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Performance Evaluation of a Solar Wind-Ventilated Cabinet Dryer

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Abstract: *This work is an attempt to utilise the benefits of using forced convection solar dryers through the use of a rotary wind ventilator in the remote areas where electricity and other power sources are non-existent. The solar wind-ventilated cabinet dryer was designed, constructed and tested in Nigeria on latitude* 7.5^{o} *N. The results obtained show that the temperatures inside the dryer and the air-heater were higher than the ambient temperature during most hours of the day-light. The drying of food items in the dryer was compared with open air-drying of similar items. Comparatively, drying with the solar cabinet dryer showed better results than open air-drying. The results also revealed the dependence of the dryer performance on the proper air circulation through the system. The system efficiency increased as the air velocity through the system increased. During the period of test, the average air velocity through the solar dryer was 1.62 m/s and the average daylight efficiency of the system was 46.7%.*

Keywords: *Solar energy, cabinet dryer, wind-ventilator; open air-drying*

Nomenclature

A	total collector area (m^2)
C	specific heat at constant pressure (kJKg^{-1}K^{-1})
D	diameter (m)
F_R	heat removal factor for a single collector
G	mass velocity of air (Kgs^{-1}m^{2})
h_c	convective heat transfer coefficient (Wm^{-2}K^{-1})
h_r	radiative heat transfer coefficient (Wm^{-2}K^{-1})
I	incident insolation (Wm^{-2})
k	thermal conductivity (Wm^{-1}K^{-1})
L	length of solar collector (m)
m	mass flow rate (kgs^{-1})
Nu	Nusselt number
Pr	Prandtl number
Q_L	rate of load (W)
Q_u	rate of heat collection (W)
Re	Reynolds number
t	temperature (K)
U	heat loss coefficient (Wm^{-2}K^{-1})
W	width of air heater (m)
y	coordinate along collector length

***Greek*:**

α	solar absorptance
η	efficiency
τ	transmittance
μ	dynamic viscosity of air (kg m^{-1}s^{-1})

***Subscripts*:**

1	first plate (glass cover)
2	second plate (absorber mesh screen)
3	third plate (absorber back plate)
a	ambient
b	back
d	drying
f	fluid (air)
H	hydraulic
i	inlet
o	outlet
t	top

1. Introduction

Many farmers of the world are faced with the problem of reducing the moisture content of their harvested crops to prevent spoilage during storage. The situation is worse for farmers in the rural areas of developing countries where there is no access to electricity and harvested crops are often stored in heaps. Most of the harvested crops are susceptible to deterioration due to poor preservation.

According to Itodo et al. (2002) and Bolaji (2005), moisture contributes greatly to the deterioration of agricultural products particularly in the tropics. When crops are harvested, the amount of moisture they contain is of little consequence if the crops are to be consumed immediately, but if the crops are to be stored for a reasonable length of time, it is essential that its moisture level be reduced to a certain well-defined limit. These will prevent the production of undesirable chemical compositional changes in the food items by bacteria, mould and enzymes which will spoil the food items

(Bolaji, 2008; Habou et al., 2003).

Drying is the reduction of moisture from the products and is a most important process for preserving agricultural products since it has a great effect on the quality of the dried products. Drying of fruit and vegetables is one of the oldest methods of food preservation. The major objective in drying agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended period. In addition, drying enhances the storability, transportability, nutritional value retention, flavour and texture of food products (Hussain and and Islam-ud-Din, 2008; Akpinar, 2010).

Artificial dryers have long been in existence. They are used for the preservation of a wide variety of agricultural products; some of these artificial dryers are powered electrically or by natural fuels (Ertekin and Yaldiz, 2004; Giri and Prasad, 2007; Ajao and Adegun, 2009; Yesilata and Aktacir, 2009). However, the ever-rising cost of electricity and natural fuels coupled with growing concern about their availability in both the short and long terms, has resulted in growing interest in the use of renewable resources especially solar energy; in both direct and indirect forms (Adaramola et al., 2004; Koua et al., 2009).

Drying of agricultural products such as corn, rice, millet, beans, sorghum, groundnut, pepper, okro, yam and plantain chips requires a considerable amount of energy, which must be available when the crop is harvested. The application of solar energy in drying of agricultural products has tremendous potential, since it can easily provide the low temperature heating required for drying. Drying processes using solar energy range from traditional open sun drying to solar dryers. The climatic conditions during harvest season in some areas may be such that unheated or natural air can be used to reduce the moisture content in the crop to safe storage moisture. This natural air (open sun) drying is practiced widely in tropical countries (Itodo et al., 2002; Togrul and Pehlivan, 2004; Bolaji, 2005). Considerable savings can be obtained with this type of drying since the source of energy is free and renewable.

However, the natural air drying technique has the problems of contamination, infestation, microbial attack, and the required drying time for a given commodity can be quite long. Where feasible, solar drying often provides the most cost-effective drying technique which uses the energy from the sun to heat a stream of air to provide air with greater drying potential which in turn flows by natural or forced convection through a bed of the product to be dried. Since the material is contained there is less contamination and it is less susceptible to adverse weather conditions (Waewsak, et al., 2006; Bolaji and Olalusi, 2008; Akbulut and Durmus, 2010).

Many dryers have been developed, designed and tested. Arinze (1985a) designed and evaluated an indirect crop dryer with an integrated thermal storage system for deep-bed drying of grains. Airflow rate of 40 $kgh^{-1}m^{-2}$ and 5.6 m^2 of collector area per m^3 of dryer were recommended. The study revealed that there is not much to be gained by multiple-layered covering of solar collectors in a tropical weather and that glass remains the best cover material.

Arinze (1985b) presented the results of a 10-ton commercial size direct natural convection solar crop dryer with a chimney incorporated. It was concluded that over 50% saving in time could be achieved by using the solar dryer as against the natural air sun drying method, and recommended the use of low-pressure fans at the inlet or outlet section of the dryer where power supply is possible so as to achieve faster drying rates.

Montero et al. (2010) designed, constructed and tested solar dryer of various operation modes (indirect, mixed, passive, active, and hybrid) for drying agro-industrial by-products. The most efficient operation mode was the forced-hybrid one, followed by the passive and active modes. 50% reduction in the drying time was obtained using forced-hybrid modes.

Bala et al (2009) investigated the performance of solar tunnel dryer for drying mushrooms. The dryer consists of a transparent UV stabilised plastic covered flat plate collector and drying tunnel unit. The drier is arranged to supply hot air directly into the drying tunnel using three dc fans powered by a 40 watt solar module. During the test, the temperatures in the drying chamber varied from 37.0^oC to 66.5^oC and the mushrooms were dried from about 89.41% to 6.14% moisture content (w.b) in about 8 hours of effective sunshine.

Falade et al. (1985) discussed the analysis of a solar grain dryer for rural areas of Nigeria. This was an indirect passive dryer, with chimney used for deep-bed drying of corn. The temperature of the air entering into the bin to dry the grains was capable of heating air in the bin by about 6-15^0C. The dryer had a rate of 3 - 8 kgh^{-1} on a fairly clear day.

Oosthuizen (1997) presented the study of a simulated indirect laboratory-scale solar rice dryer fitted with a small fan. The dryer had a collector area of $0.57m^2$ and a drying chamber volume of 1.27 m^3. Drying rate of more than twice that of a passive dryer was obtained with a fan power of less than 2 watt. Itodo et al. (2002) designed and evaluated a solar crop dryer for rural application in Nigeria. The use of low-pressure fans at the inlet or outlet section of the dryer was recommended where power supply is possible so as to achieve faster drying rates.

In all these reviews, it can be deduced that to achieve better drying rates, a proper circulation of heated air through the dryer is required. In the developing countries, the agricultural practice of drying is mostly undertaken in the rural areas where electricity does not exist to power the fan. In this study a rotary wind ventilator was incorporated into the dryer, to increase the rate of air circulation through the dryer. Also presented in this work is the detailed explanation of the design, construction and performance evaluation of the solar cabinet dryer.

2. Materials and Methods

2.1 Theoretical Considerations

The cross-sectional view of the air-heater (collector) of solar cabinet dryer is shown schematically in Figure 1. The steady-state energy balance equations for the air-heater are presented below (Dhiman et al., 2011):

$$I\alpha_1 + (h_{r\,21} + h_{c21})(t_2 - t_1) = U_t(t_1 - t_a) \qquad \text{.....}Eq.1$$

where I = incident insolation (Wm^{-2}); α_1 = solar absorptance of the glass cover; h_{r21} = radiative heat transfer coefficient from mesh screen to glass cover ($Wm^{-2}K^{-1}$); h_{c21} = convective heat transfer coefficient from mesh screen to glass cover ($Wm^{-2}K^{-1}$); t_1 = glass cover temperature (K); t_2 = mesh screen temperature (K); t_a = ambient air temperature (K); and U_t = top heat loss coefficient ($Wm^{-2}K^{-1}$).

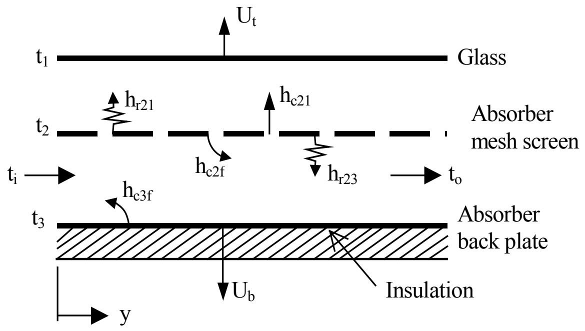

Figure 1. Cross-sectional view of the solar air-heater

For absorber mesh screen:

$$I\tau_1\alpha_2 = (h_{r21} + h_{c21})(t_2 - t_1) + h_{r23}(t_2 - t_3) + h_{c2f}(t_2 - t_f) \qquad \text{.....}Eq.2$$

where τ_1 = transmittance of the glass cover; α_2 = solar absorptance of the mesh screen; h_{r23} = radiative heat transfer coefficient from mesh screen to back plate ($Wm^{-2}K^{-1}$); h_{r2f} = forced convective heat transfer coefficient from mesh screen to the flowing air ($Wm^{-2}K^{-1}$); t_3 = back plate temperature (K); and t_f = flowing fluid temperature (K).

For absorber back plate:

$$h_{r23}(t_2 - t_3) = h_{c3f}(t_3 - t_f) + U_b(t_3 - t_a) \qquad \text{......}Eq.3$$

where h_{r3f} = forced convective heat transfer coefficient from back plate to the flowing air ($Wm^{-2}K^{-1}$); and U_b = bottom heat loss coefficient ($Wm^{-2}K^{-1}$).

For air flow:

$$\frac{m \cdot C_f}{W} \cdot \frac{dt_f}{dy} = h_{c2f}(t_2 - t_f) + h_{c3f}(t_3 - t_f) \qquad \text{......}Eq.4$$

where m = mass flow rate (kgs^{-1}); C_f = specific heat of flowing air at constant pressure ($kJkg^{-1}K^{-1}$); W = width of air heater (m); and y = coordinate along collector length.

The boundary conditions for the above equations are $t_f = t_i$ at $y = 0$; $t_f = t_o$ at $y = L$, L is the length of the air heater. These equations were solved for the outlet air temperature t_o; and the efficiency (η) was obtained by using the relation:

$$\eta = \frac{mC_f(t_o - t_i)}{I} \qquad \text{......}Eq.5$$

where t_i = air inlet temperature (K); and t_o = air outlet temperature (K).

Heat transfer coefficients:

The top heat loss coefficient, U_t (which is the summation of radiative and wind-related convective heat loss coefficients), from the glass cover to the ambient; the radiative, h_{r21}, and convective, h_{c21}, heat loss coefficient from the absorber mesh screen to the glass; the coefficient of radiative heat transfer exchange between the absorber mesh screen and the absorber back plate, h_{r23} and the back heat loss coefficient, U_b, were computed by using the relations given in Duffie and Beckman (1991). The forced convective heat transfer coefficients, h_{e2f} and h_{c3f} were obtained by using Equation 6 (Tripathy and Kumar, 2009):

$$h_{c2f} = h_{c3f} = \frac{Nu_H k_f}{D_H} \qquad \text{.....}Eq.6$$

where,

$$Nu_H = 0.0333\, Re_H^{0.8}\, Pr^{1/3} \qquad \text{......}Eq.7$$

$$\mathrm{Re}_H = \frac{GD_H}{\mu} \qquad \text{.....}\ Eq.8$$

D_H = hydraulic diameter (m); k_f = thermal conductivity of the flowing air ($Wm^{-1}K^{-1}$); Nu_H = hydraulic Nusselt number; Pr = Prandtl number; G = mass velocity of air ($kgs^{-1}m^2$); Re = Reynolds number; and μ = dynamic viscosity of air ($kg\ m^{-1}s^{-1}$).

The rate of energy collection:

The convective drying processes can be expressed by the following relation

$$Q_L = mC_f\left(t_d - t_a\right) \qquad \text{......}Eq.9$$

where, Q_L = rate of load (W); and t_d = drying temperature (K).

The heat delivered by the collector is given by the Hottel-Whillier-Bliss equation (Duffie and Beckman, 1991; Karim and Hawlader, 2006):

$$Q_u = AF_R\left[I\tau\alpha - U_L\left(t_i - t_a\right)\right] \qquad \text{.....}Eq.10$$

where, Q_u = rate of heat collection (W); A = total collector area (m^2); F_R = heat removal factor for a single collector. Since the collector draws the ambient air directly, the last on the right-hand side vanishes and the rate of energy collection is simply:

$$Q_u = AF_R I\tau\alpha \qquad \text{.....}Eq.11$$

The rate of energy collection may also be expressed as:

$$\dot{Q}_u = mC_f(t_o - t_i) \qquad \text{.....Eq.12}$$

2.2 The Experimental Set -up

The solar wind-ventilated cabinet dryer was constructed in Nigeria on Latitude 7.5^0N, using the materials that are easily obtainable from the local market. Figure 2 shows the diagram of the solar cabinet dryer.

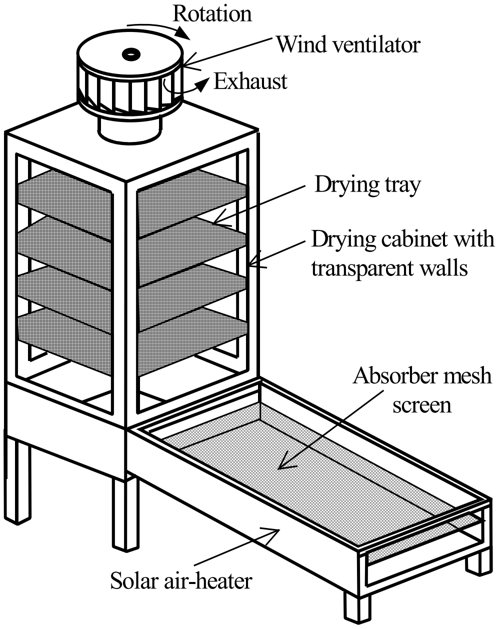

Figure 2. Solar wind-ventilated cabinet dryer

The solar air-heater of the dryer consists of an absorber back plate insulated with foam material of about 30 mm thick at the bottom and covered by transparent glass of 4 mm thick at the top. The air-heater is 420 x 980 x 150 mm in dimensions, is south-facing and tilted 17.5^0 to the horizontal so that it can take advantage of the maximum insolation. Air enters through the open end of the heater.

An absorber mesh screen midway between the glass cover 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 mesh provides an additional heat transfer surface area. The upper end of the air-heating collector is connected to the vertical drying chamber, which holds drying trays in layers.

Additional drying is also achieved from direct solar radiation incoming through the transparent walls. As shown in Figure 2, a rotary wind ventilator is located at the top for effective circulation of heated air through the cabinet dryer. The wind ventilator is a corrugated vane rotor, which sucks air from the ventilator stack as it spins. The cabinet dryer can be used to dry a wide variety of agricultural products on a small scale.

2.3 Experimental Procedure

In order to evaluate the performance of the wind-ventilated cabinet dryer, the temperature profile of the dryer was determined by measuring the hourly temperatures of the collector, drying chamber and the ambient between the hours of 08.00 and 17.00.

A thermometer was placed through the wall in the air heater and another in the drying cabinet. The ambient temperature was measured from a maximum and minimum thermometer and the relative humidity was obtained from psychometric chart. The air velocity through the dryer was measured with a portable hand anemometer. The incident solar radiation intensity was measured using a portable Kipps Solarimeter. Known weights of food items were dried until no further weight loss was attained and the time taken measured. Weight loss (moisture removed) from the item was measured hourly during the day. The rate of heat collection was calculated using Equation 12 and the efficiency of the system was calculated using Equation 5.

3. Results and Discussions

The hourly variation of the temperatures in air-heater and the drying cabinet compared to the ambient temperature for the first three days of drying are shown in Figures 3, 4 and 5, respectively. The hourly variation of the incident solar radiation is shown in Figure 6.

The dryer is hottest about mid-day when the sun is usually overhead. The temperatures inside the dryer and the air-heater are much higher than ambient temperature during most hours of the day-light. This indicates prospect for better performance than open air drying. The higher temperature observed inside the dryer is due to the additional heat received from direct solar radiation incoming through the transparent walls.

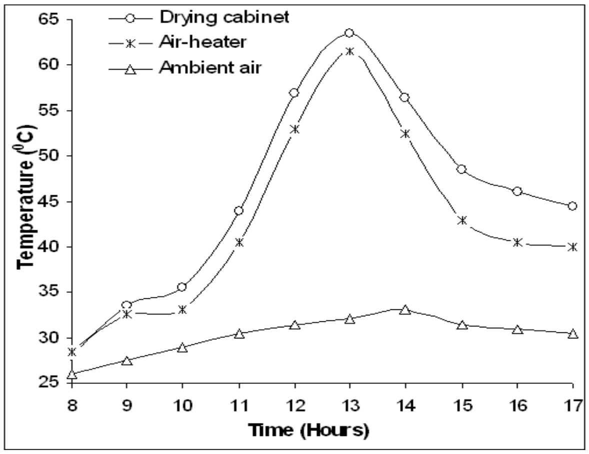

Figure 3. Diurnal variation of the temperatures in the solar dryer during the 1st day of the test

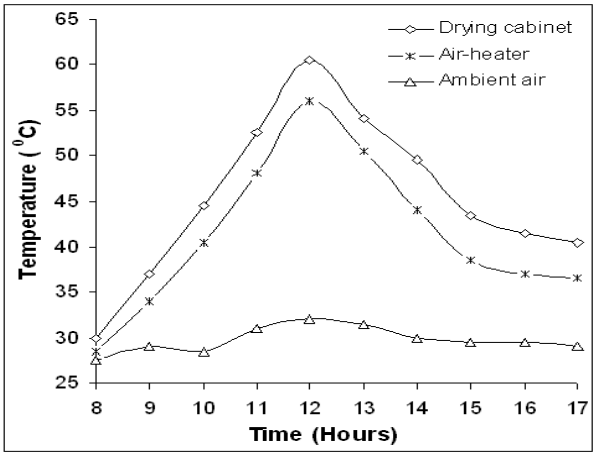

Figure 4. Diurnal variation of the temperatures in the solar dryer during the 2nd day of the test

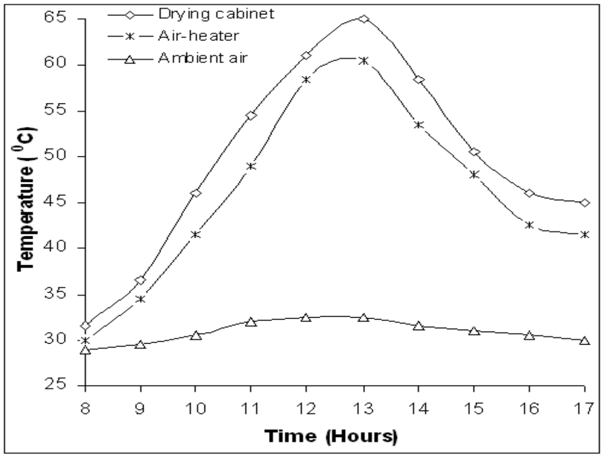

Figure 5. Diurnal variation of the temperatures in the solar dryer during the 3rd day of the test

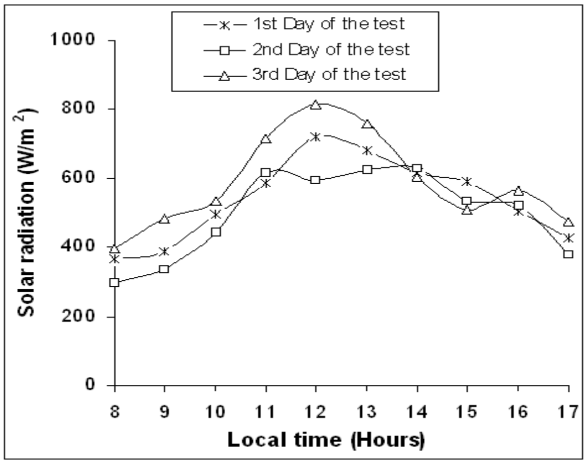

Figure 6. Diurnal variation of incident solar radiation for the first three days of the test

The results obtained in drying a fresh sample of local pepper and yam chips in the cabinet dryer and in the open air simultaneously are shown in Figures 7 and 8, respectively. For the two cases, it was observed that the products in the cabinet dryer dried faster than in the open air drying. It took the pepper in the cabinet solar dryer three days to achieve 80% weight loss and in the open air, eight days. Also, in case of yam chips, 55% weight loss was achieved in the dryer in three days compared with six days in the open air.

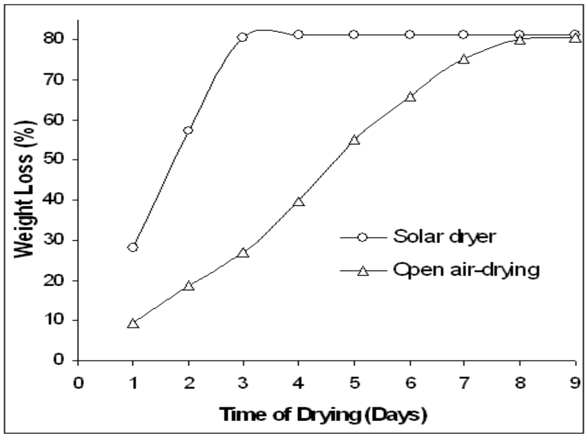

Figure 7. Drying of pepper in solar dryer compare with open air sun drying

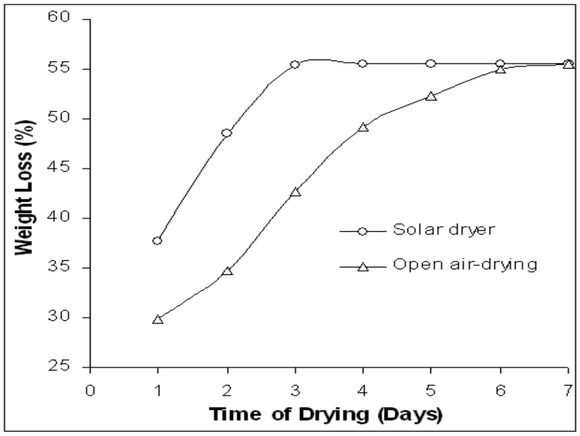

Figure 8. Drying of yam chips in solar dryer compare with open air sun drying

Figure 9 shows the effect of air velocity on the drying efficiency. The system drying efficiency increases as the air velocity increases. This clearly reveals the dependence of the dryer performance on the air velocity. The average air velocity through the solar dryer during the period of test was 1.62 ms^{-1} and the average day-light efficiency of the system was 46.7%. The solar dryer was also tested without rotary wind ventilator (with natural air circulation) and the average day-light efficiency obtained from the system was 31.2%.

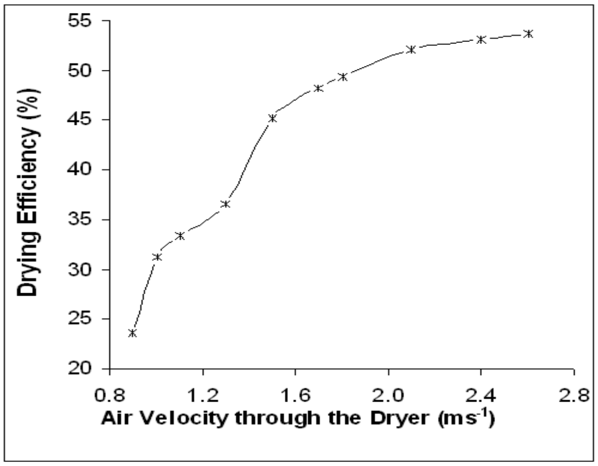

Figure 9. Variation of system efficiency with air velocity through the dryer

These results verified the high efficiency of the solar dryer with rotary wind ventilator when compared with forced convective solar crop dryer for rural application in Nigeria carried out by Itodo et al. (2002), and solar dryer with fin-type absorber air collector carried out by Matrawy (1998). The maximum efficiencies obtained from the two types of solar dryers were 10% and 36% respectively.

5. Conclusion

In this work, practical way of cheaply and sanitarily preserving food items by the use of solar dryer has been demonstrated. The fabrication of the dryer does not require high technology and once installed the maintenance cost is minimal. The dryer was tested and the following conclusions can be drawn based on the results obtained:

1) The maximum drying air temperatures was found to be 64°C inside the dryer.
2) The average drying air temperature in the drying cabinet was higher than the ambient temperature in the range of 5°C in the early hours of the day to 31°C at mid-day.
3) The average temperature in the drying cabinet was also found higher than that of the air-heater in the range of 2-5°C, which justified the additional heat received from direct solar radiation through the transparent walls.
4) 80% and 55% weight losses were obtained in the drying of pepper and yam chips, respectively, in the dryer.
5) In the two cases, the use of the dryer led to considerable reduction in drying time in comparison to the open sun drying.
6) The system efficiency increased as the air velocity increased.
7) The average day-light efficiencies obtained from the system with and without rotary wind ventilator were 46.7% and 31.2%, respectively, which justified the effect of the rotary wind ventilator installed in the system. This solar dryer compared favourably with the existing systems. The maximum efficiencies obtained in the two existing systems considered were 10% and 36%, respectively.

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