Development of a Multipurpose Solar Dryer

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Abstract— In many parts of the world there is a growing awareness that renewable energy has an important role to play in extending technology to the farmers in developing countries to increase their productivity. Solar thermal technology is rapidly gaining acceptance as an energy saving technology in agriculture application. This article presents the design, construction and performance evaluation of a solar dryer for food preservation. In the dryer, heated air from a separate solar collector is passed through beds of grains. The design of the dryer makes provision for the attachment of additional mirrors on two opposite sides of the solar collection chamber. Overall, the dryer is of simple design, cost effective, and made from affordable available materials and require little or no skills for its fabrication and operation. The results obtained from tests carried out on the dryer revealed that the temperatures inside the drying chamber and the solar collector were highest when the side mirrors were at 45° to the vertical, giving optimum performance under various experimental conditions.

Keywords—Collector, Drying chamber, Solar Dryer, Flat plate, Chimney

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1 INTRODUCTION

The sun remains the main source of energy in the world. This energy source is highly abundant in tropical parts of the world with clear sunny skies for about 12 hours daily. A solar energy utilization system such as solar dryer functions as a viable tool to maximize amount of solar irradiation absorbed from the solar system. Many researchers have worked on the natural convection solar drying of agricultural produce. Pangavhane et al. (2002) developed a natural convection solar dryer consisting of a solar air heater and a drying chamber for drying various agricultural products like fruits and vegetables. They reported that the drying airflow rate induced by the thermal buoyancy in the collector increased with increase in ambient temperature. Qualitative analysis on grapes dried in this study showed that the traditional drying of grapes, i.e. shade drying and open sun drying required 15 and 7 days, respectively, while the natural convection solar dryer took only 4 days and produced better quality raisins. The dryer could develop average temperature ranging between 50 and 55 °C, which is optimum for dehydration of the grapes as well as for most of the fruits and vegetables. The control of the drying process in natural-convection solar dryers presents a major problem, because they are designed to minimize capital and running costs. Thus, special control mechanisms are inappropriate. The best approach is to incorporate chimneys, which regulate the residency period of the drying air within the drying chamber.

Based on this approach, Ekechukwu and Norton (1997) designed a solar chimney for natural-convection solar dryers. The results showed that the solar chimneys, if designed properly, could maintain chimney air temperatures consistently above the ambient temperature which would improve the drying rate by enhancing the buoyancy-induced air flow through the chimney as desired. Similarly, Gbaha et al. (2006) designed a direct type natural convection solar dryer using local materials and used it to dry cassava, banana and mango slices. They reported that the thermal performance of the dryer in terms of heat and mass transfers influenced by solar incident radiation were found to be higher when compared to open sun drying for the selected food materials. Sacilik et al. (2006) reported on the thin layer solar drying experiments of organic tomato using the multi-purpose solar tunnel dryer under the ecological conditions of Ankara, Turkey. They reported that organic tomatoes could be dried to the final wet basis moisture content of 11.5 from 93.3% in 4 days of drying in the solar tunnel dryer as compared to 5 days of drying in the open sun. There is need to develop more enhanced solar dryers suitable for tropical applications. In this study, a semi-active solar dryer was developed by enhancing drying using two-phase principle by utilizing the heated working fluid and forced convective of heated air in the dryer compartment.

2 MATERIAL AND METHODS

2.1 Materials

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 (chimney) was constructed at the upper end of the drying chamber 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 well lagged wood made of 1/8″ plywood, which overlapped each other to prevent air leakages when closed.
The solar dryer works in two stages:

(a) the solar heating of the working fluid i.e. the inlet air, and
(b) the circulation of the heated air to extract moisture from the crops in the drying chamber.

2.2 Methods

Solar heating of the working fluid: A separate solar collector is used to pre-heat the ambient air (the working fluid) drawn into it by natural convection before conveying it to the drying chamber through natural convection.

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The Circulation of the Pre-heated Air: The hot air will naturally flow into the drying chamber by convection due to the inclination of the absorber plate such that the air inlet end is at a lower level than its other end that links it with the drying chamber. In the chamber, the heated air passes through beds of crops arranged on metal gauze where the exchange of heat takes place between the wet crop and the heated air. Consequently the temperature of the drying air is reduced and the air is laden with moisture. The moisture-laden air will be heated by direct solar radiation through the transparent cover on the drying chamber; this will lighten it up and cause it to rise into the chimney through which it flows out of the drying chamber.

Operation of the Dryer: The dryer is a passive system in the sense that it has no moving parts. It is energized by the sun's rays entering through the collector glazing. The trapping of the rays is enhanced by the inner surfaces of the collector that is painted black to act as a blackbody and the trapped energy heats the air inside the collector. The greenhouse effect that will be achieved within the collector drives the air current through the drying chamber. If the vents are open, the hot air rises and escapes through the chimney in the drying chamber while cooler air at ambient temperature enters through the lower vent in the collector. Therefore, an air current is maintained, as cooler air at a temperature, T_a, enters through the lower vents and hot air at a temperature T_e leaves through the upper vent. The incoming air at a temperature 'T_a' has relative humidity 'H_a' and the out-going air at a temperature 'T_e', has a relative humidity 'H_e'. Because $T_e>T_a$ and the dryer contains no item, $H_a>H_e$. There is tendency for the out-going hot air to pick more moisture within the dryer as a result of the difference between H_a and H_e.

2.3 Design Theory

2.3.1 Energy balance equation for the heat absorption process

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

$$IA_c = Q_u + Q_{cond} + Q_{conv} + Q_R + Q_Q \qquad (1)$$

The collector's heat removal factor, FR, is the quantity that relates the actual useful energy gained by a collector to the useful energy gained by the air. Therefore,

$$F_R = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{A_c[\propto \tau I_T - U_L(T_c - T_a)]} \qquad (2)$$

2.3.2 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 (Youcef-Ali, *et al.*,2001; Bolaji, 2005):

$$m_w L_v = m_a C_p (T_1 - T_2) \qquad (3)$$

2.3.3 Efficiency of the Solar Dryer

The efficiency of solar drying systems can be evaluated based on the thermal performance. The thermal efficiency of a solar dryer can be defined as the thermal energy utilized for drying over the thermal energy available for drying.

Thus, the thermal efficiency of solar drying system is given by:

$$\text{Efficiency SD} = \frac{\text{Heat}_{\text{Sensible (H\&F)}} + W_v \lambda_v}{q_{\text{input}}} \qquad (4)$$

The net input energy in Equation (4) is mainly the incident solar radiation. The amount of radiant solar energy is determined by the intensity of solar radiation during the drying period and surface area of absorber receiving the radiant heat. Here, the surface area of the absorber that is exposed to the solar radiation is constant for the dryer and thus the thermal efficiency will be dependent only on intensity of solar radiation for the whole drying period.

2.4 Components of the Semi-Active Solar Dryer

The solar dryer consist of the following:

(a) A flat plate solar collector with detachable side mirrors,
(b) The drying chamber, and
(c) The chimney.

Concentrating flat plate collector (air heater): The heat absorber (inner box) of the solar air heater was constructed using 2 mm thick galvanized plate, painted first with red-oxide and then later painted black to extend the useful life of the absorber. The absorber was mounted in an outer box built from well-seasoned woods. The space between the inner box and outer box was filled with insulating foam material of about 30 mm thick. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). The glazing is a single layer of 4 mm thick transparent glass sheet; with surface area of 1070 mm by 760 mm. The effective area of the collector glazing is 0.8132 m^2. One end of the solar collector has an air inlet vent of area 0.152 m^2, which is covered by a stainless steel wire mesh to prevent entrance of intruders like rodents and have long useful life; the other end is open to the plenum chamber of the drying chamber.

The Drying Cabinet: The drying chamber is essentially used to reduce the moisture content of the crops to a level suitable for storage. It achieves this by passing dry, hot air over the crops. In this instance, the drying chamber has three shelves each assumed to hold equal weight of crops.

(2)

In terms of the drying chamber design the following were taken into consideration:

I. Relative humidity of ambient air. For example for maize to dry effectively the ambient relative humidity of the air should be less than 65% (Amir et al.). If the relative humidity exceeds 80% the maize starts to absorb moisture from the air.
II. Drying chamber air temperature. The main constraint on the design is the temperature of the air in the dryer. In terms of maize the air temperature should not exceed 60 °C, and not be lower than 10 °C above ambient. For optimal drying the air temperature should be approximately 45 °C (Amir et al.).

The Chimney: the solar chimney is an integral component of the solar dryer. It is necessary to aid flow through the device which is essential to remove the moisture rich air away from the drying produce and into the atmosphere. The chimney is similar to the solar collector in that it has a collector surface which uses solar energy to heat the air. After drying the produce in the drying cabinet, the air from the collector will have higher moisture content and will have lost energy. This results in the air being less buoyant and hence a major problem with drying the produce is expelling this moisture rich air. This is where the solar chimney has an advantage as it will add energy to the air flow, ensuring that the humid air is removed, avoiding potential spoilage and bacteria problems. Another advantage of the use of the chimney is to regulate flow through the device in times of unexpected external conditions (i.e. enough flow rate so that during high solar energy, temperatures don’t soar and spoil crop).

Table 1. Technical specification of the designed semi-active solar dryer

S/N	Parameter	Description
1	Mode of heating	single
2	Number of glazing	1
3	Incoming air	Preheated
4	Loading provision	Opening
5	No of doors/trays	2/3
6	Air Outlet provision	Vent
7	Air circulation	Natural
8	Height of stand	1.402 m
9	Collector area	0.8132 m2
10	construction materials	Wood, Galvanized and, Glass sheet, glass wool, mirror.

3 TESTING AND EVALUATION

The testing of the dryer was done at no load i.e. without putting in any crop to be dried. The load test was further carried out using banana and yam samples.

Fig. 1. Front and Rear view photographs of the semi active solar dryer

Fig. 2. Semi-active solar dryer when mirrors were attached

3.1 Tests at no load

The experiments at no load condition were conducted during the month of October at Ile-Ife Osun State (7.5^{o}N latitude). The dryer was placed in the south facing the sun from 8:00am, but readings were taken hourly from 11:00 am to 4:00 pm.

3.2 Evaluation Procedure

With the inner walls of the dryer left unpainted, evaluation tests were carried out on the dryer at no-load condition in the month of October at Obafemi Awolowo University solar laboratory in Ile-Ife, Osun state, Nigeria. Two cotton threads were laid in space in a horizontal position across the width of the tray in each of the upper, middle and lower drying chambers, as well as within the space between the solar radiation absorber and its glass cover. The dryer was located in an open space and a mercury-in-glass thermometer was placed approximately centrally on the pair of threads in each chamber. The temperature developed in the chambers were read from these thermometers at intervals of one hour from 11:00 a.m to 4:00 p.m every day for twelve (12) consecutive days; 4 days with the side mirrors removed, 4 days with the mirrors installed and inclined at an angle of 25° (approximately) to the vertical, and 4 days with the mirrors inclined at an angle of 45° (approximately) to the vertical. The ambient air temperature was also monitored from another mercury-in-glass thermometer. Having confirmed from the results of the above tests that the 45°

mirror inclination resulted in the development of the highest temperatures in the various chambers, the inner walls of the chambers were painted black and the mirrors were installed at 45° inclinations to the vertical. The temperatures developed in various chambers were then monitored and recorded on an hourly basis for four days between 11:00 a.m. and 4:00 p.m. every day.

Fig. 3 shows the graph of maximum temperature obtained when the mirror was at angle 45°C and the drying chamber painted black. The profile was shown over the range of hours of between 11:00 am and 4:00 pm. The figure shows a gradual increase in the chamber temperature till optimal were obtained between the hours of 1:00 and 3:00 pm. A decline was observed thereafter in the temperature within the drying chamber.

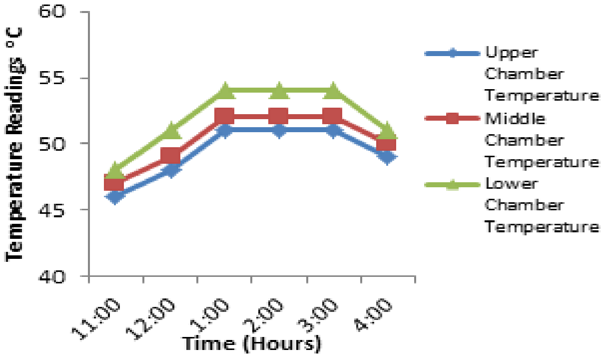

Fig 3. Maximum temperature profile of mirror at 45^{o}c with drying chamber painted black

In Fig. 4, the temperature profile was shown for mirror position of 45 °C over the range of hour of investigation. The profile also depicts the fact that temperature decreases from the lower chamber to the upper chamber of the dryer. The maximum temperature at this mirror position is less than 50 °C. Fig. 5 and 6 also shows similar trends for the temperature profiles within the drying chamber. The temperature decrease from the lower tray section towards the upper section. Optimal temperature values were observed around 2:00 pm and this decrease from 3:00 pm hour of the day.

There is a distinct increase in the temperature in all the chambers from 11:00 am to 12:00 am. The temperature behaves constant till about 2:00 pm of the day but start declining from 2:00 pm till 4:00 pm. This results shows that optimizing the dryer performance could be sought between the 12:00 noon and 2:00 pm of the days of operation as the solar radiation is at its pick at this period of the day.

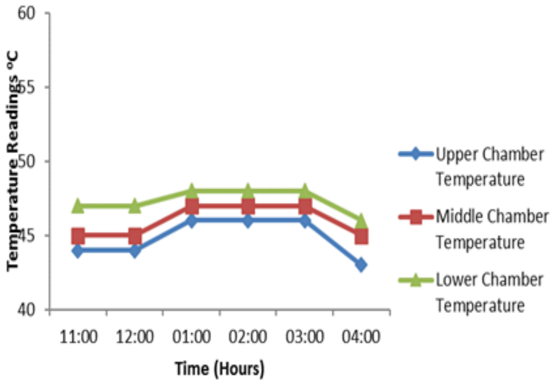

Fig 4. Maximum Temperature Profile Of Mirror at 45^{o}C

Table 2 presents the summary of the temperature of the different section of the dryer for different position of the mirror. The table shows that optimal temperature of the absorber and the air within the dryer is obtained at 45 °C when the drying chamber was painted black.

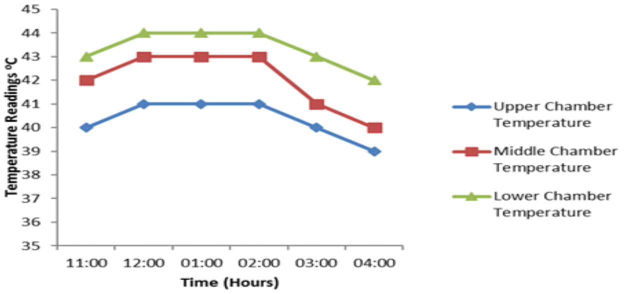

Fig 5. Maximum Temperature profile of Mirror at 25^{o}C

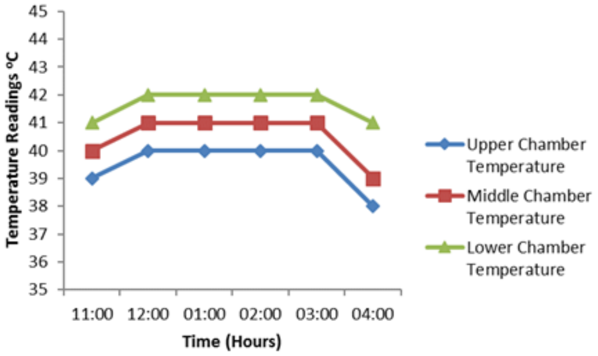

Fig 6. Maximum Temperature Profile at No Mirror

3.3 Load Test

The performance of the semi-active solar dryer was examined by conducting experiments drying unripe banana, plantain and yam in the dryer. The dryer was used to dry up to 5 kg of unripe banana and yam at different periods. The results indicate the superior performance of this dryer as compared to traditional sun drying. The weight of the product in the sample trays was recorded every hour to monitor the progress of the drying process. Control samples were dried in the open sun also for comparison. At the end of the day, the products were collected. After drying was complete, the dried produce

Table 2. Temperature readings at different experimental condition

	Average Ambient Temperature	Average Absorber Temperature	Temperature of air between glass and absorber
No mirror	28 °C	52 °C	48 °C
Mirror at 25°C	29 °C	55 °C	50 °C
Mirror at 45°C	29 °C	62 °C	57 °C
Mirror at 45°C drying chamber painted black	29 °C	70 °C	62 °C

was packaged to prevent insect losses and to avoid re-gaining moisture. Table 3 below shows the measured mass of the banana test samples before and after drying.

The moisture in percentage that was removed during the drying hour test can be expressed using equation 5:

$$W = \left\{1 - \left(\frac{m_2}{m_1}\right)\right\} \% \ 100 \qquad (5)$$

Table 3. Temperature readings at different experimental condition

Time	Mass of 1mm sliced test samples (kg)	Mass of 2mm sliced test samples (kg)
Before drying (m_1)	2.0170	1.5547
After drying test (m_2)	1.4006	1.073

Where, W = moisture content in per cent,

m_1= mass in kg of the test samples before drying, and

m_2= mass in kg of the test samples after drying, (Jensen, 2002).

Table 4 shows the calculated moisture content for two test samples of banana.

Drying of unripe banana in the open sun takes 3-4 days depending on the thickness of the banana slices and weather conditions. However, it only takes two days in the semi-active solar dryer under similar weather conditions. The quality of dried banana is remarkably better in the solar dryer compared to open sun drying as the product is protected from dust, rodents, contamination, rain and insects. Figure 7 shows the test samples (Banana and Plantain) after drying.

Table 4. Moisture Content in % for banana samples

	1 mm test samples	2 mm test samples
Moisture content (%)	30.56	28.78

Table 5 shows the measured mass of the yam test samples before and after drying:

Drying yam slices in the open sun takes 4-5 days depending on the thickness of the yam slices and weather conditions. However, it only took three days in the semi-active solar dryer under similar weather conditions. The quality of dried yam slices is remarkably better in the solar dryer compared to open sun drying as the product is protected from dust, rodents, contamination, rain and insects. The banana samples dried faster when compared with the yam samples. This is likely related to the fiber nature of the two samples affecting the ability to release moisture content. Table 6 depicts the percentage moisture content for the yam samples.

Fig. 7. The Dried Banana and Plantain after No Weight Loss Readings

Table 5. Mass of yam samples before and after drying

Time	Mass of 4mm sliced test samples (kg)
Before drying (m_1)	2.6249
After drying test (m_2)	0.8721

4 CONCLUSIONS

A semi-active solar dryer was developed and evaluated under the weather condition of Ile-Ife, Osun State. The dryer was tested for no load evaluation at different experimental conditions and also tested with up to 5 kg of unripe plantain/banana and yam samples. Results indicate excellent performance, with significant increase in drying air temperature when the side mirrors were attached to the solar collector at 45° to the vertical. The results were compared with traditional method of open air drying. The results indicate that these dryers have good performance. The dryer is cost effective, easy to build and require only semi-skilled labor and limited facilities to fabricate. Thus, the dryer is suitable for use in rural areas of Nigeria where subsistence farming is highly concentrated. The large scale fabrication of the semi-active solar dryer will greatly enhance the storage of agricultural produce especially during the opulent harvesting periods and subsequently increase food availability. Solar food drying is fast, safe and low-cost process.

Table 6. Moisture Content in % for yam samples

	4 mm test samples
Moisture content (%)	66.78

REFERENCES

Amir, E.J., Grandegger, K. E, A. Sumarsono, M. D, and Mühlbauer W., (1991), Development of a multi-purpose solar tunnel dryer for use in humid tropics, *Renewable Energy*, 1 (2): 167-176.

Ekechukwu, O. V and Norton, B., (1997), Design and measured performance of a solar chimney for natural-circulation solar-energy dryers, *Renewable Energy*, 10 (1):81-90.

Gbaha, P., YobouetAndoh, H., KouassiSaraka, J., KamenanKoua, B. and Toure, S.(2007), Experimental investigation of a solar dryer with natural convective heat flow, *Renewable Energy*, 32:1817-1829.

Jensen, S. O., Frank, F. C. and Kristensen, E. F., (2002), *Survey on solar dryers for drying of food and wood in Ghana*, Solar Energy Centre Denmark and Wood Technology, Danish Technological Institute and Department of Agricultural Engineering, Danish Institute of Agricultural Sciences.

Pangavhane, D. R., Sawhney, R. L and Sarsavadia, P. N., (2002), Design, development and performance testing of a new natural convection solar dryer, *Energy*, 27: 579-590.

Sacilik, K., Keskin, R. and Elicin, A. K. (2006), Mathematical modeling of solar tunnel drying of thin layer organic tomato, *Journal of Food Engineering*, 73 (3): 231-238.