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Comparative Energy Audit of Mixed-Mode and Direct Mode Solar Grain Dryers

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Abstract

This work presents a thermodynamic comparison of two locally designed dryers, the direct and mixed-mode solar dryers. The materials used for the construction of the dryers were locally sourced and used for drying restaurant wastes. The mixed-mode dryer (MSD) is made up of flat-plat collector and a drying chamber while the direct (DSD) has double glazed glass as collector. The properties of air which serve as the working fluid were measured at the entrance and exit points of the dryers. The balanced energy equations were developed for each segment of the dryers. They are the based on solar dryers. The compared results show better energy efficiency and product quality of the MSD over the DSD. The results can be used by farmers to select solar grain dryers for specific jobs.

Keywords: *thermodynamic comparison; restaurant wastes, solar dryers, flat-plate collector.*

I TRODUCTION

Drying of product from Agricultural crops is one the oldest traditional methods practiced in the tropical region like Nigeria where the heat energy source comes from the sun and it is readily available. The availability of energy source has led to more studies on various type of dryer in this region to harness the free gift of nature and to transform it into useful way of preserving product from fungal and bacterial attacks. The heat from the sun is capture by the dryer which is redirected to supply the product under ambient conditions subsequently increasing the vapor pressure of the moisture held within the product. This improves moisture flow from within the product and significantly decreasing the relative humidity of the drying air thereby increasing its moisture level carrying capability to ensure sufficiently low equilibrium moisture content.

There is great awareness of the use of renewable energy as an important part in extending technology to the farmer in developing countries for better efficiency and better productivity [Waewsak. et al. 2006]. Solar thermal technology is one area that is rapidly gaining acceptance as a measure energy saving and agricultural application. Solar energy is abundant in nature and is preferred to other renewable sources as wind and shale, since it is inexhaustible, and non-polluting [Akinola 1999; Akinola and Fapetu 2006; Akinola, et al.2006]. This type of thermal energy audit is of fundamental importance to engineers to improve the efficiency of their system design and minimize the losses as well as reduce the operational and capital investment cost [Riviere et al; 2009].

Basically, solar dryers are categorized into direct, indirect and mixed- mode. The direct type is designed such that the air heater contains the grains where the solar energy is absorbed. The energy is transmitted through a transparent glass lid or cover. The drying of the grain is done by a combine effect of direct radiation from the sun and recirculation of convective hot air which is the working substance. In the indirect mode the grain is solely dried by hot air from the solar air heater. In the mixed mode, a collector heats the air separately and the air current is passed through the grain bed. Solar energy is also absorbed directly by the drying cabinet through the transparent cover or roof [Gatea, 2010].

Further studies have been carried out on mixed mode dryer both by modeling and experiment. A mathematical model for drying agricultural product was proposed. The model was developed in parallel with his experiment and comprises the drying model, the air heating process and the technical performance criteria [Forson, et al., 2007]. Sekyere also carried modelling and experimental work on natural convection solar dryer with backup heater. He considered the buoyancy characteristics and the drying conditions of a mixed –mode natural convection solar crop dryer with integrated collector storage [Sekyere, 2013]. From the thermodynamic view point, energy is made of available and unavailable forms. Work on the system is obtained from the available energy, while the unavailable form of energy remains unexploited [Ozegerner and Ozegerner, 2006; Kotas, 1995]. The available energy which is converted to maximum useful work is known as exergy as it comes to equilibrium with its environment from its original state [Coskun *et al*., 2009; Hou *et al*., 2007]. Exergy is dependent on the thermodynamic properties of the working fluid [Coskun *et al*., 2009].

This work presents a systematic energy analysis for a direct solar dryer (DSD) and mixed-mode flat-plate solar dryer (MSD) employed in drying restaurant wastes [Ikem *et al*., 2016]. This compares their performance characteristics and quality of the dried product. Their costs of production are also compared to see which is better for the rural dwellers. This work was carried out in Makurdi, Nigeria, 2011. It was necessitated because; this community in Nigeria is blessed with abundant sun light and also very rich in various agricultural products. The wastes usually produced from their restaurants are never recycled to feed the animals [Ikem et al,. 2016]. Many other researches on solar food dryers concentrate on drying single products like pepper, okra, ground nut etc., it was necessary to apply it to dry restaurant wastes.

II System Process Description and Model

The system process was previously described by [Ikem *et al*, 2016] in their work but can be briefly described for broader understanding of the set up. The mixed-mode solar dryer (MSD) consists of an air-heater and drying chamber (DC). The direct solar dryer (DSD) shown in Figure 1 consists of just the collector. Figure 2, has no air-heater but a transparent glass cover to the drying chamber. Sun rays fall directly on the product to be dried. The initial air temperature and relative humidity (T_0, Φ_0) are recorded at point (0) of the MSD and the DC of the DSD. The waste is heated by solar energy absorbed in the AH of the MSD and through the glass on the DC of the DSD. The properties of the working fluid are changed from (T_0, Φ_0) to (T_1, Φ_1) at the collector outlet (point1) of the MSD and of the outlet of the DSD. Here ($T_0 < T_1$), ($\Phi_0 < \Phi_1$). The relative humidity of the air in the case of the MSD is lowered as its temperature increases to be able to absorb more moisture from the wet solid materials in the DC whereas in the DSD it is higher as it contains moisture carried from the wet product in the DC. The working fluid at (T_1, Φ_1) enters the DC and comes in contact with the wet solid materials at the initial temperature and moisture contents (T_{s2}, X_2).

The wet solid is heated to (T_s, X) in the DC. The working fluid exits the CD of the MSD at point (3) at lower temperature and higher relative humidity (T_3, Φ_3) with ($T_1 > T_3$), ($\Phi_{3\,>}\,\Phi_1$) and the DSD at point (2) lower temperature and higher relative humidity (T_2, Φ_2) with ($T_0 > T_2$), ($\Phi_{2\,>}\,\Phi_0$).

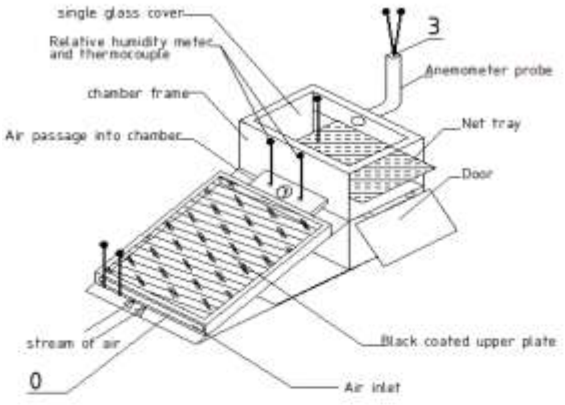


Figure 1: Schematic of Mixed-Mode Solar (MSD) Dryer

1 Equipment

The MSD consists of an AH attached to a fixed drying chamber (DC). The heater measures 2.0 m x 1.0 m x 0.02 m or 0.04 [m^3] in capacity. Thickness of the collector is 0.7 mm and pre-heats the air before entering the DC. The air heater was insulated at the bottom by polystyrene sheets of 10 mm thick. The DC measures 1.0 meter by 1.0 meter by 0.44 m in depth. The total capacity of the DC is 0.44 [m^3]. The chamber is insulated with 50 mm thick polystyrene at the bottom and 30 mm at the sides.

Thermocouples and relative humidity meter installed at the inlet and exit to the chamber to measure the drying air properties. The drying chamber was fitted with thermocouples to measure the solid waste temperature. The air velocity leaving the system is measured to give an indication of the amount of water lost to the air, and the heat loss from the surface of the collector. The system setup was directed due south at an inclination of 23^0, to give the maximum energy gain throughout the day, at that location of Makurdi, Nigeria during the month of testing, March 2011.

Solar insolation was measured directly using an SL200 solarimeter, which was controlled to give readings at hourly interval. The solarimeter was placed at an angle of 23^0, with the dryer.
With the measuring devices in place, the dryer was left onto the open sky void of any obstructing shadows.

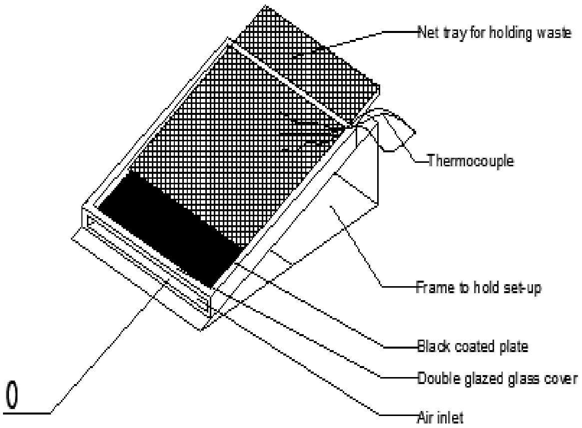


Figure 2: Direct Solar (DSD) Dryer

Figure 2 shows the direct solar dryer (DSD) with same materials and dimension as the MSD except that it has double glazed glass cover as collector instead of a black coated metal plate. While the collector arrangement in the MSD serves as an air heater, it serves as the drying chamber whose drying surface area is twice that of the MSD and the sun rays fall directly on the product, hence its name. The net tray carrying the product is introduced to and withdrawn from the drying chamber from either side of the dryer.

In this case, thermocouple was connected to record the temperature of the solid in the drying chamber and the properties of the exiting air. The ambient conditions are the same for both dryers.

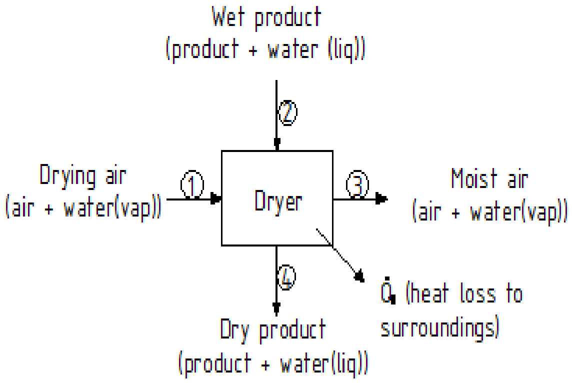


Figure 3: Schematic of a Drying Process Showing Input and Output Terms

2 Energy Equations

$$IA_s = Q_u + Q_{cond} + Q_{conv} + Q_R + Q_{ref} \qquad (1)$$

where:

I = Insolation falling on the absorber's surface [Wm^{-2}];

A_s = Surface area of collector facing the sun [m^2]:

Q_u = Energy collected by the working fluid [W];

Q_{cond} = conduction heat losses from the absorber [W];

Q_{conv} = convective heat losses from the absorber [W];

Q_R = radiation heat losses from the absorber [W]:

Q_{ref} = reflection losses from the absorber [W].

$$Q_L = Q_{cond} + Q_{conv} + Q_R \qquad (2)$$

where Q_L is the sum or combined heat losses from the collector's surface.

$$IA_c = \boldsymbol{\tau} I_t A_c. \qquad (3)$$

Where τ is the transmittance of the glazed collector surface and I_t is the total solar insolation on the surface.

We can calculate the reflected energy from the absorber surface from the expression:

$$Q_{ref} = \rho \boldsymbol{\tau} I_T A_s, \qquad (4)$$

where ρ is the reflection coefficient of the absorber. Substituting Equations (2), (3) and (4) in Equation (1) yields:

$$\boldsymbol{\tau} I_T A_s = Q_u + Q_L + \rho \boldsymbol{\tau} I_T A_s \quad \text{or}$$

$$Q_u = \boldsymbol{\tau} I_T A_c (1 - \rho) - Q_L.$$

For an absorber ($1 - \rho$) = α and hence,

$$Q_u = \propto \boldsymbol{\tau} I_T A_s - Q_L \qquad (5)$$

where α is solar absorptance.

Q_L (sum of radiation and convection). (Bansai *et al* 1990):

U_L = overall heat transfer coefficient of the absorber [Wm^{-2}K^{-1}]; is given by:

$$Q_L = U_L A_s(T_c - T_a) \qquad (6)$$

where:

T_c = temperature of the collector's surface [K];

T_a = ambient air temperature [K].

Combining (5) and (6) the energy gained by the collector is:

$$Q_u = \propto \boldsymbol{\tau} I_T A_s - U_L A_s(T_c - T_a) \qquad (7)$$

$$q_u = \propto \boldsymbol{\tau} I_T - U_L(T_c - T_a). \qquad (8)$$

Where q_u is the collector's energy per unit area.

The heat generated on the surface of the collector, and is gained by the working fluid is given by:

$$Q_{gen} = {}_a C_{pa}(T_c - T_a) \qquad (9)$$

where:

$\square_a$ is the air flowrate [kgs^{-1}], according to [Duffie Beckman ,1974] is given as

$$_a \approx \frac{U_L A_c F'}{C_{pa}} \qquad (10)$$

where $q_p^{\cdot}$ is the solar irradiance on the plate, [kW/m^2], according to [Howel *et al.*, 1982] is given as

$$q_p^{\cdot} = H_T \boldsymbol{\tau}_c \propto$$

$$= HR\boldsymbol{\tau}_c \propto \; = [H]\left[\left(1 - \frac{H_d}{H}\right) R_b + \frac{H_d}{H} R_d + \rho_{gr} R_r\right]\left[\frac{2are^{-k_c \ell_c}}{(r^2+1)[1-(1-\propto)\rho_{gr}]}\right] \qquad (11)$$

the monthly average daily global irradiance on a horizontal surface,

$$H = k_T H_0$$

$$= \frac{24}{\pi} I_{sc}\{a + b(\frac{N}{n})\}\left\{\left(\frac{\left[1+0.033\cos\left(\frac{360n}{365}\right)\right]}{[\cos \emptyset^0 \cos \delta^0 \sin {}^{0}_{s} + \frac{2\pi^0_s}{360} \sin \emptyset^0 \sin \delta^0]}\right)\right\}$$

H_0, the monthly average daily extraterrestrial irradiance incident on a horizontal surface is:

$$H_0 = \frac{24}{\pi} I_{sc} \left\{\frac{24}{\pi} I_{sc} \left\{\left(\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\left[\cos \emptyset^0 \cos \delta^0 \sin {}^{0}_{s} + \frac{2\pi^0_s}{360} \sin \emptyset^0 \sin \delta^0\right]\right)\right\}\right\} \qquad (12)$$

H_d, the monthly average daily diffused irradiance on the horizontal surface, according to Liu and Jordan (1960) is:

$$\frac{H_d}{H} = 1.271 - 2.7604\frac{H_d}{H_0} + 1.8036\left(\frac{H}{H_0}\right)^2 \qquad (13)$$

where H_b is the monthly average daily solar beam addition to the global irradiance on a horizontal surface,

$$H_b = H - H_d \qquad (14)$$

The ratio of the beam insolation on tilted surface to that on the horizontal surface,

$$R_b = \frac{\cos({}^0 - s^0)\cos\delta^0 \cos^0 + \sin({}^0 - s^0)\sin\delta^0}{\cos \square^0 \cos\delta^0 \cos^0 + \sin\square^0 \sin\delta^0} \qquad (15)$$

Where the tilt and hour angle, respectively are s^0 and $\square^0$.

R_d is the ratio of the diffused irradiance on a tilted surface to that on the horizontal surface given as

$$R_d = \cos^2\left(\frac{s^0}{2}\right) \qquad (16)$$

the radiative configuration factor from the ground and surroundings to the tilted surface is:

$$R_r = \sin^2\left(\frac{s^0}{2}\right) \qquad (17)$$

where ${}^{0}_{s}$ is the sun rise hour angle

$${}^{0}_{s} = \cos^{-}(-\tan\delta^0 \tan(\emptyset^0 - s^0)),$$

$$sign(\delta^0) = sign(\emptyset^0) \qquad (18)$$

alternatively

$${}^{0}_{s} = \cos^{-}(-\tan\delta^0 \tan(\emptyset^0 - s^0)),$$

$$sign(\delta^0) \neq sign(\emptyset^0) \qquad (19)$$

where δ^0 is the angular position of the earth-sun at solar noon with respect to the plane of equator,

$$\delta^0 = 23.45 \sin \left(360 \left(\frac{284+n}{365}\right)\right) \qquad (20)$$

n represents the number of days starting from January 1^{st} to the given date.

C_{pa} = specific heat capacity of air [$kJkg^{-1}K^{-1}$].

The heat removal factor, F_R which is the quantity that relates the actual useful energy gained of a collector, (7), to the useful energy gained, (9),

$$F_R = \frac{{}_aC_{pa}(T_c - T_a)}{A_c[(\propto \tau I_T - U_L(T_c - T_a)]} \qquad (21)$$

or

$$Q_{gen} = A_s\, F_R\, [(\propto \boldsymbol{\tau} I_T - U_L A_s(T_c - T_a)] \qquad (22)$$

The thermal efficiency of the collector is defined as [Itodo *et al*., 2002]:

$$\eta_c = \frac{Q_g}{A_c I_T} \quad \text{or} \quad \frac{\rho V C_{pa} \Delta T}{A_c I_T} \qquad (23)$$

where ρ = density of air [kg/m^3],

V = volumetric flowrate [m^3/s]

C_p = specific heat capacity of air at constant pressure [J/kg K]

ΔT = Temperature elevation

I_T = the irradiance on the collector [W/m^2]

3 Energy Balance 'Equation for the Drying Process

The total energy required for drying a given quantity of food is estimated using the basic energy balanced evaporation equation of water [Youcef-Ali. *et al*. 2001; Bolaji 2005]:

$$M_w L_v = {}_aC_{pa}(T_1 - T_2) \qquad (24)$$

where:

M_w = mass of moisture loss from the sample item [kg];

L_v = latent heat of vaporization of water [kJ/kg]

m_a = mass of drying air [kg];

T_1 and T_2 = initial and final temperature of the drying air [K];

C_{pa} = specific heat at constant pressure [$kJkg^{-1}K^{-1}$]

The moisture loss:

$$M_w = M_i - M_f \qquad (25)$$

where:

M_i = mass of the sample before drying [kg];

M_f = mass of the sample after drying

Heat energy Q needed for sample drying at moderate temperature [kJ];

$$Q = M_i L_v = \rho V C_{pa}(T_a - T_b) \qquad (26)$$

where, L_v = latent heat of vaporization of water [J/kg]

ρ = density of water [kg/m^3]

T_a = ambient temperature

T_b = dryer temperature

4 Moisture content (M.C) [%];

$$M.C = \frac{M_i - M_f}{M_i} \times 100 \qquad (27)$$

Dryer Efficiency (η_d)

$$\eta_d = \frac{M_i L_v}{A_c I_T\, t} \qquad (28)$$

where

L_v = latent heat of vaporization of water [J/kg]

5 Measurement

2.5.1 Solid material

The waste food used in the work was obtained from local domestic kitchens or restaurants and was manually separated from any non-organic materials within it, such as glass, paper, plastic, foil, etc. The waste was made homogeneous by pounding using local pestle and mortar, and this was done to ensure a good mixture of the constituents. To determine the moisture content of the waste, a weighed sample was heated gently in a crucible and re-weighed to obtain a constant weight. By simple ratio, the water in the sample dried is calculated and recorded. The waste was manually formed into spheres of approximately 6.0 cm diameter and placing equal weights of the waste on the net- trays and inserted into the different dryers and samples placed at the opened space to serve as control. This is done earlier in the morning before the scheduled time of drying.

III Experimentation

4.0 kg of the paste was placed on the net trays and each placed in the drying chambers. Samples taken out of each dryer were weighed before the start of dying and placed in the drying chambers and as control sample which were withdrawn at every 60 minutes interval and the new weights recorded for 11 hours. The air temperature and relative humidity at the collector unit; temperature of the solid in the drying chambers were all recorded hourly throughout the duration of drying. The moisture content of the solid was determined by Standard Test Method (ASTMD2216). Samples from both dryers and control were weighed at hourly interval for comparison purpose. The weighing was done fast in order to avoid error due to moisture loss during the process.

The purpose of this experiment was to compare the dryers (MSD and DSD), overall thermal (η_{MSD} and η_{DSD}) efficiencies and the suitability of the dried products for storage qualities and suitability as animal feed.

IV Results and Discussion

The input data were made up of the thermodynamic properties of air and water vapor obtained from steam tables fitted in table 1. The mean results obtained from section 3 and psychrometric chart are shown in tables 2 and 3.

The results in Figure 4 show that the drying cabinet temperature values of the MSD were always higher than those of the DSD throughout the duration of drying and all attaining highest values between 13:00hrs and 15:00hrs. Figure 5 shows the same trend that the highest amount of moisture loss occurred during this period. Between 14:00 and 16:30hrs, the DSD performed better than the MSD as the temperature dropped gradually; and due to the fact that the surface area of exposure of the waste in the DSD is twice that of the MSD, the moisture has better chance of escaping than was the case with MSD where moisture began to condense within the glass cover thereby blocking solar insolation to reach the wastes directly.

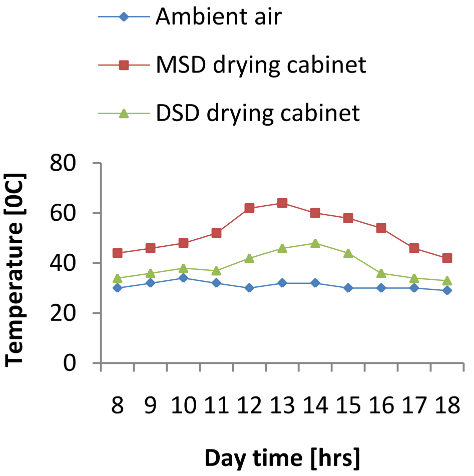
Figure 6 shows the relationship of the mass of the solid with time as moisture leaves. It clearly shows that the performance of the MSD is better than the DSD as the solid weighs lesser at the end of experimentation. Figure 7 shows the relationship of the solid moisture content with time. Less moisture is retained in the solid in the mixed-mode dryer than in the direct dryer.

The amount of moisture removed from the MSD, DSD and the open air was 86.5, 48.3 and 27.1 % respectively. The rate of moisture removal from the MSD, DSD and open air was 1.89, 1.76 and 0.99 kg/hr respectively.

The efficiencies of the dryers were 58.2% for the MSD and 32.5 % for the DSD respectively.

Table 1 Input Constants

S/№	Symbol	Units	Value
1	g	m/s^2	сен.81
2	A_C	m^2	2.0
3	б	W/m^2K^4	5.6×10^{-8}
4	P_0	kPa	101.3
5	w	m	1.0
6	m_s	kg	5.0
7	$C_{p,a}$	kJ/kg^0C	1.004
8	$C_{p,v}$	kJ/kg^0C	1.872
9	R_a	kJ/kg^0C	0.287
10	R_v	kJ/kg^0C	0.4615



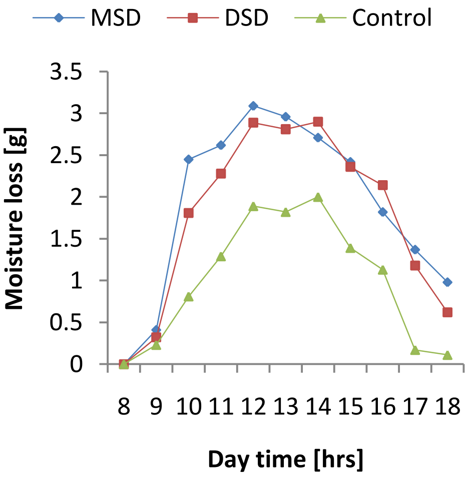
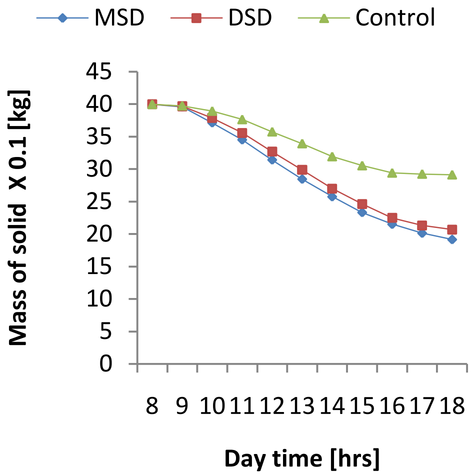


Figure 4 Variation of chamber temperature
Figure 5: Variation moisture loss from solid

Figure 6: Variation of mass of solid
Figure 7: Variation of solid moisture content



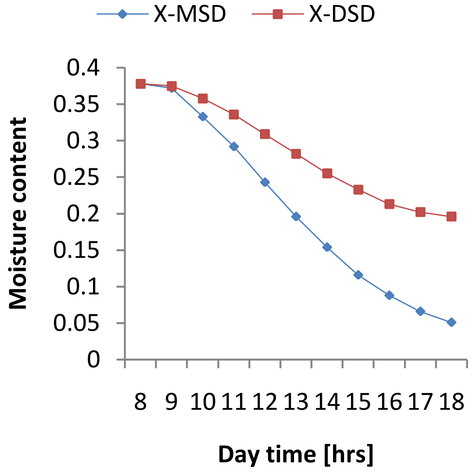


Table 2 *Mean Input Data* ***for the Mixed-Mode Dryer***

			Temperature				RH				
Time	Insolation	Solid Moisture	Point (0)	Point (1)	Point (3)	Solid	Point (0)	Point (1)	Point (3)	Wind speed	Air mass flowrate
t	I	X	T_0	T_1	T_3	T_s	Φ_0	Φ_1	Φ_3	S_{wind}	$\dot{m}_a$
[hr]	[W/m^2]	[kg/kg]	[^{0}C]	[^{0}C]	[^{0}C]	[^{0}C]	[-]	[-]	[-]	[m/s]	[kg/s]
8:00	74	0.378	30	36	34	44	0.33	0.25	0.31	1.00	0.0482
9:00	180	0.372	32	38	36	46	0.31	0.24	0.30	1.00	0.0482
10:00	290	0.333	34	44	40	48	0.30	0.23	0.28	1.00	0.0482
11:00	360	0.292	32	46	42	52	0.29	0.22	0.26	0.99	0.0477
12:00	460	0.243	30	56	46	62	0.29	0.22	0.26	0.89	0.0429
13:00	450	0.196	32	60	50	64	0.28	0.20	0.25	0.99	0.0477
14:00	350	0.154	32	58	48	60	0.28	0.20	0.25	1.00	0.0482
15:00	300	0.116	30	54	48	58	0.29	0.21	0.26	1.00	0.0482
16:00	250	0.088	30	52	44	54	0.30	0.22	0.28	0.99	0.0477
17:00	93	0.066	30	44	42	46	0.31	0.23	0.28	0.99	0.0477
18:00	70	0.051	29	40	38	42	0.32	0.24	0.30	1.00	0.0482

Table 3 *Mean Input Data for the Mixed-Mode Dryer*

			Temperature			Relative Humidity			
Time	Insolation	Solid Moisture	Point (0)	Point (2)	Solid	Point (0)	Point (2)	Wind speed	Air mass flowrate
t	I	X	T_0	T_2	T_s	Φ_0	Φ_1	S_{wind}	$\dot{m}_a$
[hr]	[W/m^2]	[kg/kg]	[^{0}C]	[^{0}C]	[^{0}C]	[-]	[-]	[m/s]	[kg/s]
8:00	74	0.378	30	32	34	0.33	0.30	1.00	0.0482
9:00	180	0.375	32	30	36	0.31	0.28	1.00	0.0482
10:00	290	0.358	34	35	38	0.30	0.27	1.00	0.0482
11:00	360	0.336	32	34	37	0.29	0.26	0.99	0.0477
12:00	460	0.309	30	36	42	0.29	0.26	0.89	0.0429
13:00	450	0.282	32	40	46	0.28	0.25	0.99	0.0477
14:00	350	0.255	32	42	48	0.28	0.25	1.00	0.0482
15:00	300	0.233	30	38	44	0.29	0.25	1.00	0.0482
16:00	250	0.213	30	31	36	0.30	0.28	0.99	0.0477
17:00	93	0.202	30	30	34	0.31	0.29	0.99	0.0477
18:00	70	0.196	29	30	33	0.32	0.30	1.00	0.0482

V Conclusion

Two simple solar dryers; the mixed-mode and direct mode were designed and constructed using locally inexpensive materials. The drying cabinet temperature, rate of moisture removal and efficiencies were (MSD > DSD > ambient air), (1.89 > 1.76 > 0.99 kg/hr) and (86.6 > 48.3 %) each having peak values between 11:00hrs and 15:00hrs corresponding to the amount of solar insolation falling on the collectors. In any case, the dryers exhibited better performance than open air drying and can be used to rapidly dry the wastes to ensure superior quality. The MSD should be preferred above the DSD though more expensive to construct if quality of product is desired. The performance of the MSD could be enhanced further by introducing two to three drying racks instead of a single drying rack, as in this case.

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