Performance Evaluation of a Mixed-Mode Solar Dryer

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Abstract

This paper presents the design, construction and performance evaluation of a mixed-mode solar dryer for food preservation. In the dryer, the heated air from a separate solar collector is passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls and roof. The results obtained during the test period revealed that the temperatures inside the dryer and solar collector were much higher than the ambient temperature during most hours of the day-light. The temperature rise inside the drying cabinet was up to 74% for about three hours immediately after 12.00h (noon). The drying rate and system efficiency were 0.62 kg/h and 57.5% respectively. The rapid rate of drying in the dryer reveals its ability to dry food items reasonably rapidly to a safe moisture level.

Keywords: *solar energy, dryer, mixed-mode, food preservation, performance evaluation.*

Introduction

In many parts of the world there is a growing awareness that renewable energy have an important role to play in extending technology to the farmer in developing countries to increase their productivity (Waewsak, *et al.* 2006). Solar thermal technology is a technology that is rapidly gaining acceptance as an energy saving measure in agriculture application. It is preferred to other alternative sources of energy such as wind and shale, because it is abundant, inexhaustible, and non-polluting (Akinola 1999; Akinola and Fapetu 2006; Akinola, *et al.* 2006).

Solar air heaters are simple devices to heat air by utilizing solar energy and employed in many applications requiring low to moderate temperature below 80°C, such as crop drying and space heating (Kurtbas and Turgut 2006). Drying processes play an important role in the preservation of agricultural products.

They are defined as a process of moisture removal due to simultaneous heat and mass transfer (Ertekin and Yaldiz 2004). According to Ikejiofor (1985) two types of water are present in food items; the chemically bound water and the physically held water. In drying, it is only the physically held water that is removed. The most important reasons for the popularity of dried products are longer shelf-life, product diversity as well as substantial volume reduction. This could be expanded further with improvements in product quality and process applications.

The application of dryers in developing countries can reduce post harvest losses and significantly contribute to the availability of food in these countries. Estimations of these losses are generally cited to be of the order of 40% but they can, under very adverse conditions, be nearly as high as 80%. A significant percentage of these losses are related to improper and/or untimely drying of foodstuffs such as cereal grains, pulses, tubers, meat, fish, etc. (Bassey 1989; Togrul and Pehlivan 2004)

Traditional drying, which is frequently done on the ground in the open air, is the most

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widespread method used in developing countries because it is the simplest and cheapest method of conserving foodstuffs. Some disadvantages of open air drying are: exposure of the foodstuff to rain and dust; uncontrolled drying; exposure to direct sunlight which is undesirable for some foodstuffs; infestation by insects; attack by animals; etc (Madhlopa, *et al.* 2002).

In order to improve traditional drying, solar dryers which have the potential of substantially reducing the above-mentioned disadvantages of open air drying, have received considerable attention over the past 20 years (Bassey 1989). Solar dryers of the forced convection type can be effectively used. They however need electricity, which unfortunately is non-existent in many rural areas, to operate the fans. Even when electricity exists, the potential users of the dryers are unable to pay for it due to their very low income. Forced convection dryers are for this reason not going to be readily applicable on a wide scale in many developing countries. Natural convection dryers circulate the drying air without the aid of a fan. They are therefore, the most applicable to the rural areas in developing countries.

Solar drying may be classified into direct, indirect and mixed-modes. In direct solar dryers the air heater contains the grains and solar energy passes through a transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed.

In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed, while in the mixed-mode type of dryer, the heated air from a separate solar collector is passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or roof. Therefore, the objective of this study is to develop a mixed-mode solar dryer in which the grains are dried simultaneously by both direct radiation through the transparent walls and roof of the cabinet and by the heated air from the solar collector. The performance of the dryer was also evaluated.

Theory, Materials and Methods

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,

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

where:

I = rate of total radiation incident on the absorber's surface (Wm^{-2});

A_c = collector area (m^2);

Q_u = rate of useful energy collected by the air (W);

Q_{cond} = rate of conduction losses from the absorber (W);

Q_{conv} = rate of convective losses from the absorber (W);

Q_R = rate of long wave re-radiation from the absorber (W);

Q_ρ = rate of reflection losses from the absorber (W).

The three heat loss terms Q_{cond}, Q_{conv} and Q_R are usually combined into one-term (Q_L), i.e.,

$$Q_L = Q_{cond} + Q_{conv} + Q_R. \qquad (2)$$

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

$$IA_c = \tau I_T A_c. \qquad (3)$$

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

$$Q_\rho = \rho\tau I_T A_c, \qquad (4)$$

where ρ is the reflection coefficient of the absorber. Substitution of Eqs. (2), (3) and (4) in Eq. (1) yields:

$$\tau I_T A_c = Q_u + Q_L + \rho\tau I_T A_c, \text{ or}$$

$$Q_u = \tau I_T A_c(1 - \rho) - Q_L.$$

For an absorber $(1 - \rho) = \alpha$ and hence,

$$Q_u = (\alpha\tau)I_T A_c - Q_L, \qquad (5)$$

where α is solar absorptance.

Q_L composed of different convection and radiation parts. It is presented in the following form (Bansal *et al.* 1990):

$$Q_L = U_L A_c(T_c - T_a), \qquad (6)$$

where:

U_L = overall heat transfer coefficient of the absorber ($Wm^{-2}K^{-1}$);

T_c = temperature of the collector's absorber (K);

T_a = ambient air temperature (K).

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

$Q_u = (\alpha\tau)I_T A_c - U_L A_c(T_c - T_a)$. (7)

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

$q_u = (\alpha\tau)I_T - U_L(T_c - T_a)$. (8)

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

$Q_g = \dot{m}_a C_{pa}(T_c - T_a)$, (9)

where:

$\dot{m}_a$ = mass of air leaving the dryer per unit time (kgs^{-1});

C_{pa} = specific heat capacity of air ($kJkg^{-1}K^{-1}$).

The collector heat removal factor, F_R, 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,

$$F_R = \frac{\dot{m}_a C_{pa}(T_c - T_a)}{A_c[\alpha\tau I_T - U_L(T_c - T_a)]} \quad (10)$$

or

$$Q_g = A_c F_R[(\alpha\tau)I_T - U_L A_c(T_c - T_a)]. \quad (11)$$

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

$$\eta_c = \frac{Q_g}{A_c I_T}. \quad (12)$$

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

$m_w L_v = m_a C_p(T_1 - T_2)$, (13)

where:

m_w = mass of water evaporated from the food item (kg);

m_a = mass of drying air (kg);

T_1 and T_2 = initial and final temperatures of the drying air respectively (K);

C_p = Specific heat at constant pressure ($kJkg^{-1}K^{-1}$).

The mass of water evaporated is calculated from Eq. 14:

$$m_w = \frac{m_i(M_i - M_e)}{100 - M_e}, \quad (14)$$

where:

m_i = initial mass of the food item (kg);

M_e = equilibrium moisture content (% dry basis);

M_i = initial moisture content (% dry basis).

During drying, water at the surface of the substance evaporates and water in the inner part migrates to the surface to get evaporated. The ease of this migration depends on the porosity of the substance and the surface area available. Other factors that may enhance quick drying of food items are: high temperature, high wind speed and low relative humidity. In drying grains for future planting, care must be taken not to kill the embryo. In drying items like fish, meat, yam chips, plantain chips etc., excessive heating must also be avoided, as it spoils the texture and quality of the item.

Construction of the Mixed-Mode Solar Dryer

The materials used for the construction of the mixed-mode solar dryer are cheap and easily obtainable in the local market. Fig. 1 shows the essential features of the dryer, consisting of the solar collector (air heater), the drying cabinet and drying trays.

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 40 mm thickness and thermal conductivity of 0.043 $Wm^{-1}K^{-1}$. The solar collector assembly consists of air flow channel enclosed by transparent cover (glazing). 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 glazing is a single layer of 4 mm thick transparent glass sheet; it has a surface area of 820 mm by 1020 mm and of transmittance above 0.7 for wave lengths in the rage 0.2 – 2.0 μm and opaque to wave lengths greater than 4.5 μm. The effective area of the collector glazing is 0.8 m^2. One end of the solar collector has an air inlet vent of area 0.0888 m^2, which is covered by a galvanized wire mesh to prevent entrance of rodents, the other end opens to the plenum chamber.

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 three 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 glass sheets of 4 mm thick, 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 17.5^o to the horizontal. This is approximately 10^o more than the local geographical latitude (Ado-Ekiti a location in Nigeria, 7.5^oN), which according to Adegoke and Bolaji (2000), is the best recommended orientation for stationary absorber. This inclination is also to allow easy run off of water and enhance air circulation.

Operation of the Dryer

Fig. 2 shows the isometric drawing of the mixed-mode solar 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 inside surfaces of the collector that were painted black and the trapped energy heats the air inside the collector. The green house effect 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 upper vent 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.

When the dryer contains no items to be dried, 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, $H_a > H_e$. Thus 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. Therefore, insulation received is principally used in increasing the affinity of the air in the dryer to pick moisture.

Dryer Performance Evaluation

The mixed-mode solar dryer shown in Fig. 2 was tested in the month of September, 2005 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 bulb thermometers (accuracy ± 0.5^0C) at regular interval of one hour between the hours of 0.800 and 18.00 local time. The solar intensity was measured by means of a portable Kipps Solarimeter placed at an inclination of 17.5^o facing south.

The dryer was loaded with yam chips (4 mm average thickness) 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 chips was attained, the weight loss was used to calculate the moisture removed in kg water/kg dry matter at intervals as the yam 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 (Itodo, *et al.* 2002):

$$\frac{dM}{dt} = \left(\frac{M_i - M_f}{t} \right) \times 100\% . \qquad (15)$$

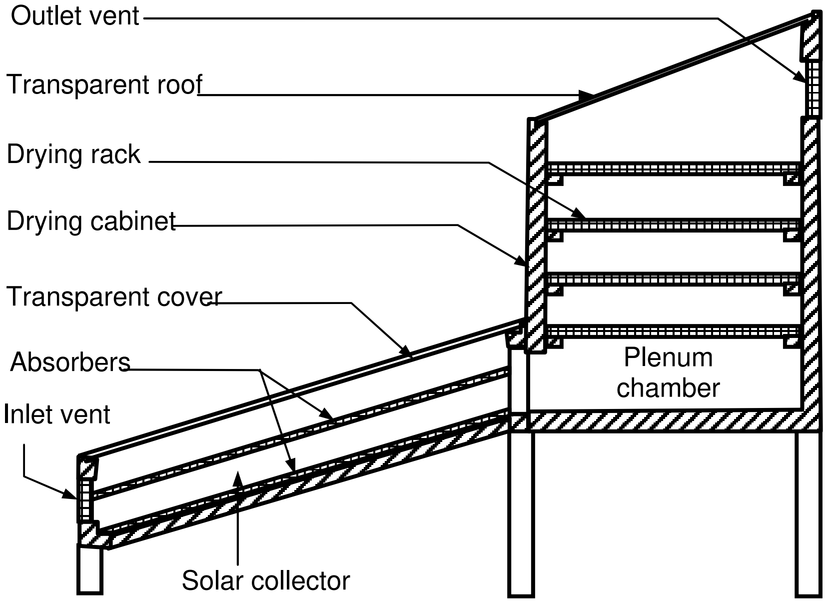

Fig. 1. Sectional view of the mixed-mode solar dryer.

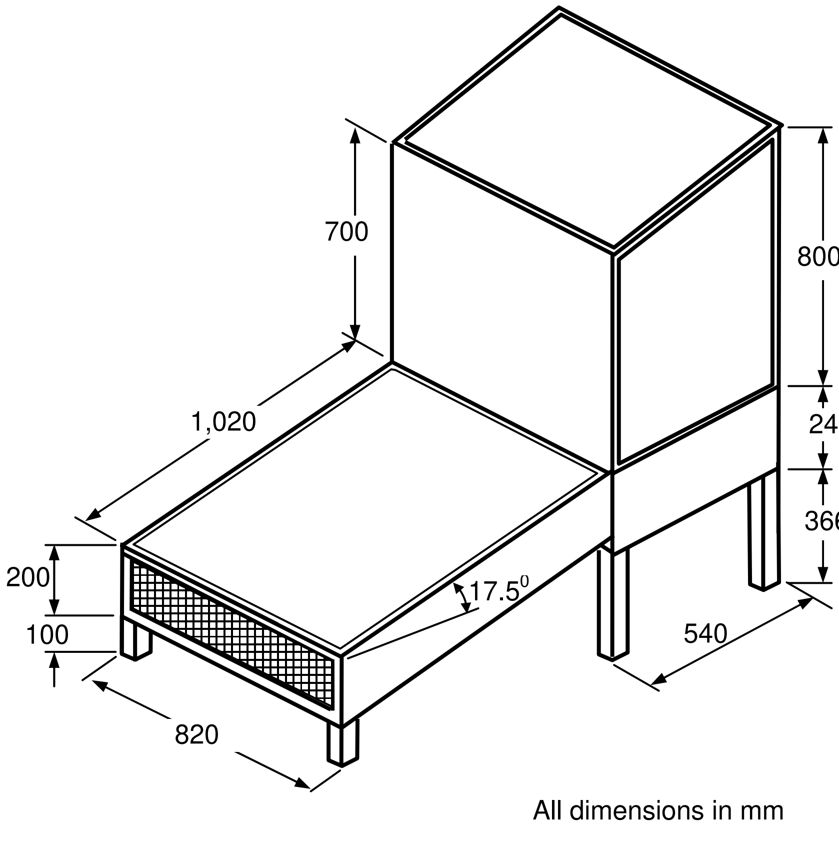

Fig. 2. Isometric drawing of the mixed-mode solar dryer.

Results and Discussion

Fig. 3 shows a typical day results of the hourly variation of the temperatures in the solar collector and the drying cabinet compared to the ambient temperature. The dryer is hottest about mid-day when the sun is usually overhead. The temperatures inside the dryer and the solar collector were much higher than the ambient temperature during most hours of the daylight. The temperature rise inside drying cabinet was up to 24°C (74%) for about three hours immediately after 12.00h (noon). This indicates prospect for better performance than open-air sun drying. Fig. 4 shows the diurnal variation of the relative humidity of the ambient air and drying chamber. Comparison of this figure with Fig. 3 shows that the drying processes were enhanced by the heated air at very low humidity.

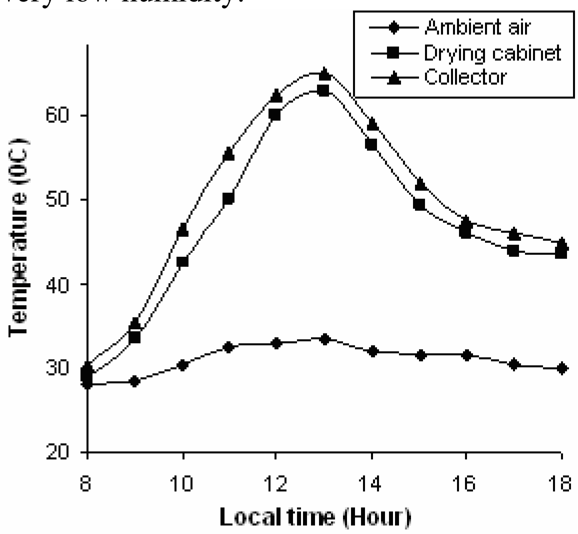

Fig. 3. A typical day results of the diurnal variation of temperatures in the solar dryer.

Fig. 5 shows the drying curve for yam chips in the mixed-mode solar dryer. It was observed that the drying rate increased due to increase in temperature between 10.00h and 14.00h but decreased thereafter, which shows the earlier and faster removal of moisture from the dried item. The dryer was able to remove 85.4% of moisture, dry basis, from 6.2 kg of yam chips in one day of 10.00h drying time, which is about 0.62 kg/h drying rate. The collector efficiency of the mixed-mode solar dryer during the test period was found to be 57.5%.

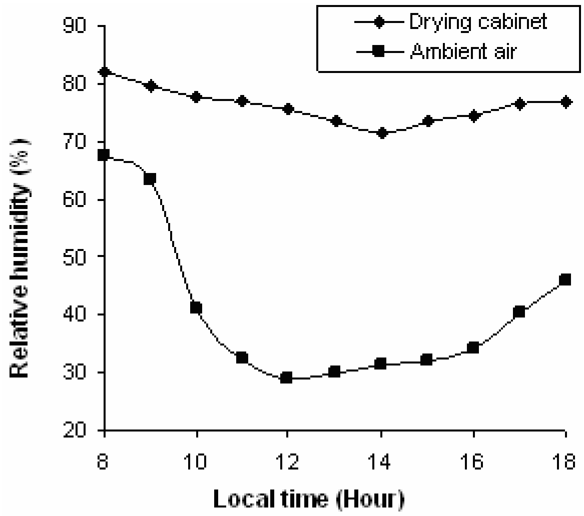

Fig. 4. A typical day results of the diurnal variation of relative humidity in the dryer.

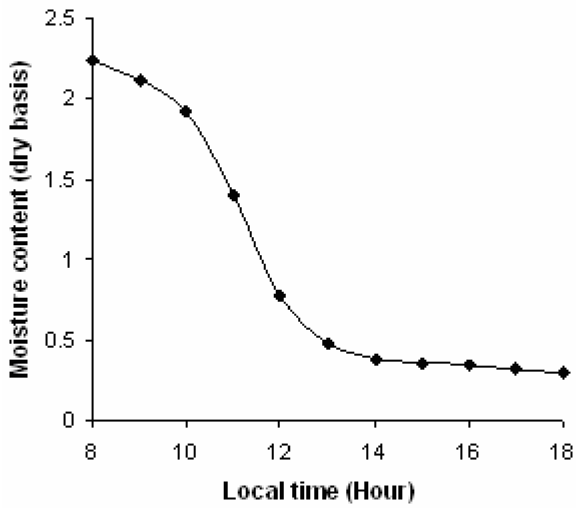

Fig. 5. Drying curve for yam chips.

Conclusion

A simple and inexpensive mixed-mode solar dryer was designed and constructed using locally sourced materials. The hourly variation of the temperatures inside the cabinet and air-heater are much higher than the ambient temperature during the most hours of the day-light. The temperature rise inside the drying cabinet was up to 24°C (74%) for about three hours immediately after 12.00h (noon). The drying rate, collector efficiency and percentage of moisture removed (dry basis) for drying yam chips were 0.62 kgh^{-1}, 57.5 and 85.4%, respectively. The dryer exhibited sufficient ability to dry food items reasonably rapidly to a safe moisture level and simultaneously it ensures a superior quality of the dried product.

However, a lot still has to be done to improve the performance of passive solar dryers. A possible area of improvement is on the use of solar storage systems in the dryer to store heat for use when insulation is insufficient due to adverse weather conditions and in the night when insulation is totally absent.

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