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Design and Development of a Mixed-Mode Domestic Solar Dryer

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Abstract

This work focuses on the design and development of a mixed-mode domestic solar dryer in which the slices of pepper, okra and yam were dried simultaneously by both direct radiation through the transparent glass roof of the drying chamber and by the heated air from the solar collector. The dryer was made up of the solar collector, the desiccant chamber and the drying chamber which contains a rack of three trays. The air comes in through the air inlet and heated up within the solar collector and then channeled through the drying chamber by natural convection where it is utilized for drying purposes. The development was done using locally sourced and readily available materials such as wood, transparent glass sheet, mild steel metal sheet, mosquito galvanized wire mesh and chicken galvanized wire mesh. The maximum temperature attained by the solar collector, drying chamber during test were 69^{o}C and 55^{o}C respectively, with a corresponding ambient temperature of 39^{o}C. The mass of water removal of 43g, 136g and 255g from pepper, okra and yam slices respectively was achieved making use of the passive solar food dryer as against the water removal of 39g, 126g and 218g from pepper, okra and yam slices respectively achieved using the sun drying method which indicates a difference of 4g, 10g and 37g for pepper, okra and yam slices respectively. The rapid rate of drying achieved with the use of this dryer shows that it has the ability to dry food items rapidly to an acceptable moisture content level.

Index Terms: Mixed-mode, domestic, solar dryer, solar collector, drying chamber.

1. Introduction

Drying is one of the oldest methods of food preservation [1.15]. Traditionally, drying is carried out openly in the field. Open air drying using direct sunlight has numerous draw backs which include subjection to adverse

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weather conditions like rain, dusts, wind, insects and sometimes rodents. This ultimately slows down the drying rate, causing mold formation. For several thousand years, people have been preserving dates, figs, apricots, grapes, herbs, potatoes, corn, milk, meat, and fish by drying [4,17]. Until canning was developed at the end of the 18th century, drying was virtually the only method of food preservation. Open sun drying has no quality control and also has a risk of contamination, creating a potential health hazard. The product's quality is seriously degraded, sometimes to the extent that they are inedible [17,3,12]. Food deterioration and spoilage is caused by the action of yeasts, bacteria, and enzymes. The drying process removes enough moisture from food to greatly decrease these destructive effects. Food drying can reduce loss of a harvest surplus, allow storage for food shortages, and in some cases facilitate export to high value markets. To guide against the aforementioned disadvantages and also to speed up the rate of drying the produce, control the final moisture content and elimination of bacterial effect, various types of solar dehydrators can be used [18]. With subsequent development in the technical world, efforts are focused towards improve drying and this led to solar drying as an upgrade from sun drying.

Solar dehydrators are special drying enclosure that is used to dry food produce and has numerous advantages which include controlled drying rate, drying at a higher temperature, lower relative humidity, and reduced moisture content of dried food. Also it protects the produce against adverse weather conditions, pests and rodents. 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 farmer in developing countries to increase their productivity [16]. In order to improve traditional drying, solar dryers which have the potential of substantially reducing the disadvantages of open air drying; have received considerable attention over the past 20 years [2,8,7,12,1,15]. Currently, several solar dehydrator designs exist on the market, and most of these designs require expensive materials and source of energy, which makes the prototype expensive and difficult to obtain for small scale producers [10,12]. This work focuses on the design and development of a mixed-mode solar dryer for domestic purpose.

2. Materials and Design Calculations

2.1. Materials

The following materials were used for the development of the passive food solar dryer:

a. Wood for the housing of the entire system; wood was preferred being a very good insulator and relatively cheaper than metals.
b. Transparent Glass (4mm thick) for the solar collector and the drying chamber cover plate. It allows into the system solar radiation but resists the outflow of heat energy from the system. The solar collector is the part of the solar dryer responsible for heating up the air used for drying purpose. It consists of the cover plate, absorber plate and insulator. The drying chamber which has dimensions 70cm×60cm×80cm is where the actual drying takes place. It is made of wood with the outer surface painted black. It has three layers with each having a drying tray. The drying tray is made up of a wooden frame and a chicken galvanized wire mesh.
c. Insulator to minimize the heat loss from the solar collector. Styrofoam as insulator is capable of withstanding heat and also fire resistant.
d. Mild steel sheet (1mm thick) for the absorber plate. The absorber plate is the plate used as the base of the solar collector. It is painted black so as to convert solar radiation entering the system into heat energy which helps to heat up the air entering the system
e. Perforated mild steel sheet (1mm thick) as a separator of the drying chamber from the desiccant chamber. It also allows for even distribution of heated air. The purpose of the desiccant chamber is to reduce the relative humidity of air.
f. Mosquito galvanized wire mesh for covering the air inlet and outlet so as to prevent insects and rodents from entering the system.

g. Nails and glue as fasteners and adhesives.
h. Hinges and handle for the dryer door.
i. Black Paint for the solar collector absorber plate and the exterior of the dryer structure.
j. Chicken galvanized wire mesh for drying trays where what is to be dried are kept

2.2. Determination of the Tilting Angle for the Solar Collector

The tilting angle for the solar collector was determined from [14]:

$$\beta = 10^O + Lat\ \Phi \quad (1)$$

Where,

$\beta =$ Tilting angle
$Lat\ \Phi =$ Latitude angle of the solar collector location

The latitude angle of Minna where the dryer was designed and developed is 9.39 °N, substituting into equation (1) gives

$$\beta = 10^o + 9.39^o = 19.39^o$$

The flat-plate solar collector is normally tilted and oriented in such a way that it receives maximum solar radiation in the desired season of use. The best stationary orientation is due south in the northern hemisphere and due north in southern hemisphere. The solar collector for this work was therefore oriented facing the south and tilted at 19.39^o to the horizontal.

2.3. Determination of Total Solar Radiation Incident on the Absorber Surface

The total solar radiation incident on the absorber surface was determined from [11]:

$$I_T = H \times R \quad (2)$$

Where,

$I_T =$ Total solar radiation incident on the absorber surface (W/m^2)
$H =$ Average daily solar radiation on horizontal surface
$R =$ Average effective ratio of solar energy on the tilted surface to that on the horizontal surface = 1.0035.

2.4. Determination of Useful Energy Gained by the Collector

The useful energy gained by the collector was determined from [7]:

$$Q_u = \alpha\tau I_T - U_L(T_C - T_A) \quad (3)$$

Where,

$Q_u =$ Useful energy gained by the collector (W/m^2)
$\alpha =$ Absorption

τ = Glass transmittance = 0.9
U_L = Overall heat transfer coefficient of the absorber ($W/m^2/K$)
T_C = Temperature of the collector absorber (K)
T_A = Ambient air temperature (K)

2.5. Determination of the Volume Flow Rate of Air in the Collector

The volume flow rate of air in the collector was determined from:

$$\dot{V} = \upsilon_a A_{ag} = \upsilon_a h_{ag} w_{ag} \quad (4)$$

$\dot{V}$ = Volume flow rate of air (m^3/s)
A_{ag} = Air gap area (m^2)
υ_a = Velocity of air (m/s) = 0.15m/s
h_{ag} = Air gap height (m) = 0.056m
w_{ag} = Air gap width (m) = 0.60m

2.6. Determination of the mass flow rate of air in the collector

The mass flow rate of air in the collector was determined from:

$$\dot{M}_a = \dot{V}\rho \quad (5)$$

Where,

$\dot{M}_a$ =Mass flow rate of air (kg/s)
ρ = Density of air (kg/m^3) = 1.225kg/m^3 at STP

2.7. Determination of Collector Surface Area

The collector surface area was determined from:

$$A_C = \frac{\dot{M}_a C_P (T_C - T_A)}{I_T} \quad (6)$$

Where,

A_C = Collector surface area (m^2)
C_P = Specific heat capacity of air at constant pressure (J/kg/K) = 1000J/kg/K

2.8. Determination of Collector Length

The collector length was determined from:

$$L_C = \frac{A_C}{w_{ag}} \quad (7)$$

Where,

L_C = Collector length (m)

2.9. Determination of the Insulator base Thickness for the Collector

For the design, the thickness of the insulator was taken as 6 to 8cm. The side of the solar collector was made of finished wood, the loss of heat and emittance through the side of the collector will be considered negligible.

2.10. Determination of Collector Efficiency

The collector efficiency was determined from [5]:

$$\eta_C = \frac{\rho C_P \dot{V}(T_C - T_A)}{A_C I_T} \times 100 \tag{8}$$

Where,

η_C = Collector efficiency (%)

2.11. Determination of Dryer Efficiency

The dryer efficiency was determined from [9,5]:

$$\eta_d = \frac{M L_V}{A_C I_T t} \times 100 \tag{9}$$

Where,

η_d = Dryer efficiency (%)
M = Mass of evaporated moisture (kg)
L_V = Latent heat of vaporization of water (J/kg)
t = Time of drying (s)

2.12. Determination of Moisture Content

The moisture content on percentage wet basis was determined from [5,6,13]:

$$MC = \frac{M_i - M_f}{M_i} \times 100 \tag{10}$$

Where,

MC = Moisture content (%)
M_i = Mass of sample before drying (g)
M_f = Mass of sample after drying (g)

3. Testing of the Solar Dryer

The testing of the solar dryer shown in Figure 1 was done in the month of March in Minna, a city in Nigeria on latitude 9.39^o. The dryer was placed outside with the solar collector facing the sun. Three tests were carried out to evaluate the performance of the solar dryer. Firstly, for the no load test, the temperature of the heated air inside the solar collector and the drying chamber, together with the ambient temperature of the air was taken every one hour interval, starting from 9am to 6pm. In the absence of a hygrometer, two thermometers were used to measure the relative humidity. One of the thermometer has its sensor whirled with a wick, with the wick touching water in a beaker to get the wet bulb temperature, the other thermometer provided the normal temperature which gives the dry bulb temperature. The wet bulb and dry bulb temperature were used to obtain the relative humidity on the psychometric chart, which was done every one hour interval from 9am to 6pm. A clinical thermometer was used for the temperature measurement in the solar dryer, and the variation in weight loss was done using an electronic weighing scale. The maximum temperatures obtained for the solar collector, drying chamber and ambient were 69°C, 55°C and 39°C respectively. Secondly, tests were carried out to determine the drying rate of pepper, okra and yam. The drying chamber was loaded with the pepper, okra and yam (sliced to about 1cm and blanched) estimated to weigh averagely 80g, 190g and 310g respectively. Thirdly, the results obtained from the solar dryer were compared with that obtained from sun drying.

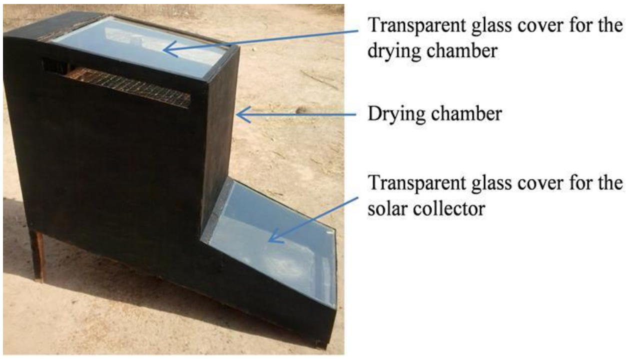

Fig.1. Constructed Mixed-mode Solar Dryer

4. Results and Discussion

Table 1 show the result of variations of temperature with time within the dryer. The solar dryer generated the most heat when the sun is over-head during mid-day, which resulted in very high temperatures within the solar collector and the drying chamber as compared to the ambient temperature as indicated in Table 1. This signifies that the solar dryer performance and efficiency will improve significantly when compared with that of sun drying. Table 2 show the result of variations of relative humidity with time within the dryer. Comparison of Table 1 and Table 2 shows that the process of drying using the solar dryer was greatly enhanced by the heated air at very low humidity.

Table 1. Result of Variations of Temperature with time Within the Dryer

Time (hours)	Ambient Temperature (°C)	Collector Temperature (°C)	Drying Chamber Temperature (°C)
9.00	26.00	54.00	41.00
10.00	29.00	58.00	46.00
11.00	32.00	61.00	48.00
12.00	34.00	63.00	49.00
13.00	38.00	69.00	54.00
14.00	39.00	69.00	55.00
15.00	35.00	68.00	54.00
16.00	31.00	65.00	51.00
17.00	32.00	60.00	47.00
18.00	30.00	56.00	43.00

Table 2. Result of Variations of Relative Humidity with time Within the Dryer

Time (hours)	Ambient Relative Humidity (%)	Drying Chamber Relative Humidity (%)
9.00	65.00	81.00
10.00	41.00	81.00
11.00	32.00	80.00
12.00	30.00	79.00
13.00	31.00	78.00
14.00	32.00	77.00
15.00	32.50	78.00
16.00	38.00	79.00
17.00	42.00	79.00
18.00	48.00	80.00

Table 3. Daily Moisture Loss for Pepper Sample using Solar Dryer

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Ambient Temp. (^oC)	Dryer Temp. (^oC)
1	80.00	70.00	10.00	12.5	38.00	54.00
2	68.00	62.00	6.00	8.82	39.00	55.00
3	57.00	52.00	5.00	8.77	40.00	52.00
4	49.00	44.50	3.50	7.14	38.00	54.00
5	42.50	37.00	5.50	12.16	39.00	55.00

Table 4. Daily Moisture Loss for Pepper Sample using sun Drying

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Drying Temp. (^oC)
1	80.00	74.00	6.00	7.50	40.00
2	72.00	66.00	6.00	8.33	39.00
3	61.00	56.00	5.00	8.19	39.00
4	53.00	48.50	4.50	8.49	38.00
5	46.50	41.00	5.50	11.82	39.00

Table 3 and 4 shows the masses of samples of pepper considered and their initial and final masses, which was used to determine the moisture loss in grams of the samples from day 1 when they were placed in the drying chamber to day 5 and the daily moisture content on percentage wet basis of the pepper slices. The result show a total moisture loss of 43g using solar dryer and 39g using sun drying method.

Table 5. Daily Moisture Loss for Okra Sample using Solar Dryer

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Ambient Temp. (^oC)	Dryer Temp. (^oC)
1	190.00	144.00	46.00	24.21	38.00	52.00
2	132.00	110.00	22.00	16.66	39.00	53.00
3	102.00	84.00	18.00	17.64	37.00	56.00
4	80.00	66.00	14.00	17.5	40.00	55.00
5	61.00	54.00	7.00	11.47	40.00	54.00

Table 6. Daily Moisture Loss for Okra Sample using sun drying

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Drying Temp. (°C)
1	190.00	144.00	46.00	24.21	34.00
2	124.00	110.00	14.00	11.29	36.00
3	101.00	91.00	10.00	9.90	37.00
4	86.00	76.00	10.00	11.62	35.00
5	75.00	64.00	11.00	14.66	39.00

Table 5 and 6 shows the masses samples of okra slices considered and their initial and final masses, which was used to determine the moisture loss in grams of the samples from day 1 when they were placed in the drying chamber to day 5 and the daily moisture content on percentage wet basis of the okra slices. The result show a total moisture loss of 136g using solar dryer and 126g using sun drying method. Table 7 and 8 shows the masses of samples of yam slices considered and their initial and final masses, which was used to determine the moisture loss in grams of the samples from day 1 when they were placed in the drying chamber to day 5 and the daily moisture content on percentage wet basis of the yam slices. The result show a total moisture loss of 255g using solar dryer and 218g using sun drying method. Figure 2 and 3 shows the dried samples of pepper, okra, and yam slices using the solar dryer and under the sun. The drying rate was observed to increase continuously between 9.00h and 3.00h but decreased slowly thereafter. This shows earlier and faster removal of moisture from the dried items in the drying chamber. The appearance of the pepper, okra and yam slices as captured in Figure 2 and 3 reveals uniform and better drying in passive solar drying as compared with sun drying. Table 9 gives some of the values of the evaluated parameters of the dryer.

Table 7. Daily Moisture Loss for Yam Sample using Solar Dryer

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Ambient Temp. (°C)	Dryer Temp. (°C)
1	310.00	249.00	61.00	19.67	38.00	46.00
2	200.00	167.00	33.00	16.50	37.00	43.00
3	135.00	109.00	26.00	19.25	34.00	45.00
4	92.00	73.00	19.00	20.65	35.00	47.00
5	69.00	55.00	14.00	20.28	34.00	46.00

Table 8. Daily Moisture Loss for Yam Sample using sun drying

Day	Initial mass M_i (g)	Final mass M_f (g)	Moisture loss (g)	Moisture content (%)	Drying Temp. (°C)
1	310.00	252.00	58.00	18.71	36.00
2	204.00	174.00	30.00	12.50	35.00
3	144.00	123.00	21.00	14.58	34.00
4	126.00	114.00	12.00	9.52	36.00
5	101.00	92.00	9.00	8.91	37.00

Fig.2. Sun Dried Yam, Pepper and Okra Slices

Fig.3. Solar Dried Yam, Pepper and Okra Slices

Table 9. Evaluated Parameters of the Dryer

Parameter	Values obtained
β	19.39^o
I_T	956.11W/M^2
A_C	0.36m^2
η_C	37.9% (average)

5. Conclusions

The following conclusions are made from the test carried out: The solar dryer raises the ambient air temperature to a considerable high value which absorbs moisture content in food faster and thus, increasing the drying rate of food; The product/food inside the solar dryer's drying chamber requires lesser frequent attention compare with those in the open air/sun drying in order to prevent attack of the food produce by rain or rodents (both human and animals); The dryer was used to dry yam perfectly and can be used to dry cassava; The monitoring was done with relative ease when compared to the sun drying technique; The capital cost involved in the construction of a passive solar dryer is much lower to that of active/mechanical dryer; The mass of water removal of 43g, 136g and 255g in pepper, okra and yam slices respectively using the passive solar dryer was achieved as against 39g, 126g and 218g in pepper, okra and yam slices using the sun drying method.

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