Design, Construction and Performance Evaluation of Ginger Mixed Mode Solar Dryer Integrated with Latent Heat Storage

[1]Lanre A., Agbetiloye,[1,2]Fatai O. Anafi and [1,3] Nua O. Omisanya
[1]Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria.
[2]Africa Centre of Excellence on New Pedagogies in Engineering Education, Ahmadu Bello University, Zaria, Nigeria.
[3]National Automotive Design and Development Centre, Abuja, Nigeria.
olanrewajuagbetiloye@gmail.com|{fataianafi|ominua}@yahoo.com

Received: 23-DEC-2021; Reviewed: 06-MAR-2022; Accepted: 12-APR-2022

https://doi.org/10.46792/fuoyejet.v7i2.759

ORIGINAL RESEARCH ARTICLE

Abstract- This study is concerned with the design, simulation, construction and performance evaluation of a ginger solar dryer integrated with latent heat storage. It was done to address the problem of complete non-availability of conserved energy to precede the drying process for some times immediately after the sunshine hours have elapsed; thereby reducing the wide gap between the solar energy demand and supply. The ginger solar dryer was tested to dry 6 kg of sliced ginger rhizomes. The dimensions of the dryer were calculated by design to be as follows: 1.5638 m, 1.6302 m^2 and 1.155 m for collector length, collector area and chimney height respectively. An experiment was conducted to blend Aluminium powder with shea butter at elevated mass fraction of (1 – 5) %wt of Aluminium powder. The third level composition (3%/97%) was considered the most appropriate due to its moderate thermal conductivity of 0.053762 W/mK and highest latent heat of fusion - 164.53 KJ/kg. The ginger solar dryer was tested with ginger slices of (3 – 5) mm average thickness from 9:00 am to 11:00 pm of 11th June, 2019. The average drying rate, collector efficiency and drying efficiency for the period were 7.22×10^{-5} kg/s, 77% and 30% respectively.

Keywords- Mixed-mode solar dryer, Shea butter, Pure PCM, Blended PCM, Latent heat storage

1 Introduction

One of the most encountered challenges in the solar drying system is the discontinuity of the dehydration process after sunset, thereby amounting to a substandard quality of the dried food product. Therefore, the conservation of readily available solar energy is required to enhance the dryer efficiency and production of higher quality products. The energy of the sun is readily available in country like Nigeria during the day and can be stored for later use at night. Solar drying application is speedily gaining ground as an energy conservation method in agricultural industry (Adetan *et al.*, 2016).

Ginger (*Zingiber Officinale Roscoe*), of family *Zingiberaceae*, is a monocotyledonous tropical herbs grown for its pale yellow pungent aromatic rhizomes. Dried ginger can be grounded and used directly for culinary or medicine. The capacity to preserve food is closely related to the level of technological development and the slow progress in upgrading ancient food processing and preservation techniques (Adeyeba, 2014). Over the years, a few methods have been used to dry farm produce and these methods are continuously being upgraded. (Baniasadi *et al.*, 2017) developed a forced convection mixed mode solar dryer to dry fresh apricot slices.

*Corresponding Author

Section C- MECHANICAL/MECHATRONICS ENGINEERING & RELATED SCIENCES
Can be cited as:
Agbetiloye, L.A., Anafi, F.O. and Omisanya, N.O. (2022): "Design, Construction and Performance Evaluation of Ginger Mixed Mode Solar Dryer Integrated with Latent Heat Storage", *FUOYE Journal of Engineering and Technology* (FUOYEJET), 7(2), 210-216. http://doi.org/10.46792/fuoyejet.v7i2.759

The main goal was to develop an efficient and cost-effective dryer integrated with PCM so as to maintain drying process after sunset. The overall thermal efficiency of the dryer was 11%. (Jain *et al.*, 2015) developed a new solar crop dryer with thermal energy storage that provides continuous drying of about 12 kg herbs and maintains their colour and flavour. The dryer consists of a solar collector with area of 1.5 m^2 and six trays with an effective area of 0.50 × 0.75 m2 and thermal energy storage with capacity of 50 kg PCM. This energy storage system maintained the drying temperature between 40 °C and 45 °C.
Two known techniques for thermal energy storage are sensible and latent (hidden) heat method. Among the three states of TES Thermal Energy Storage, latent heat energy storage (LHES) shows a high energy storage capacity and a small variation in operating temperature due to the phase transition of phase change materials (PCMs) at the melting point. Phase change material (PCM) can be classified into organic, inorganic and eutectic materials. Some of the advantages of this work over the previous study is that the solar dryer was designed single tray as an alternative measure to combat the problems of uneven drying. Secondly, the solar dryer was designed using the maximum drying temperature of 60^{o}C for ginger rhizomes so as to prevent the denaturation of the product in terms of structure and flavour. Lastly, the use of PCM (shea butter blend) with latent heat of fusion which ranks closely with that of the technical grade of paraffin wax applied in solar drying.

2 Materials and Methods

The following materials were used for the construction of the solar dryer chamber. The PCM was prepared by following the procedures.

2.1 MATERIALS

Materials used were:

i. Solar collector box is made up of plywood and Arere white wood
ii. Glazing (3mm thick glass)
iii. Insulator (Sawdust)
iv. Drying Chamber (Plywood and Arere white wood)
v. PCM storage tube (Type M copper of 1.24mm wall thickness)
vi. Shea butter (PCM)

2.2 METHODOLOGY

2.2.1 Preparation of aluminium/shea butter blends

Aluminium Powder (Al) was used as the nanoparticles with relatively uniform size. Phase change material (Shea butter) was used as the base fluid with a phase change temperature of 40.08°C.

2.2.2 Determination of the heat of fusion for the blends

The Differential Scanning Calorimetry Analyzer (DSC) was used to measure heat flow associated with the thermal transitions of the Phase change material (Shea butter). DSC Specification are: Temperature accuracy $\pm 0.2K$; Temperature precision $\pm 0.02K$

2.2.3 Thermal conductivity of the Aluminium powder/shea butter blend

Searle's apparatus was used to measure the thermal conductivity of Al/Shea butter blend samples. The principle of dynamic equilibrium was employed. The measurements were verified as the amount of heat flowing out and flowing in were measured since they must remain constant. The thermal conductivity for the blend samples of five mass fractions of Aluminium powder (1wt. % to 5wt. %) were measured twice, and comparison of the two set of results ensured accurate measurements. The heat output was estimated by measuring the temperature increased resulting from the heat carried by water from the cold end of the bar.

2.3 DESIGN CONSIDERATION

The following specifications in Table 1 were considered in the design of the ginger mixed mode solar dryer:

Table 1. Design Specifications and Assumptions

Parameters	Optimum values and assumptions
Crop	Ginger (Zingiber officinale)
Design Capacity	6 kg
Bulk Density	920kg/m^3 (Ajavi and Ogunlade, 2014)
Max. Allowable Temperature for Drying	60^0C (Agrawal and Sarviya, 2014)
Initial Moisture Content	71% (Kumar *et al.*,2015)
Final Moisture Content	13% (Kumar *et al.*,2015)
Average Ginger Thickness	0.005m (Salihu *et al.*, 2017) (2 - 5) mm
Location and Latitude	Zaria (Latitude 11.2^0)
Design Month	August [Lowest Solar Radiation-Worst Case Scenario]
Wind speed	1.52m/s Average for Zaria (Abubakar *et al.*, 2017)
Ambient Temperature	28.6^0C Average for Zaria (Abubakar *et al.*, 2017)
Monthly Average Incident Solar Radiation for August	$795.5W/m^2$ (Ahmadu *et al.*, 2016)
Collector Type	Flat Plate
Collector tilt angle (∅)	11.2^0
Thermal Storage Material	Shear Butter (PCM)
PCM Storage Tube	41.28mm nom. Dia. Copper pipe ASTM B88 Type M, Wall thickness 1.24mm
Collector Channel Depth	$h > 90mm$ ($h = 92mm$ Forson *et al.*, 2007)
Glazing Thickness	3mm and 4mm low iron glass sheet; of transmittance (approximately 0.85 – 0.87) (Tian *et al.*,2017)
Specific Heat Capacity of PCM In Solid State	$C_{ps} = 8123.4J/kgK$
Specific Heat Capacity of PCM In Liquid State	$C_{pl} = 3936.9J/kgK$
Heat of Fusion of PCM	$L_{PCM} = 60{,}000J/kg$ (Glenn, 2018)
Density of PCM (	$\rho_{PCM} = 927kg/m^3$ (Honfo *et al.*, 2014)
Onset Temperature (°C)	35.75^0C
Peak Temperature (°C)	40.08^0C
Endset Temperature (°C)	45.17^0C

2.4 DESIGN PROCEDURE OF THE DRYER

i. **Total Volume of Ginger:** Total volume of Ginger, V_T is

$$V_T = \frac{m_i}{\rho_b} \quad (1)$$

ρ_b is Bulk density of ginger ($\rho_b = 920\, kg/m^3$) (Ajavi and Ogunlade, 2014)

ii. Drying Chamber Capacity and Other Dimensions

$$V_T = nV_y = nW_T L_T Y_l \quad (2)$$

$$A_y = 80\% \times A_d \quad (3)$$

For the optimum performance of the air heater, the ratio of the length to width of the collector is 1.5 (Forson *et al.*, 2007)

$$L_C : W = 1.5 \quad (4)$$

$$W = W_d = W_T \quad (5)$$

iii. Mass of Moisture to be extracted from Ginger Slices

Mass of moisture m_w to be extracted is given by (Alonge and Hammed., 2007)

$$m_w = m_i \left[\frac{M_i - M_f}{100 - M_f}\right] \quad (6)$$

iv. Latent Heat of Vaporization

Latent heat of vaporization L_v is given by (Messaoudi *et al.*, 2001)

$$L_v = 4.186 \times 10^3 \left(597 - 0.56(\mathrm{T_{pr}})\right) \quad (7)$$

were, the maximum drying temperature of ginger: $\mathrm{T_{pr}} = 60^0 C$

v. Drying Heat Load

Dryer heat load Q_{load} is given by (Kamble *et al.*, 2013)

$$Q_{load} = m_w \times L_V \quad (8)$$

vi. Efficiency of the drying system

Efficiency of the drying system $\boldsymbol{\eta_d}$ is given by (Forson *et al.*, 2007)

$$Q_{load} = m_w \times L_V \quad (9)$$

$$\eta_d = = \frac{m_w \times L_V}{I_T A_C t_d} \times 100\% \quad (10)$$

vii. Temperature of Air Leaving the Drying Bed

Temperature of air T_f leaving the chamber is given by (Forson *et al.*, 2007)

$$T_f = T_a + 0.25(T_O - T_a) \quad (11)$$

$$= T_a + 0.25\Delta T \quad (12)$$

viii. Air Volume Required for Moisture Extraction

Volume of air V_{Air} required to extract moisture is given by (Forson *et al.*, 2007)

$$V_{Air} = \frac{m_w L_V R_a T_a}{C_{pa} P_a (T_O - T_f)} \quad (13)$$

ix. Mass Flow Rate of Air Needed to Effect the Drying

Mass flow rate m_f of air to effect drying is given by (Tonui *et al.*, 2014)

$$m_f = V_f \rho_a \quad (14)$$

x. Volume Flow Rate of Air Needed to Effect the Drying

Volume flow rate V_f of air required to effect drying is given by (Forson *et al.*, 2007)

$$V_f = \frac{V_{Air}}{t_d} \quad (15)$$

xi. Average Drying Rate

Average mass drying rate m_{dr} is given by (Tonui *et al.*, 2014)

$$m_{dr} = \frac{m_w}{t_d} \quad (16)$$

xii. Solar collector efficiency

$$\eta_C = \frac{m_f C_{pa}(T_O - T_a)}{A_C I_T} \quad (17)$$

xiii. Chimney Height above the Air Inlet

Chimney height H is given by (Forson *et al.*, 2007)

When all pressure drops are eventually estimated experience has shown that the gross pressure drop is (6) six times the ΔP_T (Forson *et al.*, 2007)

$$\Delta P_T = 6 \times (2 \times \Delta P_B) \quad (18)$$

Applying Bernoulli's equation between the relevant sections of the dryer and simplifying the resulting expressions leads to the relation

$$\mathrm{H} = \frac{\Delta P_T}{g\left(\frac{1}{T_a} - \frac{1}{T_C}\right)^{P_a} / R_a} = \frac{\Delta P_T \times R_a}{g\left(\frac{1}{T_a} - \frac{1}{T_C}\right) P_a} \quad (19)$$

xiv. Width of the Chimney/Air Outlet

Chimney width W_{Ch} is given by (Forson *et al.*, 2007)

$$A_{inlet} = 2 \times A_{outlet} \quad (20)$$

Area of inlet vent = (2) two times Area of outlet vent

$$W \times h = 2 \times W_{Ch}^2 \quad (21)$$

xv. Mass of PCM Required for the Drying Process

Mass of PCM m_{PCM} needed for drying is given by (Bolaji, 2005). If energy balance equation for the phase change of water from food product is given by:

$$m_w L_v = m_{Air} C_{pa}(T_O - T_a) \quad (22)$$

Heat Energy Balance Equation for the phase change of Butter (PCM) in the Storage System is given by:

$$m_{Air} C_{pa}(T_O - T_a) = m_{PCM} \times L_{PCM} \quad (23)$$

$L_{PCM} = 60KJ/kg$ (Glenn, 2018)

xvi. Volume of PCM Required for the Drying Process

$$V_{PCM} = \frac{m_{PCM}}{\rho_{PCM}} \quad (24)$$

$\rho_{PCM} = 927kg/m^3$ (Honfo *et al.*, 2014)

xvii. Numbers of Tubes Required for the Drying Process

Volume of PCM (Butter) = numbers of tubes required × volume of each tube

$$n_t = {V_{PCM}}/{V_t} \quad (25)$$

xviii. Thermal Energy Capacity of the PCM (Butter)

$$E_{Th} = m_{PCM}\left[\left\{\int_{T_1}^{T^*} C_{ps} dT\right\} + L_{PCM} + \left\{\int_{T^*}^{T_2} C_{pl} dT\right\}\right] \quad (26)$$

2.5 Construction of the Prototype Solar Dryer

The transparent top cover is a 3mm thick clear glass with dimensions 1320mm by 1110mm. The collector glazing is of 3mm thickness with the dimension of 1570mm × 1110mm.The storage tube made of type M copper material is of length (1000mm), outer diameter (41.27mm), inner diameter (38.79mm) and wall thickness of about 1.24mm. Glazing and access door were made available for additional incidence of insolation and to enhance easy loading and offloading of the slices of ginger rhizomes respectively.

http://doi.org/10.46792/fuoyejet.v7i2.759 http://journal.engineering.fuoye.edu.ng/

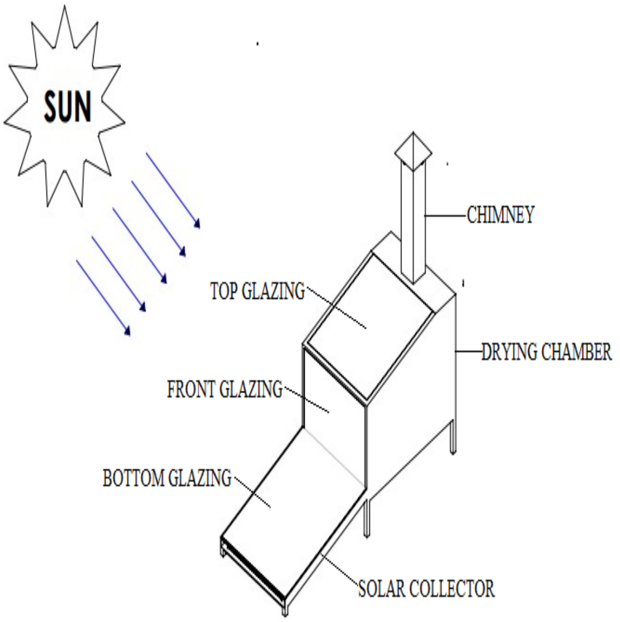

Fig. 1: Schematic Diagram of the Ginger Mixed Mode Solar Dryer

4 Results and Discussion

4.1 Thermophysical Properties of Aluminium Powder/Shea Butter Phase Change Material

Figure 2 shows the plot for the thermophysical properties of blended phase change material (PCM) against varying compositions of Aluminium powder and shea butter. The composition with the least Aluminium powder content (1% & 99%) as obtained from the laboratory test, has its latent heat of fusion 154.61KJ/kg and the least heat conductivity as 0.016129W/mK. The latent heat of fusion for the (2% Al & 98% shea butter) decreased to 142.49KJ/kg with rising heat conductivity (0.026881W/mK). The third level composition (3% Al & 97% shea butter) was considered the most appropriate because of its largest heat of fusion 164.53KJ/kg and moderate heat conductivity of (0.053762W/mK). The latent heat of fusion decreased to 143.25KJ/kg with increased heat conductivity of (0.064514W/mK). The fifth level composition (5% Al & 95% shea butter) has the highest heat conductivity (0.069891W/mK) with the least latent heat of fusion 81.17KJ/kg. As displayed in Figure 2, the line of plot for the thermal conductivity rises continuously from (1% Al & 99% shea butter) to the peak of (5% Al & 95% shea butter). This is because the higher the quantity of Al powder evenly dispersed over the fixed quantity of compositions for each of the five samples, the closer the particles of Al powder then, the better and faster the heat conductivity.

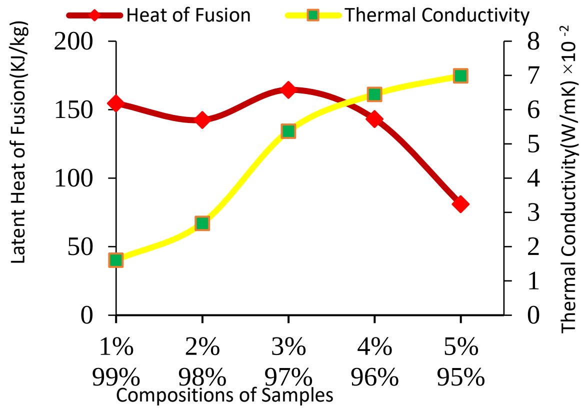

Fig. 2: Variation of Latent Heat of Fusion and Thermal Conductivity of PCM Samples over various Compositions Percentage (%)

The result obtained from the rising thermal conductivity in Figure 2 is in agreement with the studies conducted by (Chaichan *et al.*, 2015) as regards the PCM thermal conductivity by adding Alumina Al_2O_3 and TiO_2 in a mass fraction of 1, 2, 3, 4 and 5% to Iraq Paraffin wax. He reported that the thermal conductivity of the PCM increased with increasing nano-particles mass fraction. Also, he recorded 190KJ/kg as the latent heat of fusion for the PCM, which is higher than the peak heat of fusion obtained in this study because they are of different materials. The latent heat of fusion for the list of commercial PCMs available for solar drying application ranges from 100KJ/kg for S50 to 289KJ/kg for Climsel C58 (Agrawal *et al.*, 2014). Therefore, blended PCM of shea butter with latent heat of fusion-164.53KJ/kg which falls within this range and closer in thermo-physical characteristics to blends of Iraq paraffin wax can be used as a readily available alternative.

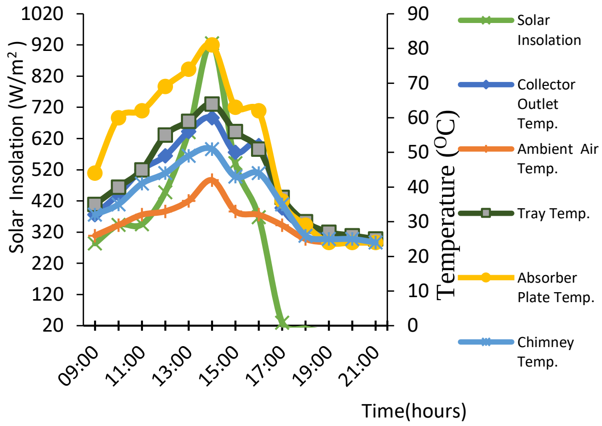

Fig. 3: Variation of temperature with time for zero-load test for 8 June 2019

Figure 3 shows how the temperature varies from each other hourly. At 9:00 hours when the experiment began, the absorber plate temperature was the highest with a value of 44°C and radiation 284W/m², as it is meant to trap the radiation during the day, convert to thermal energy and feed other part of the dryer. The drying tray temperature reached a peak of 64°C at 14:00 hours; above the collector outlet temperature of 60°C when the

http://doi.org/10.46792/fuoyejet.v7i2.759 http://journal.engineering.fuoye.edu.ng/

absorber plate temperature was 81°C at solar radiation of 935W/m².

As the insolation dropped abruptly to 551W/m² at 15:00 hours, the absorber plate, collector outlet, ambient and chimney temperature also decreased abruptly to 63°C, 50°C, 43°C and 33°C respectively but the drying tray temperature reduced gradually to a temperature of 56°C. From 17:00 to19:00 hours, the drying tray attained a temperature higher than the temperature of the other part of the dryer.

As it can be seen on the chart, between 10:00 and 11:00 hours there is small addition in radiation as it is reflected in the absorber plate temperature, which is why the collector outlet and drying tray temperature are the same at 11:00 hours. The sudden fall in radiation after 14:00 hours and slight increase from 15:00 to 16:00 hours is evident in the collector outlet and chimney temperature but not noticeable in the drying tray temperature as the PCM in the tube helps compensate by releasing heat energy to compensate for the possible drop in insolation at that instant. At 17:00 hours, the drying tray temperature started rising above the temperature of the other part of the system and sustained till the 21:00 hours. The plot above is in agreement with the studies conducted by (Abubakar *et al.,* 2018) as regards to how the collector outlet air temperature varies with the tray temperature. Although, the tray temperature has to be higher than the collector outlet temperature as it implies that the drying chamber has actually sustained substantial amount of heat energy to effect the drying of ginger. Nevertheless, during the design stage adequate caution was taken to ensure that the collector outlet air temperature is not too high to have the tray temperature extremely higher than the allowable drying temperature of the product. This is because a product can denature in its structure, taste and aroma when dried with temperature too higher than the allowable as given by (Agrawal and Sarviya, 2014). The chimney temperatures which were higher than the ambient temperatures through the duration of experiment justified the ginger solar dryer design as appropriate because it implies that the solar dryer has been designed to have attained a higher thermal potential to expel moisture from it.

Figure 4 shows that the drying process commenced with a solar radiation of 248W/m² at 9:00 hours; the collector outlet, ambient air, drying tray, absorber plate and chimney temperatures were 32°C, 25°C, 34°C, 39°C and 30°C respectively. The insolation increased to 310W/m² then reduced drastically to 235W/m² at 11:00 hours. The effect of drastic drop in Insolation on 11 June, between 9:00 to 11:00 hours on the drying tray temperature was not noticeable because PCM storage has cushioned the possible decrease in the heat energy within the solar dryer. The solar radiation increased to a peak value of 785W/m² at 13:00 hours when the collector outlet, ambient air, drying tray, absorber plate and chimney temperature were 50°C, 37°C, 59°C, 75°C and 44°C respectively. At 19:00 hours with solar radiation of 1W/m², the ginger solar dryer still sustained reasonable amount of heat capacity to continue drying when the tray temperature was 3°C; bottom and top tubes temperature were 5°C, 6°C respectively above the ambient temperature.

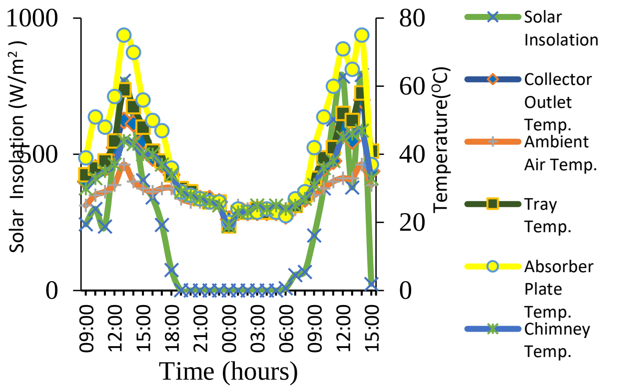

Fig. 4: Variation of Solar Insolation and temperature with respect to time for 11 – 12 June, 2019

The drying process continued till 12 June so that at 6:00 hours, the insolation was 8W/m² while the collector outlet, ambient air, drying tray, absorber plate and chimney temperature were 22°C, 24°C, 23°C, 22°C and 24°C respectively. At 12:00 hours the Insolation increased to a value of 800W/m² while the collector outlet, ambient air, drying tray, absorber plate and chimney temperatures were 48°C, 33°C, 52°C, 71°C and 45°C respectively. The solar radiation dropped drastically to 378W/m² at 13:00 hours but rose again to a peak value of 806W/m² at 14:00 hours for the day. The presence of PCM has helped to compensate for the fluctuation between 12:00 hours and 14:00 hours as the tray temperature did not drop much like others. Among all research works done on solar crop drying in Zaria before this present study, only (Abubakar *et al.*, 2018) explored the concept of thermal energy storage. He used black coated gravels as materials, he placed reasonable quantity of gravels in the solar collector then channelled to a drying chamber to dry 7kg of yam slices. This work differs from this present study as it could not dry its product beyond 18:00 hours each day. This was because he used sensible heat storage materials contrary to the latent heat storage materials (such as: organic phase change materials among others) used in this work. According to (Agrawal *et al.*, 2014) latent heat storage stores 5 – 14 times more heat per unit volume than the sensible heat storage. The Insolation dropped drastically to 24W/m² at 15:00 hours when collector outlet, ambient air, drying tray, absorber plate and chimney temperature attained 35°C, 31°C, 41°C, 37°C and 33°C.

The Insolation dropped much between 12:00 to 13:00 hours of 12 June and raised again at 14:00 hours but the impact did not have adverse effect on the tray temperature as it affected temperatures recorded for the other parts of the solar dryer, which revealed that the solar dryer is thermally efficient. On 12 June, the insolation of 806W/m² at 14:00 hours reduced drastically to 24W/m² at 15:00 hours because of unclear solar index which led to sudden rainfall. The pattern of plot for the hourly insolation, collector outlet and tray temperature as

http://doi.org/10.46792/fuoyejet.v7i2.759 http://journal.engineering.fuoye.edu.ng/

shown above is in agreement with the research conducted by (Abubakar *et al.*, 2018). It shows the possible variation and unreliability of insolation with effects on the collector air outlet and tray temperature. (Dina *et al.*, 2015) worked on solar dryer integrated with desiccant thermal storage, the plot for the unexpected drastic variation in insolation did not reduce the chamber temperature much over the period of drying, due to the presence of thermal storage, as this agrees with the thermal performance of this present work.

From Figure 5, solar radiation at 9:00 hours was 248W/m² while the bottom and top tube temperatures attained 31°C and 34°C. The solar radiation dropped to 235W/m² at 11:00 hours with the bottom and top tube temperatures as 35°C and 45°C respectively. The top and bottom tube temperatures did not fall accordingly because of the substantial content of heat energy present in the PCM (phase change material). The tubes are made of copper material which has a thermal conductivity of 386W/mK; prone to losing heat within a very short time but the tubes temperature increased steadily till 14:00 hours. This validated that this thermal storage method does not only sustain drying beyond sunset but also compensate reasonably for any possible drop in insolation during the sunshine hours.

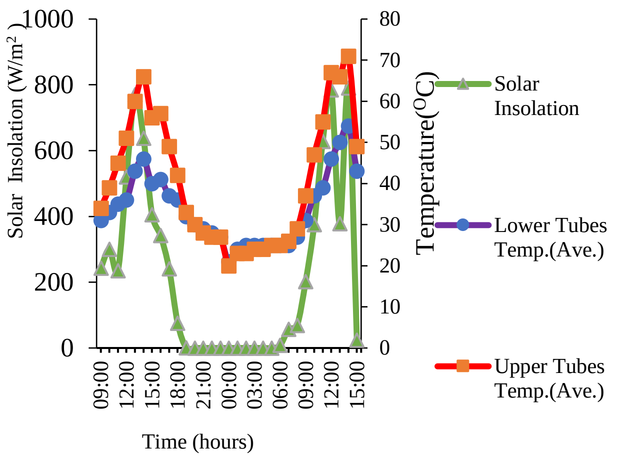

Fig. 5: Thermal Charging and discharging of PCM tubes and Solar Insolation with respect to time 11 -12 June, 2019

As it can be seen on the chart, the sudden rise and fall of Insolation between the 9:00 to 11:00 hours did not show any impact on the plot for the charging of PCM storage tube. The 15:00 to 16:00 hours shows that the PCM storage has the capacity to retain heat energy even as the insolation falls. At the 19:00 hours of 11 June, when solar radiation was 1W/m², the tray temperature was 3°C; bottom and top tubes temperature were 5°C and 6°C above the ambient respectively which showed that the solar dryer has the thermal potential to sustain drying process after sun sets. Also, the sudden fall and rise of Insolation between 12:00 to 14:00 hours of 12 June, did show little effect on the top tube storage with no impact on the bottom tube storage during charging because the solar radiation is directly incident on the PCM top tubes. The impact of drastic rise or fall in Insolation showed little or no effect on the chamber temperature as compared to the investigation done by (Dina *et al.*, 2015) on the effectiveness of continuous solar dryer integrated with desiccant thermal storage for drying cocoa bean. It revealed that the PCM storage has enhanced the thermal performance of the solar dryer which is the like of the present study.

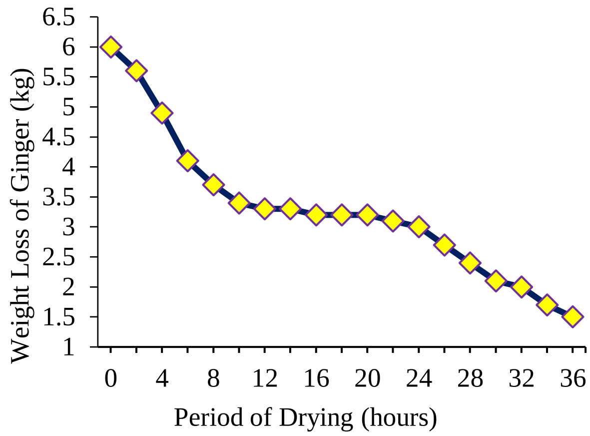

Fig. 6: Weight Loss of Ginger Mass from 11 - 12 & 13 June, 2019.

From Figure 6, displays the weight loss curve for the slices of 6kg of ginger rhizomes in the solar dryer. The dryer removed 71.7% of the moisture in 32 hours of continuous drying despite interruption by rainfall and humidity for not less than 20 hours. The average drying rate, collector efficiency and dryer efficiency were $7.22 \times 10^{-5}\ kg/sec$, 77% and 30% respectively.

5 Conclusion

In conclusion the design simulation and construction of mixed mode solar dryer was carried out and the following conclusion can be deduced from the system performance.

i. Various blends of (Al/shea butter) PCM at increasing mass fraction of (1 – 5) wt.% of conductive Aluminium particle were optimized by subjecting them to test for thermophysical properties. It was discovered that only the third level composition with latent heat of fusion (164.53KJ/kg) within the range of commercial grade of paraffin wax and of moderate thermal conductivity (0.053762W/mK) was considered the most appropriate.

ii. Ginger solar dryer integrated with PCM (phase change material) was designed using specifications peculiar to ginger rhizomes, phase change materials and Zaria weather conditions.

iii. The ginger solar dryer was constructed using ply wood of 11.4mm thickness to enclose its frame work. Arere white wood of $(50.8 \times 50.8)\ mm$ was used to make up the frame work. The top and collector glazings were of 3mm while the front glazing is of 4mm thickness.

iv. The performance of the mixed mode ginger solar dryer is evaluated using the drying rate, collector efficiency and drying efficiency. The drying rate, collector efficiency and drying efficiency of the drying system for the recommended day of 11 June are $7.22 \times 10^{-5}\ kg/sec$, $77\%\ and\ 30\%$ respectively while the over-all drying rate, collector efficiency and drying efficiency of the solar dryer are $4.58 \times 10^{-5}\ kg/sec$, $62\%\ and\ 18\%$ respectively.

Acknowledgement

I thank the Nigerian Liquefied Natural Gas Laboratory Centre for Research and Technology, Ahmadu Bello University Zaria, Kaduna State, Nigeria.

Nomenclature

A_C Area of solar collector (m^2)
A_d Drying chamber floor area (m^2)
A_{inlet} Area of inlet vent (m^2)
A_{outlet} Area of outlet vent (m^2)
A_y Drying surface area per tray (m^2)
C_{pa} Specific heat capacity of air at constant pressure (J/kgK)
C_{ps} Specific heat capacity for shea butter in solid state (J/kgK)
C_{pl} Specific heat capacity for shea butter in liquid state (J/kgK)
E_{Th} Thermal Energy Capacity of the PCM (J)
g Acceleration due to gravity, (m/s^2)
h Air gap/Absorber plate spacing (m)
H Height of chimney above air inlet (m)
I_T The monthly minimum average solar radiation (W/m^2)
L_C Length of the solar collector (m)
L_{PCM} Latent heat of fusion for PCM (J/kg)
L_T Length of tray (m)
L_V Latent heat of vaporization of water vapour (J/kg)
m_{Air} Mass of air needed for removing the moisture (kg)
m_{dr} Average mass drying rate (kg/s)
m_f Mass flow rate of Air (kg/s)
m_i Original mass of ginger (kg)
m_{PCM} Mass of PCM (kg)
m_w Mass of moisture to be extracted (kg)
M_i Initial moisture content (%)
M_f Final moisture content (%)
n Number of trays
n_t Number of tubes
P_a Partial pressure of dry air in the atmosphere (N/m^2)
ΔP_B Pressure drop across the crop bed (N/m^2)
ΔP_T Total pressure drop across the bed (N/m^2)
Q_{load} Drying heat load (W)
R_a Specific gas constant (kJ/kgK)
T_a Ambient temperature (^0C)
T_C Temperature for solar collector (^0C)
T_{pr} Maximum drying temperature of ginger (^0C)
T_1 Onset temperature (^0C)
T^* Peak temperature (^0C)
T_2 End set temperature (^0C)
T_f Temperature of air leaving the drying bed (^0C)
T_O Outlet temperature of the heated air from the collector (^0C)
t_d Time for drying (hr)
V_{Air} Volume of air needed to effect the drying (m^3)
V_f Volume flow rate of air needed to effect the drying (m^3/s)
V_{PCM} Volume of PCM (m^3)
V_t Volume for each tube (m^3)
V_T Total volume of Ginger (m^3)
V_y Volume of ginger slices per tray (m^3)
W Width of the inlet area (m)
W_{Ch} Width of Chimney/Air Outlet (m)
W_T Width of Tray (m)
W_d Width of the drying chamber floor (m)
Y_l Thickness of ginger slices (m)

Greek Symbols

ρ_a Density of air (kg/m^3)
ρ_b Bulk density of Ginger (kg/m^3)
ρ_{PCM} Density of PCM (kg/m^3)
η_d Dryer efficiency
η_C Collector efficiency

References

Abubakar, S., Umaru, S., Anafi, F. O. and Abubakar, A. S. (2018). Design and Performance Evaluation of a Mixed-Mode Solar Crop Dryer. *FUOYE Journal of Engineering and Technology (FJET)*, 3(1), 22–26. https://doi.org/10.46792/fuoyejet.v3i1.133

Adetan, D., Oladejo, K. and Obayopo, S. (2014). Development of a Multipurpose Solar Dryer. *FUOYE Journal of Engineering and Technology (FJET)*, https://doi.org/10.46792/fuoyejet.v1i1.22

Adeyeba, A. O. (2014). Storage, Preservation and Processing of Farm Produce. *Food Science and Quality Management (FSQM), 27(ISSN 2224-6088), 28–30.*

Agrawal, A. and Sarviya, R. M. (2014). A Review of Research and Development Work on Solar Dryers with Heat Storage. *International Journal of Sustainable Energy (IJSE)*, 35(6), 583–605. https://doi.org/10.1080/14786451.2014.930464

Ahmadu, T. O., Folayan, C. O., & Anafi, F. O. (2016). Modeling, Simulation and Optimization of a Solar Absorption Air Conditioning System for an Office Block in Zaria, Nigeria. *International Journal of Air-Conditioning and Refrigeration (IJACR)*, 24(2), 1–13. https://doi.org/10.1142/S2010132516500127

Ajavi, E. A., & Ogunlade, C. A. (2014). Physical Properties of Ginger (Zingiber Officinale). *Global Journal of Science Frontier Research (GJSFR)*, 14(8), 1–8. https://pdfs.semanticscholar.org/caa8/60ae5eb537f4947da320cb39fde46cdbe3ee.pdf

Alonge, A. F. and Hammed, R. O. (2007). A Direct Passive Solar Dryer for Tropical Crops. 8(1980), 1643–1646.

Baniasadi, E., Ranjbar, S. and Boostanipour, O. (2017). Experimental Investigation of the Performance of a Mixed-Mode Solar Dryer with Thermal Energy Storage. *Renewable Energy*, 112, 143–150. https://doi.org/10.1016/j.renene.2017.05.043