PERFORMANCE EVALUATION OF A PEBBLE BED SOLAR CROP DRYER

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ABSTRACT

The design, development and test performance evaluation of an integrated of passive solar energy crop drying system was undertaken. The solar crop dryer consists of an imbedded pebble bed solar heat storage unit/solar collector and crop drying chamber measuring 67 cm x 110 cm x 21cm and 50 cm x 90 cm respectively. The crop-drying chamber is made of drying trays of wire gauze while the roof is made of transparent glazing. Test performance evaluation of the solar crop dryer indicates that maximum absorber temperature of 72 ^{0}C, heat storage bed temperature of 58 ^{0}C and chamber temperature of 57 ^{0}C were obtained using the dryer when the maximum ambient temperature was 34 ^{0}C. Further test using cassava, showed a moisture reduction from 73% initial moisture content to 10.2% final moisture content in 3 days of drying process while open air sun drying was 22.2% under the same period of drying.
Products dried under the passive solar crop dryer were of high quality while there were mould build up on the open air sun dried products. This indicates that drying under solar crop dryer offers high quality products and is time saving than the open-air sun drying.

Keywords: pebble bed, solar, storage, crop dryer.

1.0 Introduction

Food drying is a major processing activity, which involves dehydration of moisture from agricultural produce for easy handling and storage. It is a preventive technique against post-harvest losses. Post- harvest losses, which amount to food insecurity, could be tamed if adequate precautionary measures are taken as soon as the farmer harvests his produce. The issue of food insecurity rested on a tripod of non-availability, non-stability of price and non-accessibility of food. According to Ogugua (2004) the situation of post harvest losses has caused a setback in the level of nutritious food consumption. Food price stability is influenced by the extent of post-harvest losses in the agricultural produce. The farmer produce so much food but along the way he losses much of the produce as he harvests the produce due mainly to lack of preservative method for a prolonged storage.

The problem of food availability all year round is not a matter of producing enough but a function of preservative methods employed by the farmer for a sustained availability. One of such methods is drying. Despite the availability of artificial methods of food drying in Nigeria, most farmers still employ the open-air sun

drying technique in order to dry their agricultural produce. The open-air sun drying is prevalent and very common in the rural areas. Farmers spread their agricultural produce such as maize, cassava, pepper, tomatoes etc. along major roads in order to get them dried. In Nigeria this is common along such roads as Ejule - Abuja, Okene - Lokoja, Obolo afor - Otukpo roads and so on. This method of drying process has inherent limitations, which include dust contamination, decay, insect and rodent attacks mould (fungal) build up due to prolonged drying periods. In most cases, what could take few hours to dry under modern techniques take days to dry. Same time, the available non-solar drying systems such as electricity and fossil fuel based systems are very expensive and therefore unattainable to the poor local farmers. A possible alternative cheaper crop drying system then could be the use of solar energy drying system.

The abundance of solar radiation in Nigeria could make crop drying with solar dryers very easy and simple. Economic appraisal of solar drying in Nigeria showed that the use of solar energy in food processing is much more cost effective than electricity and fossil fuel drying systems. The absence of national grid connections and high cost of fossil fuel in rural areas make agro-processing activities very difficult in the Nigeria. Studios (Aarinze 1985 and Adesuyi 1991), showed 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 (Duffie and beckman, 1979). 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 famers.

In this report the design, development and performance evaluation of pebble bed passive solar energy storage crop dryer is presented.

2.0   Design Consideration
The solar crop dryer is designed for drying agricultural produce that needs low temperature rise above the ambient. The produce of study is cassava. Cassava is chosen for the study because of its importance in Nigeria economy. Nigeria is the largest world cassava producer and is being exported to other countries of the world. Therefore, proper preservation of the crop through drying will enhance the storability and transportability, and hence will further increase the economic gains from the produce. The environmental impact of solar drying is considered friendly, non contaminating and non polluting. Heat transfer medium is essentially by air current and the drying method is passive. The intermittent nature of solar radiation is an important factor to consider in solar designs. The design therefore incorporates a storage system which stores and supplies heat to the drying chamber during the off-sunshine hours. Materials of construction are locally available and friendly to end-users with low maintenance cost.

2.1   Description of the Solar Dryer
The integrated solar energy pebble bed solar dryer (fig.1) is made of two important compartments

i.   The solar energy collector/storage unit (A)
     The crop drying chamber (B)

ii.

2.1.1 The solar energy collector (heat storage unit)

The solar collector is a dual function apartment, which consists of a solar energy collector and an imbedded pebble bed heat storage unit. The solar energy collector / heat storage unit (A) is a flat –plate solar energy collector that collects and stores solar energy. It has internal dimensions measuring 110cm x 65 cm x 20cm giving radiation absorption surface area of $0.715m^2$ and $0.143m^3$ volume. The wall of the collector (a) is constructed of 2 cm wooden materials, which serves as an insulating material. Three quarters (3/4) of the volume is filled with uniformly sized pebbles, which constitutes the pebble bed (b). The pebbles on the top surface of the bed are painted black to form the solar energy absorber. This is covered with transparent glass-perspex cover (c) at a 2 cm distance above the solar absorbing surface. The pebbles store solar energy during the sunny hours of the day, which could be used during off-sunshine hours such as night and cloudy periods of the day. This provision ensures that drying process takes place all the day round. The solar collector is inclined at 22^0 to horizontal and oriented towards south for all year round solar energy collection. Two openings (d) and (e) for fresh air entrance are located at the lower end of the solar collector while another opening (g) at the upper end allows exit of hot air form the collector into the drying chamber. The lower air openings are provided with shutters either to close or open for fresh air entrance into the collector. The top opening is kept opened during the sunny hours of the day while the lower one is closed. During the night and cloudy periods of the day the reverse is the case.

Also to prevent heat loss through the upper surface of the collector during the night or cloudy hours a hinged door (f) is fasten to the collector. This is used to close or open the solar collector when in operation.

2.1.2 The crop drying chamber

The crop drying chamber (B) is made of wooden material measuring 50 cm x 50 cm x 90 cm. It has an hot air inlet (h), which is located at the bottom end of the chamber. This provision allows hot air from the integrated solar collector/hear storage unit into the chamber while an exhaust air outlet (i) of 30 cm x 5 cm was provided at the upper end of the drying chamber. The roof (j) of the drying chamber is covered with a transparent glass cover. This allows direct solar radiation into the chamber thereby enhancing crop drying operation. The chamber also consists of three drying trays (k) all separated at a distance of 20 cm from the other. The trays are framed with wood while the floors are of wire mesh. The trays measure 48cm x 48cm x 5cm.The chamber is constructed of wood and this insulates the whole system against heat loss from the chamber. For access into (l) is provided. The chamber is placed on an iron stand (m).
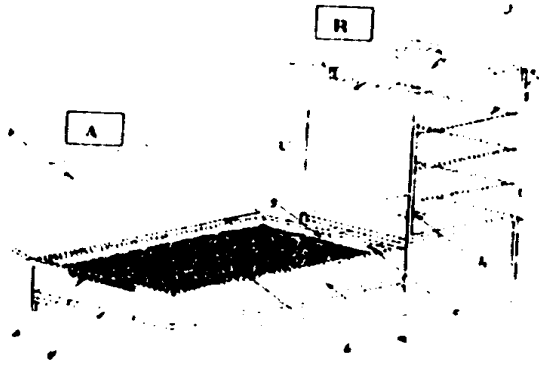
Fig. 1: Isometric view of the pebble bed solar crop dryer (a) collector casting (b) pebbled bed (c) transparent glass cover (d) lower air opening (c) upper air opening (f) collector hinged door (g) hot air exit (h) chamber hot air inlet (i) exhaust hot air exit hot air (j)transparent chamber roof (k)

2.0 Design Equations

The collector was inclined at an optimum angle equal to 22^0. The optimum tilt angle was determined by local latitude plus 15^0 Nsukka has a latitude L of 6.8^0.

$$\theta = L + 15 \qquad (1)$$

The collector area was determined by the expression

$$A_C = \frac{Q_n}{n_c I_c} \qquad (2)$$

Where

ambient is given by

$$Q_{st} = 36000_{vst} L_p C_{pp} \Delta T$$

While the total rate of heat transfer to the drying agricultural product is a combination of convective, conductive and radiative heat

Ac   =   collector area, m^2
Qu   =   useful energy gained by collector, W
Ic   =   incident radiation on the collector surface.
n   =   average collector efficiency
The useful energy gained by the collector was determined by

$$Q_n = v_{st} u C_{pp} \Delta T \qquad (3)$$

Where
V_a =   *Volumetric flow rate of air* m^3/s
l_a =   *density of air kg/m^3*
C_{pp} =   *specific heat capacity of air KJ/kg^{0}C*
The sensible heat Q_{st} stored by the pebble was established using

$$Q_{st} = v_{st} u C_{pp} \Delta T \qquad (4)$$

Where
O_u =   amount of heat stored by pebbles, W
V_{st} =   volume of pebble, m^3
ρp =   density of pebble, m^3
ΔT =   temperature change in storage, ^{0}C
C_{pp} =   specific heat capacity of storage pebble, KJ/kg^{0}C
Assuming a 10 hours of non-sunshine hours, the amount of heat needed to keep on drying at ΔT rise in a storage temperature above the

transfer, which could be expressed as

$$q = q_c + q_r + q_k \qquad (6)$$

Where
q_c =   convective heat transfer, W
q_r =   radiative heat transfer, W
q_k =   conductive heat transfer, W
and these are expressed as

$$q_c = h_c(T - T_{ch})A \qquad (7)$$
$$q_c = h_r(T - T_{ch})A \qquad (8)$$
$$q_k = U_k(T - T_{ch})A \qquad (9)$$

h_c =   convective heat transfer coefficient W/m^{2}K
T   =   temperature of hot air coming from the solar collector, ^{0}C

T_{ch} = temperature of chamber (temperature of material), ^{0}C

T_r = radiative heat transfer temperature, ^{0}C

A = drying area of material, m^2

h_r = radiative heat transfer coefficient, $W/m^2.k$

U_k = thermal conductivity of material $w/m^2. k$

Moisture loss from the drying material is expressed with

$$\times_1 = \frac{w_m - w_s}{w_s} \qquad (10)$$

Where

X_t = rate of drying %

w_m = weight of material before drying, kg

W_s = weight of material after drying

3.0 performance evaluation

The performance evaluation of the solar crop dryer was undertaken by conducting a physical test-run of the dryer and the dryer loaded with agricultural product. The study covers a prolonged period. The study covers a prolonged period of six months (December 2003 to May 2004) of evaluation. The result presented here reflects an average performance of the period. The prevailing physical conditions – temperature and relative humidity of the dryer and ambient conditions were monitored with thermometers and relative humidity sensors and thermocouple wire located at strategic points within the solar collector/heart storage unit and the drying chamber. The dryer was filled with cassava chips, which are cut into uniform size measuring 1.3 cm x 1.3 cm. a similar quantity and size of cassava were also spread outside under open-air sun drying as control. Solar radiation data within the period of experiment was collected from the meteorological unit of the national centre for Energy Research and Development, University of Nigeria, Nsukka. The rates of moisture loss of the drying materials were determined using oven method. Temperature and relative humidity measurements were

determined on hourly basis.

4.0   Results and Discussion

4.1   Solar collector/ heat storage unit

Fig, 2 shows the temperatures regime of the integrated pebble bed passive solar energy storage crop dryer. The maximum air temperature reached by the solar collector was 630°C, while the storage temperature was 58°C, the solar absorber temperature was 72°C, and the ambient environmental temperature was 34^{0}C. The average drying chamber temperature was 57 ^{0}C. These showed that the collector hot air storage, solar absorber and the chamber temperatures rose by 29 ^{0}C, 24 ^{0}C 38 ^{0}C 23 ^{0}C well above the ambient temperature respectively. The figure showed that the solar absorber had the highest rise day time. This was recorded at 12 noon (point 7 on the time scale) starting from 6 am (point 1); Ambient temperature, storage temperature and the average drying chamber temperature in that order followed this. While the temperature of storage had the highest temperature values during the night period starting from 5 pm (point 12 on the time scale), The trend continues till about 3 am (21) when it dropped below the chamber and collector air temperatures respectively. The indication showed that by this period, the energy stored the previous day by the storage unit has been exhausted. The higher temperatures above the ambient temperature exhibited by the storage and the drying chamber during the night periods indicated that the storage contributes significant heat to the dryer during off sunshine hours and therefore provides the dryer the ability to undertake drying process into the hours of night. The dryer and ambient relative humidity were ranged between 43 to 74% and 37 to 83%, respectively.

4.2.1   Drying material

Table 1 shows the result of the cassava chips drying process. The cassava was at initial moisture content of 73%. At the end of an average period of 3 days a mean moisture content of 10.5% was attained by the cassava chips under the solar crop dryer while the open

air sun drying reduced to 22.2% at the same period. It took another two additional days for the open air sun drying (control) to attain about 11.2% moisture content (fig.3.). This showed a significant reduction in time using the solar crop dryer. Moreover, the samples dried in the solar dryer were clean and of high quality with no contamination through dust or insect and did not change colour while those under open air sun drying showed change in colour indicating signs of deterioration in quality. It was also observed that the samples at different levels in the chamber trays were not drying at the same rate. The tray at the topmost of the drying chamber has the highest drying rate. However, this was not the same during the night periods as reverse was the case. This could be probably due to the direct solar radiation, which comes directly from the transparent roof cover of the dryer to the topmost ray during the day hours in addition to hot air coming from the solar collector.

Table 1: Dried samples of cassava ships

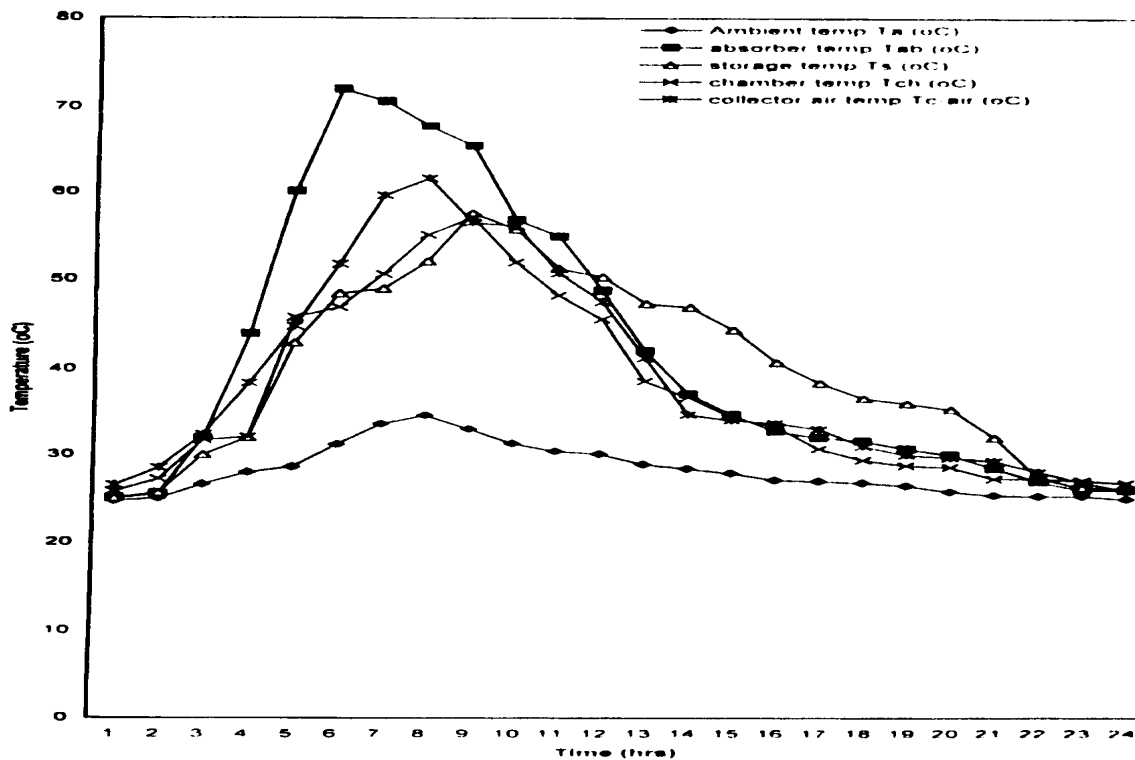| Sample	day(s) of drying	Initial moisture content(%)	Final moisture content (%)
1st tray	1	73	15.40
	3		10.00
2nd tray	1	73	16.70
	3		11.10
3rd tray	1	73	14.30
	3		10.50
Open-air Drying (control)	1	73	22.22
	3		15.65
	5		11.20

Fig. 2: temperature regime of integrated pebble bed solar collector/storage]
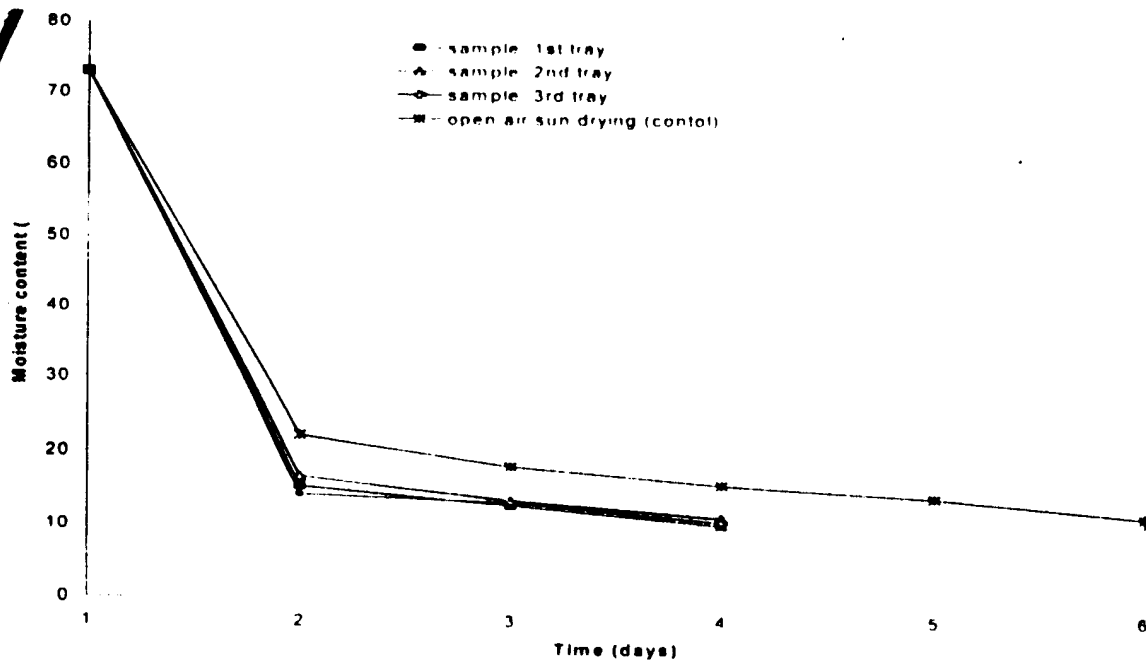
Fig.3: Plot of cassava drying rate

CONCLUSION

Pebble bed passive solar energy storage crop dryer consisting of solar collector/ heat storage unit and a drying chamber was tested with cassava chips. The result of the a prolonged performance evaluation showed that a drying chamber temperature of up to 57 ^{0}C was attained with a solar collector absorber temperature of 72 ^{0}C when the pebble bed storage temperature was 58 ^{0}C, The cassava was dried from initial moisture content of 73% to an average storage moisture content of 10.5% in 3 days of drying process while it took about 5 days for the open-air sun drying sample (control) to attain a moisture content of 11.2% from the same initial moisture- content. Materials dried under the solar dryer were of high quality and showed no sign to contamination by change of colour while the open air sun dried samples indicated some colour change showing product deterioration and decay. This showed that drying gives faster drying process, yields high quality products and is time saving than open air sun drying.

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