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Performance Evaluation of Solar Chimney Dryer for Rural Farmers Using Koko Vine

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Abstract *- The performance efficiency of a solar chimney dryer using Koko vine for rural farmers is evaluated and the results compared with open-sun drying. The solar dryer consists of the solar collector and the chimney drying chamber with four trays with dimensions of 100 x 70 x 20 cm^3 and 100 x 70 x 50 cm^3 respectively. The solar chimney dryer was used to dry Koko vine for three days at Uyo (Latitude 5°2′60N and Longitude 7°55′60E). The results show a reduction in mass from 23.00kg to 11.10kg and from 23.00kg to 11.10kg for dryer and open-sun drying respectively. The results also show that the moisture content left in Koko vine after drying was 13.28% in the dryer and 13.95% in the open-sun. The solar chimney dryer efficiency using Koko vine was about 51.70%. This efficiency is very good and can be higher under non-experimental conditions.*

Keywords - solar chimney dryer, open-sun drying, solar collector, dryer efficiency

1. INTRODUCTION

Open-sun drying and smoking was virtually the only method of food preservation until solar drying was developed in Nigeria; this method of food preservation is the most effective, particularly in the rural areas where poverty is highly prevalent. Drying is an excellent way to preserve foods that can add variety to meals and provide delicious and nutritious snacks like Koko vine (*eru* vegetable). Drying Koko vine by solar energy is of great economic importance especially in rural areas where most of the crops harvested are lost due to fungal and microbial attacks (Itodo et al., 2002). These wastages could be prevented by proper drying which enhances storage (Twidell and Weir, 1986). Preserving Koko vine by solar drying requires only the heat of the sun. In the process of drying, heat is necessary to evaporate moisture from the food item and a flow of air helps in carrying away the evaporated moisture. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of individual food items to the surface, and the evaporation of moisture from the surface to the surrounding air (Youcef-Ali et al., 2001). The drying of a product is a complex heat and mass transfer process which depends on external variables such as temperature, humidity and velocity of the air stream and internal variables characteristics (rough or smooth surface), which depend on parameters like surface chemical composition (sugars, starches, etc), physical structure (porosity, density, etc.), and size and shape of product (Gatea, 2011). In rural areas, conventional sources of energy are totally absent for the development of active dryers which have higher rates of performance. There is therefore a need for low temperature passive solar chimney dryers to be used for drying vegetables like Koko vine at low temperature and high relative humidity period of the year. One obvious advantage of low temperature drying is that it enables Koko vine to be dried evenly without burning and hence minimizes the exposure of the Koko vine to fungal and bacterial infection and wastages (Forson et al., 2007). This method is very suitable for bulk drying for long-term storage. The objective of this work is to evaluate the performance of a low temperature solar chimney dryer using Koko vine at high relative humidity.

1.1 Energy Balance Model:

This model assumes semi-steady state conditions in the collector. The temperature in the plate heat pipe is considered to be uniform and equal to the saturation temperature, since heat pipes are considered as isothermal devices (Duffie and Beckman, 1974). The energy balance equation on the glass cover is given as

$$\alpha_1 I + \sigma \frac{T_{sat}^4 - T_c^4}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_p} - 1} + h_{p-c}\left(T_{sat} - T_c\right) = \varepsilon_c \sigma \left(T_c^4 - T_{sky}^4\right) + h_w\left(T_c - T_a\right) \quad (1)$$

where I is the incident solar radiation on collector tilted surface [Wm-2],   is the absorptance,   is the Stefan-Boltzmann constant [Wm-2K-4], T is temperature [K],   is the emissivity, h is heat transfer coefficient [Wm-2K-1], c is cover, a is ambient, w is wind, p-c is plate-to-cover and sat is saturation. The energy balance equation on the plate is given as

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$$\alpha_p \tau_c I A_c = \sigma A_p \frac{T_{sat}^4 - T_c^4}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_p} - 1} + h_{p-c} A_p (T_{sat} - T_c) + U_{back} A_{back} (T_{sat} - T_a) + A_{cond} h_{cond} \frac{(T_{sat} - T_{in}) - (T_{sat} - T_{out})}{\ln \frac{(T_{sat} - T_{in})}{(T_{sat} - T_{out})}} \quad (2)$$

where *out* is outlet, *cond* is condenser, *A* is area [m^2], τ is transmittance and *U* is the overall loss coefficient [Wm^{-2}K^{-1}]. The energy balance on the condenser is given as

$$\dot{m} c_p (T_{out} - T_{in}) = A_{cond} h_{cond} \frac{(T_{sat} - T_{in}) - (T_{sat} - T_{out})}{\ln \frac{(T_{sat} - T_{in})}{(T_{sat} - T_{out})}} - A_{cond} U_{back} \frac{(T_{in} - T_a) - (T_{out} - T_a)}{\ln \frac{(T_{in} - T_a)}{(T_{out} - T_a)}} \quad (3)$$

where $\dot{m}$ is the mass flow rate [kgs^{-1}] and c_p is the pressure specific heat [Jkg^{-1}K^{-1}]. The useful heat collected is given by

$$\dot{Q} = m c_p (T_{out} - T_{in}) = IA(\tau_c \alpha_p) - UA(T_p - T_a) \quad (4)$$

where $\dot{Q}$ is the useful energy gain [W], From Hottel-Whillier-Bliss equation, (Hottel and Whillier, 1955; Bliss, 1959) where F$'$ is the collector efficiency factor, which is the ratio of the actual useful energy gain to the useful gain that would result if the collector absorbing surface was at the temperature of the fluid, then

$$\dot{Q} = F' IA(\tau_c \alpha_p) - F' UA(T_{fm} - T_a) \quad (5)$$

The collector efficiency expresses the fraction of incident energy that is collected by the working fluid:

$$\eta = \frac{\dot{Q}}{IA} = F'(\tau_c \alpha_p) - \frac{F' U (T_{fm} - T_a)}{I} \quad (6)$$

where η is collector efficiency and *fm* is fluid mean (i.e. inlet + outlet)/2.

1.2 Design Calculations

Declination (δ): This is the angle between the sun's direction and the equatorial plane and is given by (Forson et al., 2007) as,

$$\delta = 23.45 \sin [0.9863 (284 + n)] \quad (6)$$

where (n) is the day number of the year from n = 1 to n = 365. The declination for Uyo is -2.82°.

Optimum Collector Slope (β): The optimum collector slope, (β) is determined from

$$\beta = \delta + \varphi \quad (7)$$

where (δ) is the angle of declination for Uyo, Nigeria and (φ) is the latitude of the Uyo, Nigeria. The optimum collector slope for Uyo is 2°44ʹ.

Collector Efficiency (η): The collector efficiency (η) is computed from

$$\eta = \frac{\rho V c_p \Delta T}{A I_c} \quad (8)$$

where (ρ) is the density of air (kgm^{-3}), (I_c) is the insolation on the collector, (ΔT) is the temperature elevation, (c_p) is the specific heat capacity of the air at constant pressure (Jkg^{-1}K^{-1}), (V) is the volumetric flow rate (m^{3}s^{-1}), and (A) is the effective area of the collector facing the sun (m^2).

Drying Efficiency (η_d): The drying efficiency η_d is given by (Twidell and Weir, 1986; and Henry and Price, 1999) as

$$\eta_d = \frac{ML}{I_c A t} \quad (9)$$

where (L) is the latent heat of vaporization of water, (M) is the mass of the crop and (t) is the time of drying.

Rate of Heat Flow into the Dryer: This is the sum of the convective heat (q_c), conductive heat (q_k) and radiative heat (q_r) transfers (Twidell and Weir, 1986; Research and Education Association, 1999) i.e.

$$q = q_c + q_k + q_r \quad (10)$$

$$\frac{q}{A} = \frac{T_a - T_d}{\frac{1}{h_a} + \frac{\Delta x}{k} + \frac{1}{h_d}} + \varepsilon\sigma(T_a^4 - T_d^4) \quad (11)$$

where q/A is the rate of heat transfer per unit area, h_a is the heat transfer coefficient for the dryer chamber, T_a is the ambient temperature, T_d is the chamber temperature, σ is Stefan-Boltzmann constant, Δx is the thickness of the glass cover, A is the effective area of the collector, and ε is the emissivity.

Heat Energy Q needed for Crop Drying at Moderate Temperature: This is given by $Q = M_w L = \rho c_p V (T_a - T_b)$ (12)

where L is the latent heat of vaporization of water, M_w is the mass of crop before drying, ρ is the density of water, T_a is the ambient temperature, and T_b is the dryer temperature.

Moisture Content (MC): The moisture content is given as

$$MC(\%) = \frac{M_i - M_f}{M_i} \, x \, 100\% \quad (13)$$

where M_i is the mass of sample before drying and M_f is the mass of sample after drying.
Moisture Loss (ML): The moisture loss is given as

$$ML = (M_i - M_f) \quad (14)$$

where M_i is the mass (in g) of the sample before drying and M_f is the mass of the sample after drying.
Length of the Day (N): The length of the day is given by (Duffie and Beckman, 1974; Twidell and Weir, 1986; and Henry and Price, 1999) as

$$N = \left(\frac{2}{15}\right)\cos^{-1}(-\tan\varphi\tan\delta) \quad (15)$$

2. MATERIALS AND METHOD

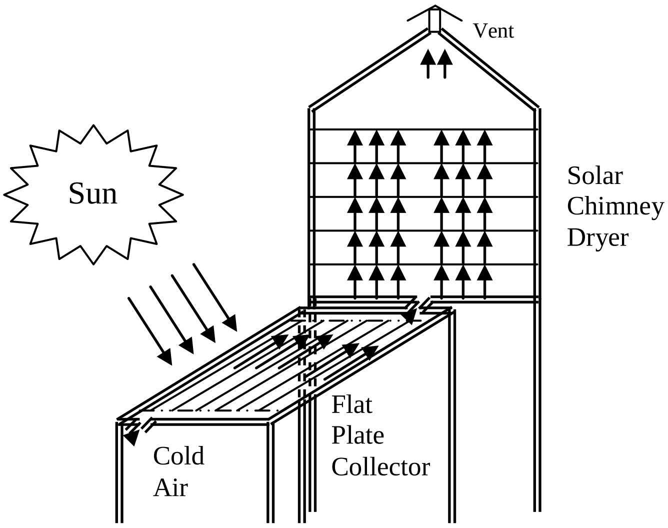

Fig. 1: Solar Chimney Dryer

The solar chimney used was made of four lengths of single iron bars, two length of 5.08m steel pipe, two sheets of 1.5mm steel plate, Perspex glass of 100 x 70cm^2, 100 x 50cm^2, wire mesh, four racks and a solar collector of 1.00m x 0.70m x 0.20m tilted 45° facing South, Fig.1. *Koko vine* of about 23.00kg was washed and sliced to pieces. It was then soaked in a 5M solution of common salt for 5 to 10 minutes. Salt was used only as a seasoning, not as a preservative. The *Koko vine* was weighed and placed on the racks. During drying the *Koko vine* was turned over occasionally to maintain uniform drying. From the Energy Balance Model (Duffie and Beckman, 1974), semi-steady state conditions were assumed. Two thermocouples were positioned at the inlet and outlet portions of the solar collector and chimney dryer to measure the air temperature. The ambient temperature was recorded using a mercury thermometer. The experiment was carried out at Uyo, Akwa Ibom State, Nigeria (Latitude 5°2′60N and Longitude 7°55′60E) (Anon., 2011). The finished product was hard, brittle and dry.

3. RESULTS AND DISCUSSION

The results obtained were presented as shown in Fig.2 to Fig.7, respectively showing change in temperature and weight loss for the three days of drying. The differences in the hours of drying from day one to three are due to logistics for day one, for day two the drying was for the whole day and for day three the *Koko vine* was completely dry before the end of the day.

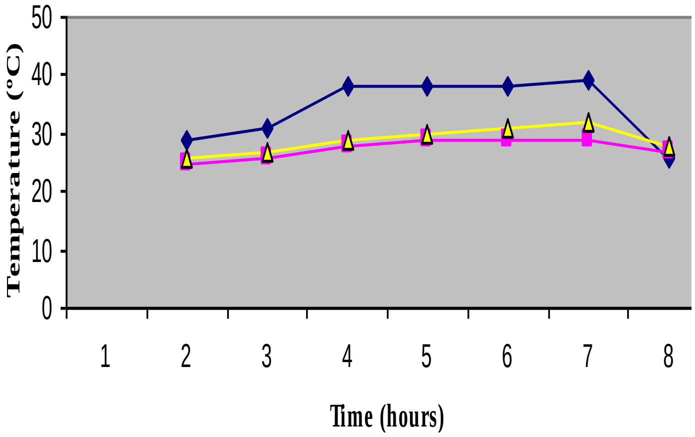

Fig. 2: System Temperature –Day One

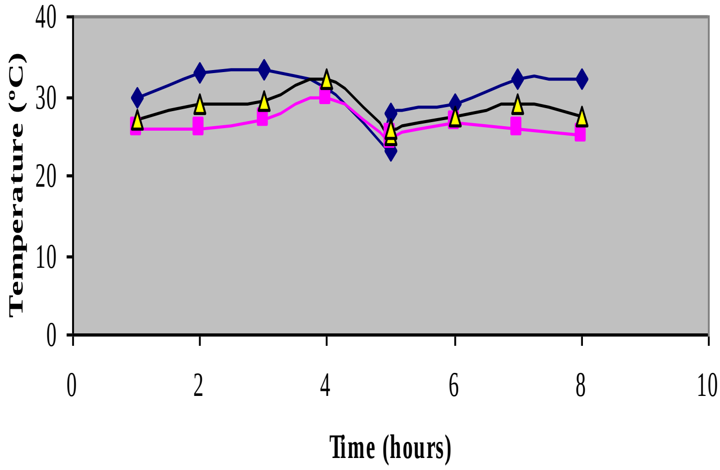

Fig. 3: System Temperature – Day Two

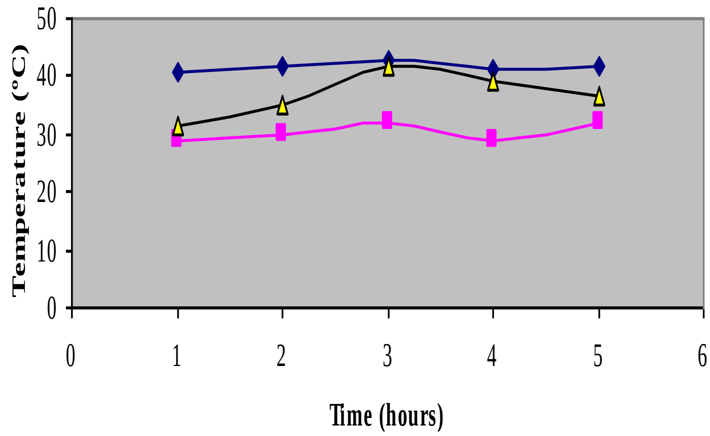

Fig. 4: System Temperature – Day Three

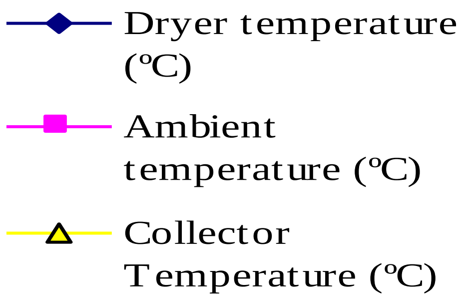

Fig. 5: Key to Figs. 2, 3, 4

The results indicate that the dryer temperature was higher than the ambient temperature but lower than the collector temperature during the three days, the minimum and maximum temperatures were 29°C and 43°C for the dryer, 25°C and 32°C for the ambient and 26°C and 36.5°C for the collector, respectively. The highest temperatures occur at 1:00 PM. The average drying temperatures were 34.1°C, 33.9°C and 41.7°C for day 1, day 2 and day 3, respectively.

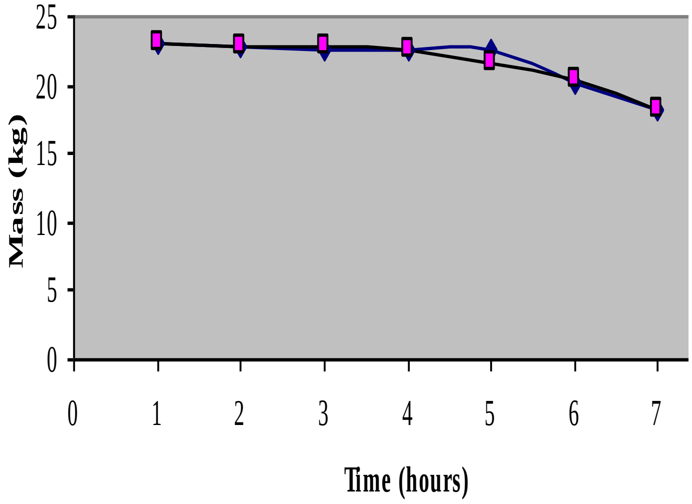

Fig. 6: Weight Loss – Day One

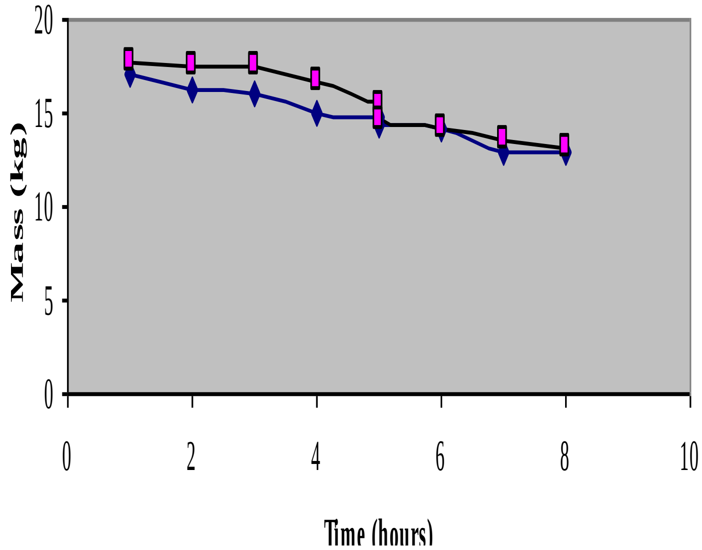

Fig. 7: Weight Loss – Day Two

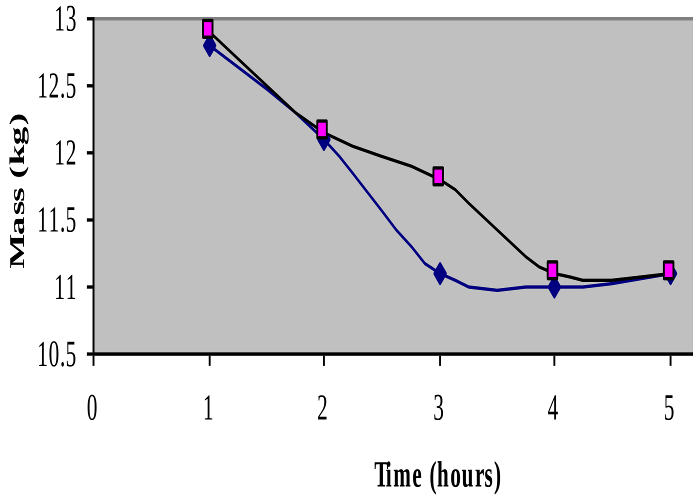

Fig. 8: Weight Lost – Day Three.

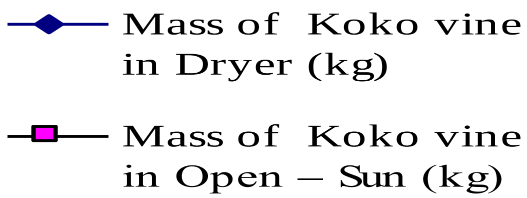

Fig 9: Key to FIG 6, 7, 8

The average weight loss for *Koko vine* in the dryer and open-sun were 4.80kg and 4.70kg for day 1, 4.15kg and 4.60kg for day 2, 1.70kg and 1.80kg for day 3 respectively. The results obtained also reveal that the moisture content left in *Koko vine* after three days was 13.28% in the dryer and 13.95% in the open-sun. Properly dried food has a moisture content which varies from 5% to 25% depending on the food as reported by Whitefield (2000), so the *Koko vine* was properly dried for long term storage. The solar chimney dryer efficiency was about 51.70%. This is lower than the actual because the dryer was opened at the top of each hour to collect the sample for weighing; this is in accordance with the study carried out by Ojike et al. (2010) and Wansah et al. (2011). The final mass of the *Koko vine* was 11.10kg. The *Koko vine* in the dryer attained a lower final mass than that in the open sun.

4. CONCLUSION

The performance efficiency of a solar chimney dryer using *Koko vine* for rural farmers at Uyo has been evaluated. The amount of moisture content decreased progressively to a minimum in the dryer due to the flow of dry warm air and the amount of insolation on the solar collector. The solar chimney dryer efficiency was good especially as the dryer was opened hourly to take measurements. The colour of dried *Koko vine* in the solar chimney dryer was brown with the taste and flavour enhanced. The solar chimney dryer is therefore recommended to rural farmers to enhance and utilize the free solar energy resource found abundantly in Akwa Ibom State which is within the tropics.

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