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DEVELOPMENT AND PERFORMANCE EVALUATION OF A NATURAL CONVECTION INDIRECT SOLAR DRYER

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ABSTRACT

The performance of a natural convection indirect solar dryer using enhanced collector design which would minimize heat losses has been investigated in this work. The collector is the non-porous type in which the absorber plate is cooled by air stream flowing on both sides of the plate. Following (Tiwari, 2002), a glass wool insulation of about 5cm thickness was used on the sides of the collector to minimize conductive heat loss from the sides. An optimum gap width of about 2.5cm is used for the collector (Madhusudan et al, 1981). Actual performance testing was carried out in Minna, a West-central Nigerian town with the annual average of daily global solar radiation of around 5.5 kWh/m^2/day and annual average of daily sunshine hours of about 8 hrs/day (Iloeje, 2004), an environmental condition typical of the entire North Central region of the country. Experimental test-drying of 20 kg fresh tomato reduces the moisture content from the initial 95.24% wb to the final 10% wb in 48 hours equivalent to six drying days. The overall thermal efficiency was obtained as 42.44%.

Keywords: Natural Convection, Moisture Content, Thermal Efficiency, Drying Rate, Performance Testing, Indirect Solar Dryer, Enhanced Design, Solar Collector.

INTRODUCTION

The necessity for sustained research and development efforts in renewable energy technologies has been emphasized by various experts. This is particularly as it is capable of enhancing the quality of lives of the people in the rural areas of developing countries. And in the area of agriculture, the application of renewable energy technology has been of tremendous benefits. One particular aspect of the application in agriculture that has attracted the attention of many researchers is in drying of agricultural products. In Nigeria it has engaged the attention of agencies and institutions like the Energy Commission of Nigeria, Sokoto Energy Research Centre, Usman Dan-Fodio University, Sokoto; National Centre for Energy Research and Development, University of Nigeria, Nsukka. At the level of the individual a lot of research efforts have also been put in. Solar thermal crop drying is one aspect of the renewable energy technology that is focused at moving away from the traditional method of open sun-drying because of the advantages inherent in the method which includes low drying rate, ease of contamination with insects, dirt and dust; reduction in ascorbic acid content resulting in loss of colour and flavour (ITDG Technical Brief, 1999) and (Encyclopaedia of Food Science, Food Technology and Nutrition). This results in the farmer incurring heavy losses in quantity and value of the product in the post-harvest period (Odogola, 1994). Solar drying has been identified as a viable alternative drying method that would eliminate most, if not all, of the above drawbacks particularly under suitable climatic conditions. Eze and Ekechukwu (1999) investigated the improved studies on tomato preservation using an existing solar dryer called the integral-type-natural circulation solar dryer, at the National Centre for Energy Research and Development, University of Nigeria, Nsukka, Nigeria. This was a direct solar dryer with application most suitable to those products which do not undergo change in colour and vitamin C content on exposure to direct sunlight. The researchers, however, treated the tomato samples in salt solutions before drying and reported that such treated tomatoes were more acceptable in colour and flavour than the untreated dried by the same method. Bolaji (2005) also conducted studies on the performance evaluation of a simple solar dryer for food preservation. He applied the dryer to drying yam chips and obtained results that indicated better performance than open sun-drying. The interest in this particular research is in drying of easily perishable goods like tomato and vegetables which change in colour and flavour when they are exposed to direct sunlight without the use of colour-retaining agents. Tomatoes and many other fruit and vegetable products are cultivated in large quantities in the Northern part of Nigeria where climatic conditions are quite suitable for the operation of the dryer. In this region, solar radiation intensities range from 3.5 – 7.0 kWh/m^2/day and sunshine duration ranges from 4.0 – 9.0 hrs/day (Iloeje, 2004). For a solar dryer to operate optimally, the available sunlight should be in the range of 4 – 7 kWh/m^2/day. A recent attempt at designing a suitable solar dryer for these products yielded encouraging results in terms of drying rate and colour retention (Ayo, 2010) but the need was observed for the use of better collector configuration and heat conservation within the collector and the drying chamber. The present work is therefore focused at designing a natural convection solar dryer with improved design of the collector that would enhance better collection of solar energy and retain much of that for a more efficient drying process. The dryer incorporates locally available material components and does not require specialized skill to operate and maintain, which translates directly into lower capital and maintenance costs. It can be used in drying different products particularly those that are colour sensitive to direct exposure to sun-light.

The Design of the Dryer

Design Description

The dryer consists of the solar collector unit, the drying chamber, and the support frame. The solar collector is the non-porous type in which the absorber plate is cooled by air stream flowing on both sides of the absorber plate, the flow being bounded at the top by the transparent cover and at the bottom by the bottom plate. This configuration enables heat to be convected away from both sides of the absorber into the drying chamber and minimizes convective and radiative heat losses from the glass cover. The absorber is made of a corrugated galvanized iron sheet, 1550mm x 773mm in dimension, painted matt black on both sides. The transparent cover is a single sheet of a 4mm thick transparent glass which admits sunlight and limit heat loss by reflection and re-radiation. The side and bottom frames of the collector are made of wooden jackets stuffed with a 5cm thick glass-wool insulation to minimize downward heat loss from the collector plate, and heat loss by conduction and convection from the sides of the collector. This thickness of insulation satisfies the minimum of 5cm stipulated by (ITDG Technical Brief, 1999). Two vertical air gaps each of width 25 mm (Madhusudan et al, 1981) are provided between the transparent glass cover and the absorber plate, and between the absorber and the bottom plate. The air inlets are provided with a wire netting screen to prevent entry of insects and other contaminants. The collector unit is inclined at 20° to the horizontal, for greater mobility of the rising heated air, and in line with the latitude of the part of the country (Minna, Nigeria, latitude 9°37 N) where the research was carried out (Chris, 2003). The angle of heat collection troughs is usually calculated as latitude plus or minus 15 degrees (Tiwari, 2002). The drying chamber is a rectangular cavity (655 mm x 460 mm x 762 mm) made of ¾-inch plywood. The chamber consists of a plenum at the bottom and four layers of trays. The trays are made from basket work and they are spaced 6 inches apart for proper ventilation of air flow (Barbara, 2005). The top of the drying chamber terminates in a short frustum and a 30 cm high chimney made of wooden material to minimize heat loss and make the chimney warm enough to prevent chimney effect. A door for loading and unloading of products into and out of the drying chamber is provided on the side of the chamber opposite to the side on which the solar collector is located. The drying chamber has a batch capacity of 20 kg tomato.

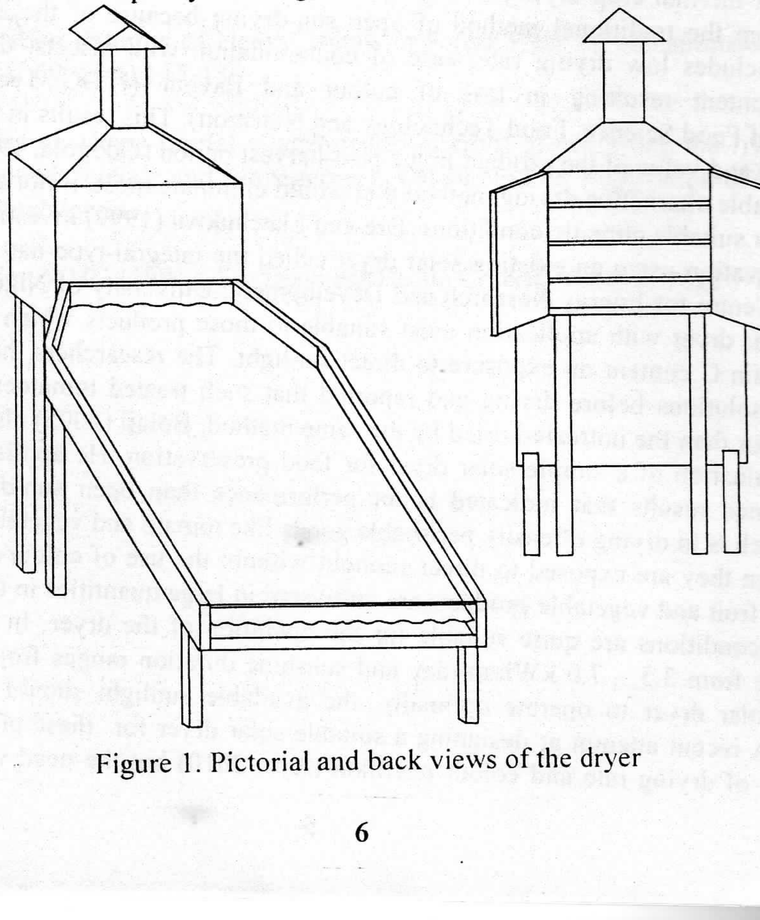

Figure 1. Pictorial and back views of the dryer

Design Analysis and Calculation

The analysis and calculations of the concept design shown in figure 1 were carried out to determine the amount of moisture to be removed from the crop, the volume flow rate of air required through the collector and the size of the collector.

Design Specifications

The following measured and selected values were considered as input in the design:

- The drier has a capacity, $D_c = 20$ kg tomato
- The measured initial moisture content (on wet basis) of the fresh product, $\omega_i = 95.24\%$
- The product is to be dried to a final moisture content, $\omega_f = 10\%$. This corresponds to the safe moisture content for tomato (Tiwari, 2002).
- Measured average ambient temperature, $T_a = (36.5°C)$
- Design (selected) average outlet air temperature from the collector, $T_{ao} = 60°C$. This corresponds to the maximum allowable temperature for drying tomato (Tiwari, 2002).
- Measured average insolation for the test environment during the drying period, $G = 817.56\ W/m^2$.
- The collector has air gap width, $C_d = 25$ mm (Madhusudan et al, 1981).
- Design (selected) duration of drying process, $D_d = 5$ days (40 hours), corresponding to 8 hours (9:00 am – 5:00 pm local time) of sunshine per day for five days when solar radiation is above the threshold level
- Latent heat of vapourization of water, $L_{vw} = 2501$ kJ/kg
- Specific heat capacity of water, $c_{pw} = 1.49$ kJ/kgK
- Specific heat capacity of air $c_{pa} = 1.005$ kJ/kgK

Quantity of Moisture to be Removed

The usual moisture content equation, on wet basis, for the fresh product is

$$\omega_w = \frac{w_w}{w_p} \times 100 \qquad (1)$$

where, w_w is weight of water in product, and w_p is weight of product. The weight of product is the sum of the weight of water and the weight of dry solids, w_s, in the product.
w_w represents the quantity of moisture to be removed in drying the product from an initial moisture content, ω_i, to a desired final moisture content, ω_f.
The instantaneous moisture content on wet basis of the product during the course of drying can be expressed as

$$\omega_{wi} = \frac{(w_{pi} - w_s)}{w_{pi}} \times 100 \qquad (2)$$

where, w_{pi} is the instantaneous weight of product. The instantaneous weights of product and that of water in the product, w_{wi}, are related as $w_{pi} = w_{wi} + w_s$.

Size of Collector

The total amount of heat required to evaporate the quantity of moisture determined above over the drying period, Q, will be used in raising the temperature of air from T_{ai} to T_{ao} in the collector at the air mass flow rate m_a such that

$$Q = m_a c_{pa}(T_o - T_i) \qquad (3)$$

The corresponding air velocity can then be determined using the continuity of air flow through the collector. For glazed collectors the quantity of energy collected per unit area per unit time, is expressed following (Duffie and Beckman, 1991) as

$$q_{coll} = F_R(\tau\alpha)G - F_R U_L \Delta T \qquad (4)$$

where, F_R is the collector's heat removal factor, τ is the transmittance of the cover, α is the short wave absorptivity of the absorber, G is the global incident solar radiation, U_L is the overall heat loss coefficient of the collector, and ΔT is the temperature differential between the working fluid entering the collectors and outside.

Where the temperature of the working fluid entering the collectors is the same as the outside ambient temperature then $\Delta T = 0$, and equation (4) becomes

$$q_{coll} = F_R(\tau\alpha)G \quad (5)$$

The total heat collected by the entire collector area can now be equated to the total heat expressed by equation (3) above and simplified to obtain an expression for the total collector area as

$$A_{coll} = \frac{m_a c_{pa}(T_o - T_i)}{F_R(\tau\alpha)G} \quad (6)$$

The theoretical area of the collector is evaluated using the generic values provided for glazed collectors as $F_R(\tau\alpha) = 0.68$, or using values selected from table of thermo-physical properties as follows: $F_R = 0.9$, $\tau = 0.84$, and $\alpha = 0.9$, which gives $F_R(\tau\alpha) = 0.6804$

Substitution of the various parameters in equation 6 gives the area of the collector as $A = 0.5990 \text{ m}^2$.

Performance Testing, and Measurements & Instrumentation

Performance Testing of the Dryer

The main objectives of the test were to determine the drying rate of tomato and the overall thermal efficiency of the drier in operating it in Minna with environmental conditions typical of the entire North-Central region of Nigeria. The quality of the dried products in terms of colour and preservation from contamination with dust, insects, and decay from fungi and microbial activity were also visually assessed. The testing was conducted at a time when there were consecutive sunny days (April 15th – April 20th, 2008). A batch quantity of 20 kg of red, soft, ripe tomato purchased from the local market was washed to remove dirt and all other foreign materials. The tomato wholes were then sliced into their halves to expose the internal structure for and enhance drying. The batch was loaded into 5 kg per tray inside the dryer, out of which 0.5 kg was maintained separately on each tray for the determination of weight loss during the drying process. The set-up was commenced for drying at 9:00 am when sunshine was established. At intervals of 4 hours, the 0.5 kg samples were brought down and weighed. On re-loading, the trays were interchanged to ensure even drying of all the products in the trays– the top-most tray being interchanged with the tray at the bottom, while the remaining two trays were used to interchange themselves. The set-up was put up for drying until 5:00 pm after which the intensity of the sun could no longer effect any significant drying. Inspection of the product and weight record after the first day of drying showed that so much water was still present in the product. The drying process was therefore continued until the sixth day after which it was observed that the desired final moisture content had been attained approximately. There was overnight break in the drying process, from 5:00 pm each day to 9:00 am the following day. At the close of the experiment each day the whole set up was covered with a polythene sheet to prevent any undesired and unmonitored moisture transfer.

Measurements and Instrumentation

At the intervals at which weight measurements of the product being dried were made, the ambient temperature and relative humidity values, and the temperature values at the inlet and exit of the solar collector were also taken. The ambient relative humidity and ambient temperature measurements were done using a hand-held digital multi-meter using M.C-7821 microprocessor and incorporating a capacitor-type sensor for relative humidity measurement and resistor-type sensor for temperature measurement. Collector inlet and exit temperature measurements were done using digital copper-constantan thermocouples. The moisture content on wet basis of the fresh tomato was determined using the oven method. The oven used was the Uniscope Sm9053 laboratory oven. The oven was turned on and the temperature limit set to 100°C. Using a Mettler Toledo digital electronic weighing balance, Type Pm400, a sample of tomato was weighed before it was sliced to enhance the drying rate. The sample was introduced into the oven after the oven had attained the pre-set temperature. The set up was maintained for 24 hours after which the sample was brought down and reweighed. The moisture content on wet basis was determined using equation (1).

Experimental Results and Analysis

The results of the performance testing of the indirect solar dryer have been presented in two parts. The first part given as table 1 depicts the psychrometric properties of the ambient air and the air passing through the collector.

Table 1. Mean collector and ambient temperature and relative humidity

Variable	Day					
	1	2	3	4	5	6
Mean Ambient Temp. (°C)	37	37.5	36.8	35.2	36.4	36.2
Mean Ambient Relative Humidity (%)	48	47	47.5	49.5	49	48
Mean Collector Inlet Temp (°C)	37	37.4	37	35	36.2	36
Mean Collector Outlet Temp. (°C)	45.5	47	46.5	41.2	44.5	43

The table 1 above shows the eight-hour-average environmental conditions of temperature and relative humidity around the place of the experiment, and the collector average inlet and outlet temperature readings during the drying period. The eight–hour averaging is based on the daily eight hours drying period.

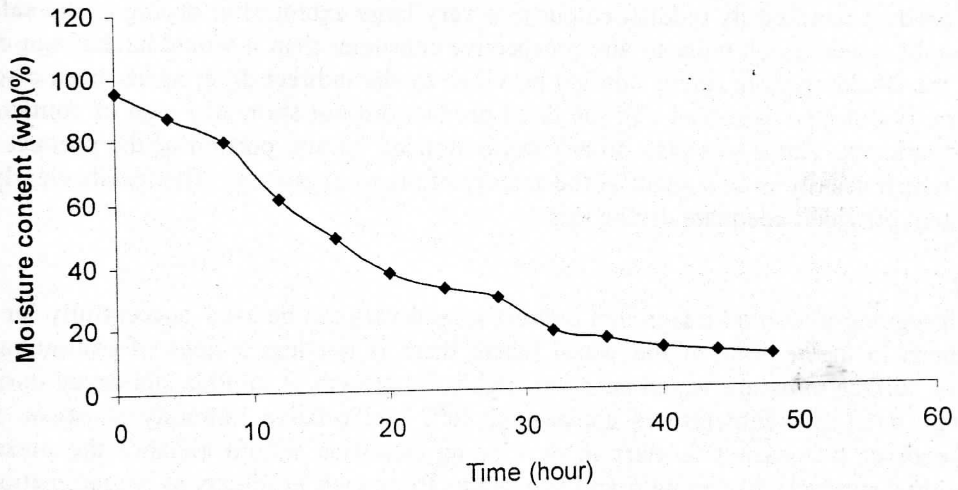

Figure 2. Drying rate pattern for the sample of tomato

Figure 2 is the graphical presentation of the performance of the dryer based on the actual drying rate. The moisture content value every eight hours starting from the zero hour represents the moisture content at the close of drying each day and the moisture content at the commencement of drying the following day.

Drying Rate
The drying rate expresses the quantity of moisture removed from a product during a drying process over a specified period. The actual drying rate during the constant rate period is normally used as a measure of how efficient the dryer is. From the experimental results the overall drying rate was determined as 0.39kg/hr.

Overall Efficiency of the Dryer
The overall efficiency of the dryer combines the efficiency of the collector and that of the drying chamber, and represents the proportion of heat collected by the dryer that is actually utilized for drying. It is defined as follows:

$$\bar{\eta}_{overall} = \frac{Q_{utl.}}{Q_{coll.}} \quad (7)$$

where, $Q_{coll.}$ is the quantity of heat collected, and $Q_{utl.}$ is the quantity of heat actually utilized. Noting that the air flow rate determined using equation 3 can only be achieved by some means of forcing the air through the collector (natural convection), a multiplier factor was applied to the area determined by equation to obtain the actual area based on natural convection used for the dryer. The parameters of equation 6 are then substituted for to obtain the overall efficiency of the dryer as, $\eta_{overall}$ = 42.44 %.

DISCUSSION OF RESULTS

It would be observed from figure 2 that the drying rate curve exhibits the two distinct regions of initial constant rate drying phase and falling rate phase associated with drying of agricultural products. The constant rate drying phase represents the period during which the surface of the food remains wet and moisture evaporates from the surface, while the falling rate phase represents the period during which moisture is diffused from within the product and the risk of spoilage is very small (Sahay and Singh, 1994). As would be seen from the figure the drying took about 48 hours for the moisture content to be reduced from the initial 95.24% level to the final 10% level (approximated by the actual 10.02 % level reached). The higher efficiency and the reduction in drying time could be attributed to the following factors: First is the larger collector surface area by which more quantity of solar radiation was intercepted and collected for drying. Secondly, the glass-wool insulation provided around the side of the collector and at the bottom greatly reduced heat loss by convection and conduction from the side, and by conduction from the bottom of the collector. There might also have been reduction of loss of energy by convection and radiation from the top of the glass cover by the configuration of the collector used. Visual inspection of the dried product showed that the product retained its reddish colour to a very large extent after drying to the safe moisture content that it should appeal much more to any prospective consumer than it would have if sun-dried . This is attributable to the shielding from direct sunlight provided by the indirect dryer as has been discovered by earlier researchers. It was also observed that the dried product did not show any sign of contamination by dirt or insect and animals. There was also no any decay noticed on any portion of the product during the course of drying which usually is as a result of the activity of micro-organisms. The results clearly indicated that the dryer system provided adequate drying rate.

CONCLUSION

Considering the foregoing it would be seen that indirect solar dryers can be used successfully for preserving agricultural products in the regions of the world where there is not less 5 days of continuous sunshine (needed to remove surface moisture which accounts highly for growth of moulds and decay during drying) and where average day-time temperatures are around 36°C and relative humidity is below 50 %. The application of the dryer by peasant farmers in developing countries should enhance the preservation of perishable agricultural products like tomato and vegetables from such problems as contamination with dirt and by insects and animals, decay from the activities of micro-biological agents and retention of the physical feature colour. On the economic aspect the dryer is cost effective and affordable by the average farmer; it is easy to maintain and requires no specialized skill to operate. It could be easily acquired for domestic use.

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