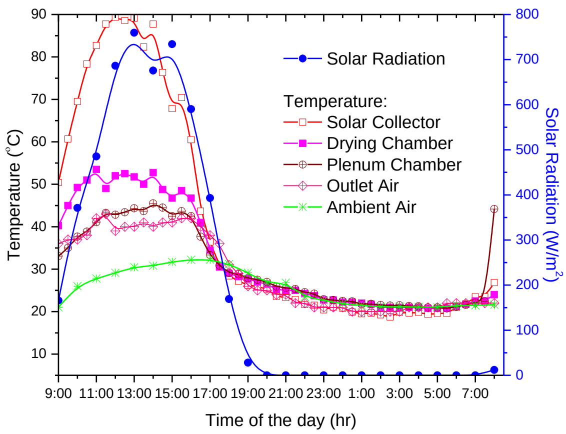

Figure 10. Plot of the solar radiation and the temperature of the solar collector, drying and plenum chamber, dryer outlet and ambient air versus time under full-load with TSMA

The dryer was tested to dry cocoa beans and the plot of temperature and solar radiation over time under full-load with TSMA is presented in Figure 10. It is evident that toward the noon time till 13:00 hr, the temperatures increased with the increase in the solar radiation and also exhibited similar trend with each other. As it can be seen in all cases, the temperature curves converged at 18:00 hr and continue to have almost the same value all through the night time (18:00 hr –8:00 hr the next morning), while the solar radiation was 0 W/m^2 beginning from 20:00 hr till 8:00 hr the following day. The measured temperatures during sunshine hours at different locations within the dryer ranged from 34 to 90.8 ^{o} C and were greater than the maximum ambient temperatures (30.8^o C). The maximum drying chamber and product temperatures were

54 and 53.5 °C respectively. It should be noted that the drying chamber temperature was regulated below 60 °C through the control sensor because drying above this temperature is considered detrimental to the quality of the agricultural products (Hii *et al.*, 2008; Bonaparte *et al.*, 1998; Jinap *et al.*, 1994; McDonald *et al.*, 1981). The measured temperatures are in good agreement with the results of Dina *et al.* 2015 who integrated solar dryer with desiccant thermal energy storage for drying cocoa beans and obtained a maximum drying temperature of 54 °C. The maximum solar radiation intensity and generated voltage for the period of drying were 779.6 W/m^2 and 11.94 V respectively at 1:00 hr.

The curve presented in Figure 11 displays the reduction in moisture content of cocoa beans different drying time during full load experiment with TSMA. The drying experiment took two full days, 10 hrs (58 hrs) to reduce initial moisture content of cocoa beans from 0.6 to 0.034 g water/g w.b. The comparison of the dryer shows its better performance than the one reported by Hii *et al.* 2008 and Fagunwa *et al.* 2009 on air ventilated oven and intermittent solar drying processes of cocoa beans for which the drying duration was 52 and 72 hrs, and reduction of initial moisture contents from 0.51 to 0.075 g water/g w.b. and 0.534 to 0.036 g water/g w.b., respectively. During the drying process, there was overnight tempering which according to Kumar et al. 2014 allows moisture uniformity (levelling) in the samples. There was small moisture reduction during the tempering periods. The drop in moisture content was as a result of the incorporated TSM and the residual heat inside the beans when the insolation was low. As indicated in the figure, the moisture content generally decreased with time throughout the drying period.

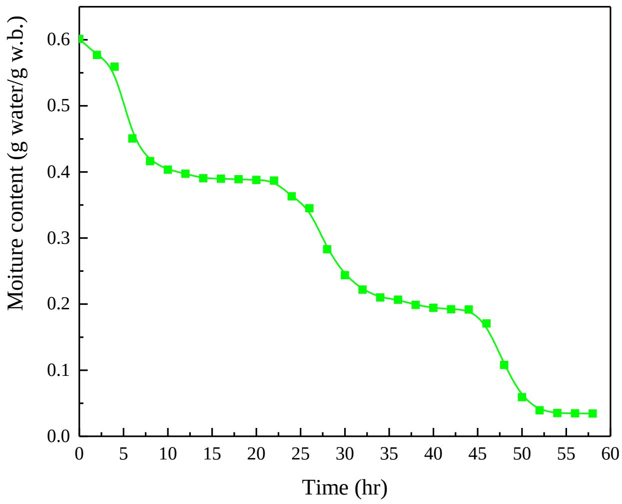

Figure 11. Moisture content of cocoa beans versus drying time

4. Conclusions

A simple and cost effective solar drying system integrated with thermal storage material for drying of agricultural products designed and fabricated using locally available materials. The experimental results with the dryer show that the temperatures of the drying air at different locations within the drying system were much higher than the ambient temperature during the day time period of 9:00 – 18:00 hr operation, while the temperatures are almost the same in the night time. The maximum drying chamber temperature and solar radiation obtained during the no-load experiments with and without thermal storage materials are 67.8, 70.8 and 54 ^{o}C; and 716, 810 and 724 W/m^2 respectively. The maximum solar radiation intensity, collector drying chamber temperature at full-load test with TSMA were 779.6 W/m^2, 90.8 and 54 ^{o}C at respectively. Based on the preliminary investigations and results from drying experiment, the dryer exhibited sufficient ability to dry agricultural products with or without thermal storage materials within a reasonable period to safe moisture content. The dryer is simple and required semi-skilled labourer to be fabricated and can be used both in the urban and rural areas.

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