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Energy and exergy analysis of a mixed mode solar dryer without using storage material

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Abstract

Solar dryer dehumidifies the moisture for food preservation using solar radiation. In this paper, performance evaluation of mixed mode solar dryer without storage device by using energy and exergy analysis tool has been presented. Experimental work on proposed design of mixed mode dryer has been carried out at Makurdi, Nigeria. Analysis has been performed by solving the model equation of solar radiation of Makurdi, Nigeria and mathematical model of solar cabinet dryer using Engineering Equation Solver. A solution of mathematical model will give the available useful energy and exergy of solar cabinet dryer. The performance of the system is evaluated by calculating energy utilized in the drying process using experimental data. The analysis highlights the energy losses, irreversibility, exergy losses and exergy destruction at different stages. Performance comparison of solar dryer with storage device and without a storage device is also discussed. It has been concluded that the mixed mode solar dryer with storage material is able to convert 39% of solar energy as the available useful energy of dryer and convert about 13% of useful energy to exergy of the dryer system. While dryer without a storage material converts 42% of solar energy into available useful energy and converts about 17% of available energy to exergy of the dryer. Comparison of both dryers shows that mixed mode dryer without storage material has twice the exergy as compared to the dryer with a storage material.

Keywords: Solar; Dryer; Exergy; Performance; Energy

1. Introduction

Drying is one of the most important means for the preservation of different kinds of agricultural products. where the product is exposed directly to the sun allowing the solar radiation to be absorbed by the material, is called open drying, one of the oldest techniques employed in agriculture.

Contamination and infestation by fungi and bacteria, makes this method to be unhygienic since the crops are exposed to animal droppings, consequently, human health is thus endangered as a result of food poisoning. Problem of deterioration of the crops is some times encountered due to prolong drying which affects the quality of the crops. Moreover, more labour is involved as the crops are being moved frequently in and out during the day and night and from rain. They are also monitored in order to prevent physical attacks from birds and other animals. Conventional sources of energy like petrol and electricity are either totally absent or are not readily available to develop active dryers, which have higher rate of performance. A low temperature passive solar dryer has therefore been developed, which will be appropriate for crops and grains during the low temperature and high relative humidity periods of the year. The significance of low temperature drying is that, it enables crops to be dried without cracking and hence reduces the exposure of the crops to fungal and bacterial infestation and wastage, this is also appropriate for bulk drying for long-term storage (Forson *et al.,* 2007). The application of solar dryer to a structure made for the deliberate use of solar energy to heat air and/or the products so to attain dehumidification, or drying, of the products, and the process is called

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solar drying. There has been adequate documentation of the advantages of solar drying over sun drying. [1]; [2]. However, solar dryers continue to struggle to gain acceptance by commercial producers of dried products compared to some other solar technologies,. The reasons for this are intricate and varied, and depend on many factors [3]; [4]. The absence of national grid connections and high cost of fossil fuel in rural areas make agro-processing activities very difficult in the Nigeria. Studies [5] and [6], show that the use of solar energy in crop drying is possible, the studies are commendable ones. Solar drying is nonetheless without some major problems such as inability to undertake drying process over the night or during the off sunshine hours. A solar dryer that could dry agricultural materials during the off sunshine periods could be have an advantage over the existing system and will be of immense benefit to farmers. Such a solar dryer would incorporate energy storage device for drying purposes when needed or for all the day round. Many methods of solar energy storage materials are available [7]. One such method is storage of solar energy as sensible heat using materials such as pebbles (rocks) Pebble is an inexpensive material and therefore locally available in Nigeria. Its utilization in solar crop dryers could pose no burden to farmers. Mixed mode dryers are normally indirect dryers with transparent tops or sides with the crops located such that they receive direct with transparent tops or sides with the crops located such that they receive direct heating from the sun as well as being dried by the air heated in the collector [8]. This project work seeks to address the constraints of lack of proper preservation of a selected tuber by famers through drying only in day time. The mixed mode solar dryer with storage material will be constructed and drying will be carried both day and night to improve on its efficiency and provide more value for its useful energy.

2. Materials and instrumentation for the dryer evaluation

2.1. Basic Theory

The energy balance on the absorber is obtained by equating the total heat gained to the total heat loosed by the heat absorber of the solar collector. Therefore,

$$IAc = Qu + Qcond + Qconv + Qr + Q\rho \text{ .. (1)}$$

where: I = rate of total radiation incident on the absorber's surface (Wm^{-2}); Ac = collector area (m^2); Qu = rate of useful energy collected by the air (W); $Qcond$ = rate of conduction losses from the absorber (W); $Qconv$ = rate of convective losses from the absorber (W); Qr = rate of long wave re-radiation from the absorber (W); $Q\rho$ = rate of reflection losses from the absorber (W).

The three heat loss terms, $Qcond$, $Qconv$ and Qr are usually combined into one-term (Ql), i.e., Ql =

$$Qcond + Qconv + Qr \text{ ....(2)}$$

If τ is the transmittance of the top glazing and IT is the total solar radiation incident on the top surface, therefore,

$$IAc = \tau ITAc \text{ ....(3)}$$

The reflected energy from the absorber is given by the expression:

$$Q\rho = \rho\tau \; ITAc \text{ ....(4)}$$

where ρ is the reflection coefficient of the absorber.

Substitution of Eqs. (2), (3) and (4) in Eq. (1) yields:

$$\tau ITAc = Qu + Ql + \rho\tau \, ITAc \text{ c or } Qu = \tau \, ITAc \, (1 - \rho) - Ql$$

For an absorber (1 – ρ) = α and hence,

$$Qu = (\alpha\tau) \, ITAc - Ql \text{ ....(5)}$$

Where;

α is solar absorptance.

Ql composed of different convection and radiation parts. It is presented in the following form (Bolaji, 2005):

$$Ql = UlAc\,(Tc - Ta) \quad \text{.................(6)}$$

where:
Ul = overall heat transfer coefficient of the absorber ($Wm^{-2}k^{-1}$);
Tc = temperature of the collector's absorber (k)
Ta = ambient air temperature (k).

From Eqs. (5) and (6) the useful energy gained by the collector is expressed as:

$$Qu = (\alpha\tau)\,ITAc - UlAc\,(Tc - Ta) \quad \text{......(7)}$$

Therefore, the energy per unit area (q_u) of the collector is

$$q_u = (\alpha\tau)\,IT - Ul\,(Tc - Ta) \quad \text{................(8)}$$

If the heated air leaving the collector is at collector temperature, the heat gained by the air Q_g is:

$$Q_g = maCpa\,(Tc - Ta) \quad \text{..................(9)}$$

where:
ma = mass of air leaving the dryer per unit time (kg/s);
Cpa = specific heat capacity of air (kJ/KgK).

The collector heat removal factor, FR, is the quantity that relates the actual useful energy gained of a collector, Eq. (7), to the useful gained by the air, Eq. (9). Therefore,

$$F_R = maCpa\,(Tc - Ta)$$

$$Ac\,[\alpha\tau\ IT - Ul\,(Tc - Ta)] \quad \text{..............(10)}$$

Or

$$Q_g = AcF_R\,[(\alpha\tau)\,IT - UlAc\,(Tc - Ta) \quad \text{..(11)}$$

The thermal efficiency of the collector is defined as (Itodo et al. 2002):

$$\eta_C = \frac{Q_g}{ACIT} \quad \text{.....................(12)}$$

Energy Balance Equation for the Drying Process

The total energy required for drying a given quantity of food items can be estimated using the basic energy balance equation for the evaporation of water [9]:

$$MwLv = MaCp\,(T1 - T2) \quad \text{.........(13)}$$

where:

Mw = mass of water evaporated from the food item (kg);
Ma = mass of drying air (kg);
$T1$ and $T2$ = initial and final temperatures of the drying air respectively (K);
Cp = Specific heat at constant pressure (KJ / KgK).

To check for mass of water used;

$$Mw = Mi\left(\frac{Mi - Me}{100 - Me}\right)$$

Where;
Mi = initial mass of the food item (kg);
Me = equilibrium moisture content (% dry basis);
Mie = initial moisture content (% dry basis).

2.2. The Experimental Set-up

The type of solar dryer considered for this investigations is the mixed mode solar dryer without storage material shown below

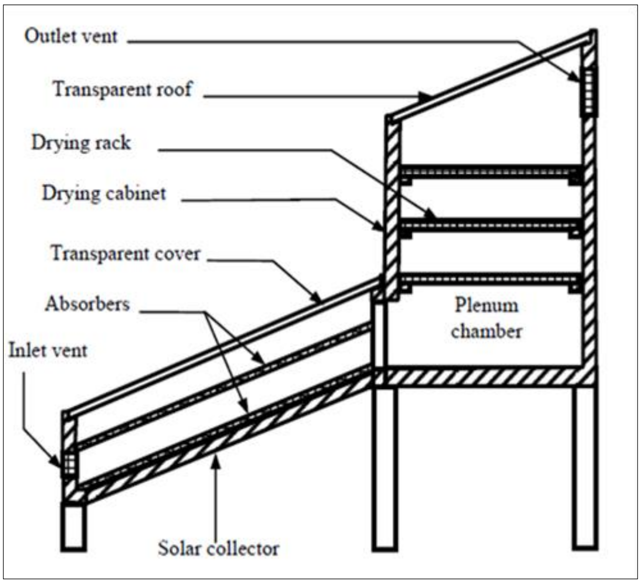

Figure 1 Mixed Mode Solar Dryer Without Storage Material

Collector (Air Heater): The heat absorber (inner box) of the solar air heater was constructed using 2 mm thick aluminum plate painted black, is mounted in an outer box built from well-seasoned woods. The space between the inner box and outer box is filled with foam material of about 22 mm thickness. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). An absorber mesh screen and the absorber back plate provides effective air heating because solar radiation that passes through the transparent cover is then absorbed by both the mesh and back-plate. The glazing is a single layer of 4mm thick transparent glass.

One end of the solar collector has an air inlet vent of area 0.059 m2, which is covered by a galvanized wire mesh to prevent entrance of rodents, the other end opens to the plenum chamber.

- **Section for storage materials:** Pebbles of even sizes painted black were placed in the collector and a 2 mm aluminium plate covered on them. The pebbles store heat and release it the sun goes down.
- **The Drying Cabinet**: The drying cabinet together with the structural frame of the dryer was built from well-seasoned woods which could withstand termite and atmospheric attacks. An outlet vent was provided toward the upper end at the back of the cabinet to facilitate and control the convection flow of air through the dryer.

Access door to the drying chamber was also provided at the back of the cabinet. This consists of two removable wooden panels made of 13 mm plywood, which overlapped each other to prevent air leakages when closed. The roof and the two opposite side walls of the cabinet are covered with transparent leather, which provided additional heating.

- **Drying Trays:** The drying trays are contained inside the drying chamber and were constructed from a double layer of fine chicken wire mesh with a fairly open structure to allow drying air to pass through the food items.
- **The orientation of the Solar Collector:** The flat-plate solar collector is always tilted and oriented in such a way that it receives maximum solar radiation during the desired season of used. The best stationary orientation is due south in the northern hemisphere and due north in southern hemisphere. Therefore, solar collector in this work is oriented facing south and tilted at 22.2o to the horizontal. This is approximately 14.5^{o} more than the local geographical latitude (Makurdi a location in Nigeria, 7.7^{o}N).This inclination is also to allow easy run off of water and enhance air circulation.

2.3. Design Calculations

Angle of Tilt (β) of Solar Collector/Air Heater.

The angle of tilt (β) of the solar collector is given by the formula below:

$$\beta = 15 + Lat\Phi$$ β (Alamu, 2010)

where $Lat\Phi$ is the latitude of the collector location, the latitude of Makurdi where the dryer was designed is latitude 7.7°N.

Hence, the suitable value of β use for the collector:

β = 15 + 7.7 = 22.7° to the horizontal.

2.4. Insolation on the Collector Surface Area

A researcher obtained the value of insolation for Makurdi i.e. average daily radiation H on horizontal surface as H = 978.69W/m^2 [10] and average

effective radiation of solar energy on tilted surface to that on the horizontal surface R as; R = 1.0035 [10].

Thus, insolation on the collector surface was obtained as:

1 c = HT = HR = 978.69 x 1.0035 = 982.11W/m^2 (GEDA-Gujarat Energy Development Agency, 2003).

2.5. Determination of Collector Area and Dimension

The air gap height was taken as 5.6cm – 0.056m and the width of the collection assumed to be 45cm – 0.45m.

Thus, volumetric flow rate of air V'a =Va x 0.056 x 0.38

Va = 0.15 x 0.056 x 0.38 = 3.19 x 10m^3/s

Thus, mass flow rate of air: Ma = vapa (Dorf, 1989)

Density of air is taken as 1.2252kg/m^3 at S.T.P.

Ma = 3.19 x 103 x 1.2252 = 3.91 x 103 kg/s

Therefore, area of the collector Ac

Ac = (3.91 x 10-3 x 1000 x 30)/(0.5 x 982.11) = 0.239m^2

The length of the solar collector (L) was taken as;

L = Ac/ B = 0.3537/0.45 = 0.53m. Thus, the length of the solar collector was taken approximately as 0.6m.

Therefore, collector area was taken as $(0.45 \times 0.53)^2 = 0.239m^2$

2.6. Determination of the Base Insulator

Thickness for the Collector For the design, the thickness of the insulator was taken as 7cm.

The side of the collector was made of wood, the loss through the side of the collector will be considered negligible.

Where M1 is the mass of the sample before drying and M2 is the mass of the sample after.

2.7. Dryer efficiency

Efficiency (%) = work output/work input x 100/1 [11]

Where (work output) is the final mass of the crop after drying and (work input) is the initial mass of the crop before drying.

2.8. Moisture Content ($M.C$)

The moisture content is given as:

$$M.C = \left(\frac{M1 - M2}{M1}\right) \text{..... [11]}$$

Where $M1$ = mass of sample before drying and $M2$ = mass of sample after drying.

2.9. Moisture loss ($M..L$)

The moisture Loss is given as

$M.L = M1 - M2$ (g).... [11]

Where $M1$ is the mass of the sample before drying and $M2$ is the mass of the sample after.

2.10. Design dimension of the chamber

Dimensions are in cm

1000cm = 1litre

capacity:

$$\frac{(L \times W \times B)}{1000}$$

Capacity: (45 x 45 x 50)/ 1000 =101.25 litres

2.11. Experimental Procedure

The mixed-mode solar dryer shown in Fig. 3 was tested in the month of April, 2016 to evaluate its performance. During the testing period, the air temperatures at collector inlet, collector outlet, plenum chamber, drying chamber and ambient were measured by laboratory type mercury wet and dry bulb thermometers (accuracy ± 0.50C) at regular interval of one hour between the hours of 8:00 and 20:00 local time. The solar intensity was measured by means of a portable Kipps Solarimeter placed at an inclination of 22.2^0 facing south.

The dryer was loaded with yam chunks of 8mm thickness (1kg on each rack) and its weight was measured at the start and at one-hour intervals thereafter. Knowing the initial weight and the final weight at the point when no further weight loss of yam chunks was attained, the weight loss was used to calculate the moisture removed in kg water/kg dry matter at intervals as the yams dried. The dryer performance was evaluated using the drying rate and collector efficiency. The collector efficiency was computed using Eq. 12 and the drying rate, which is the quantity of moisture removed from the food item in a given time, was computed from Eq. 15 below [12].

$$\frac{Dm}{dt} = \left(\frac{Mi - Mf}{t} \right) \times 100\%$$

3. Result and discussion

It is observed that the rise in air temperature due to the generated air flow rate in the collector is sufficient for the purpose of most agricultural products drying.

After completing the construction of the dryer, different tests were performed in order to evaluate its performance. Potato was dried during the test period.

3.1. Exergy Variation

Figures 2, 4 and 4 shows the variation of exergy inflow, outflow and exergy efficiency for rack 1 and 2 as observed their respective values increased with increase in time and began to decrease beyond 14:00, with some level of fluctuation or up and down variation as time kept increasing [13]; [14].

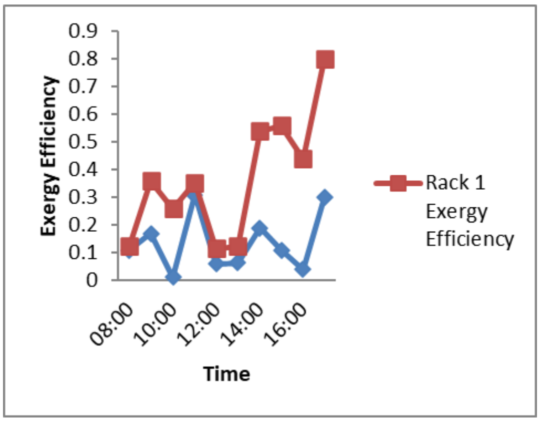

Figure 2 Exergy Computations for 23rd April, 2016

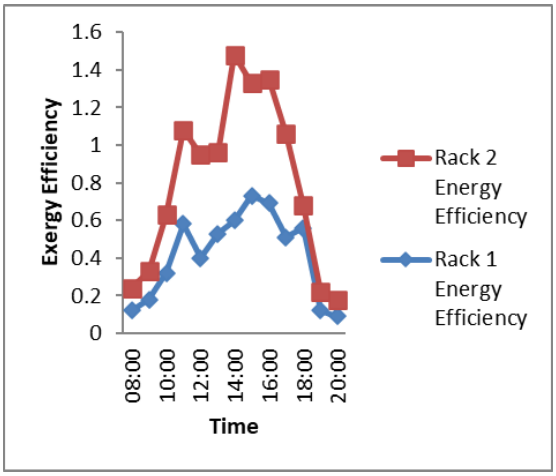

Figure 3 Exergy Computations for 24th April, 2016

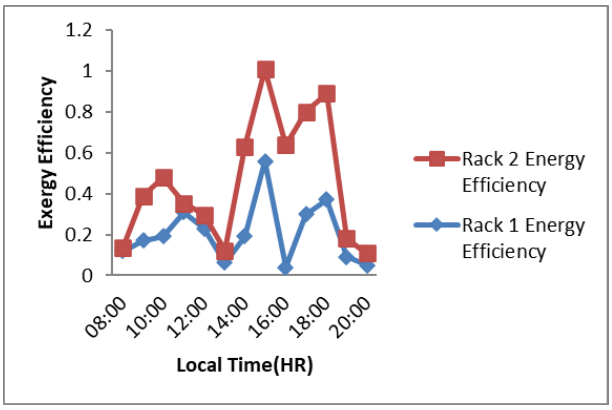

Figure 4 Exergy Computations for 25th April, 2016

3.2. Drying Efficiency

The weight loss per hour for rack 1 and 2 computed for 27th, 28th and 29th are shown in Figures 5, 6 and 7. This shows a drop from 6.0 to 0.1, 6.3 to 1.0 and 4.6 to 0.05 and

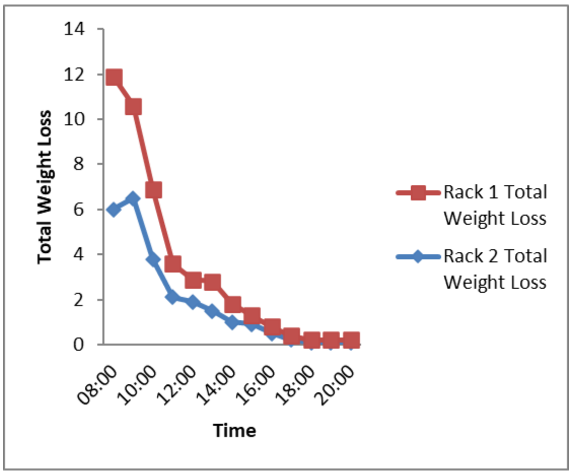

Figure 5 Computation of weight on the 27th day of April, 2016

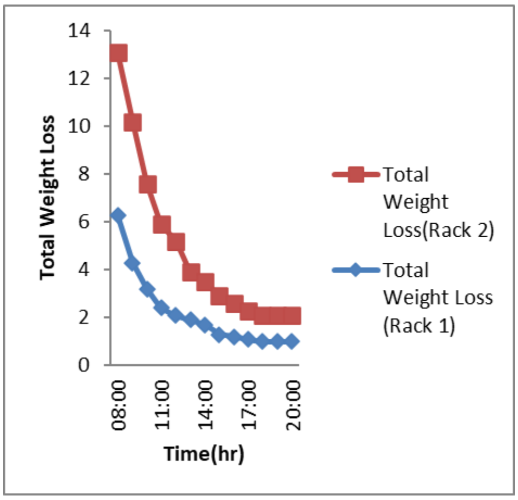

Figure 6 Computation of weight on the 28th day of April, 2016

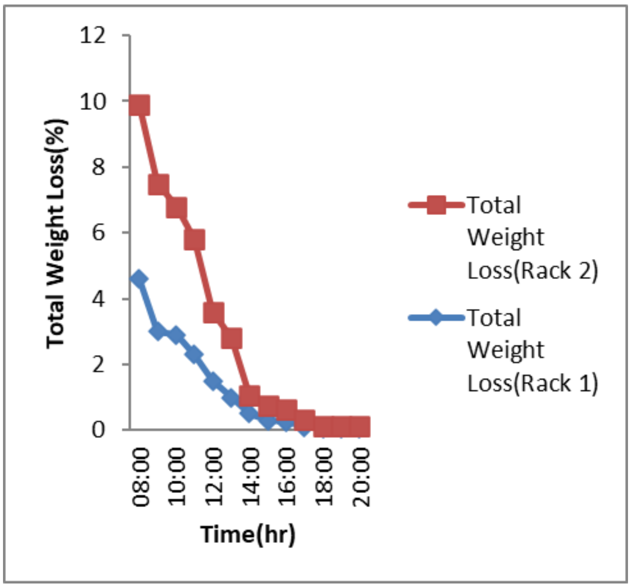

Figure 7 Computation of weight on the 29th day of April, 2016

3.3. Solar Insulation

Average solar insulation was 394.8 W/m^2

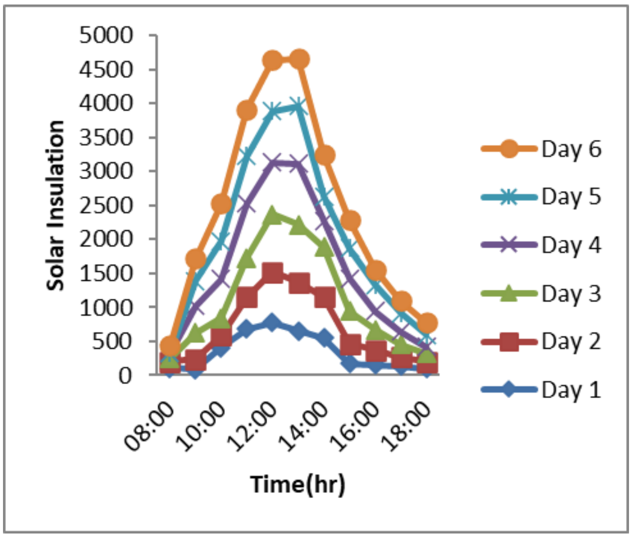

Figure 8 Solar Insulation, W/m^2 (Solarimeter)

4. Conclusion

The following conclusions can be drawn.

A mixed-mode solar dryer without storage device was designed, constructed and tested and on an average, it takes 3 days to dry a batch of yam sample. Drying rate varies with coordinate position of trays; it decreases from the top tray up to a minimum at the bottom tray and starts increasing up to the top tray. The exergetic efficiency, weight loss and solar insulation were respectively measured.

Compliance with ethical standards

Disclosure of conflict of interest

Authors declare that they have no conflicts of interest or financial conflicts to disclose.

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