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# DESIGN AND CONSTRUCTION OF FORCED/NATURAL CONVECTION SOLAR VEGETABLE DRYER WITH HEAT STORAGE

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## ABSTRACT

This paper presents the design and construction of forced/natural convection solar vegetable dryer for food preservation. The system was constructed using local materials. The temperatures of 53, 52, 52, 44 and 36°C were reached at the collector unit, inlet, energy storage unit, air outlet and ambient temperature, respectively. When using the forced mode system, the drying time of tomato, onion, pepper, okra and spinach were 14, 15, 12, 11 and 1 hr (s) while the drying rate were 0.20, 0.020, 0.21, 0.22 and 0.77 kg/h, respectively; when using the natural mode system, the drying time of tomato, onion, pepper and spinach were 24, 27, 25, 21 and 2 hrs while the drying rate were 0.12, 0.08, 0.09, 0.11 and 0.39 kg/h, respectively. The collector efficiency was 45% and the useful heat of 48.9 W/m$^2$K was used for about six hours in drying during the night.

**Keywords:** solar vegetable dryer, collector efficiency, drying rate, heat, local materials, temperature.

## INTRODUCTION

Solar drying is a process of using solar energy to heat air and/or the products so as to achieve drying of agricultural products (Ajay *et al*., 2009). Solar air heaters are simple devices to heat air by utilizing solar energy and employed in many applications requiring low grade to moderate temperature below 80$^0$C such as crop drying and space heating (Bukola and Ayoola, 2008). According to Bugaje and Mohammed (2008), there is a constraint associated with convectional energy source such as fossil fuels, environmental concern and rising prices, it is therefore, imperative to exploit the solar renewable source. Fossil fuel provide about 90% of the total word energy (Idiata *et al*., 2008); the burning of fossil based fuel causes some of these environmental problems like materials and properties corrosion, acid rains, visibility problems, greenhouse and ozone layer depletion (global warming). In many rural areas, farmers grow vegetables which have to be sold in the market immediately after harvesting, when the production is high, the farmers have to sell the products at very low price, there by incurring great economic losses. The convectional sun drying is commonly practiced in most of the developing countries like Nigeria where, vegetable processing/storage facilities and solar dryers are either not available, or are too expensive for the local farmers to afford. Bukola (2008) reported that, solar energy has been used for centuries by man for drying animal skins and clothes, preserving meat and fish, drying agriculture crops and evaporating sea water in order to extract salt. Many developing countries enjoy a superfluous supply of solar energy (Chineke and Nwafor, 2003). For instance, radiation climate maps show that the lowest and highest monthly mean values of radiation in Nigeria are around 12 and 20 mJ/m$^2$ day for about 8 months in a year (Bobboi, 2000).

This paper present the design and construction of a forced/natural convection mode solar dryer integrated with heat storage to ensure drying during the night. It is the aim of this paper to explore the renewable energy source specifically solar energy which is clean and suitable for rural farmers in the interest of agricultural products handling, processing and storage for sustainable development and environmental protection.

## MATERIALS AND METHODS

### Design considerations

The stages in the design and development of the solar dryer system require:

a) Meteorological data collection.
b) Identify temperature levels to be reached by the product during drying process (thermal performance).
c) The physical features of the dryer were considered i.e., type, shape, collector area, number of trays and material of construction. The solar radiation of a location can be used as starting points in solar equipment design.

### Basic theory

The total energy required for drying a given quantity of food item can be estimated using the basic energy equation for the evaporation of water (Bukola and Ayoola, 2008).

$$MwLv = ma\,Cp(T1 - T2) \qquad (1)$$

Where

$Mw$ = Mass of water evaporated from the food item (kg)
$ma$ = Mass of drying air (kg)
$Cp$ = Specific heat at constant pressure (kJ/kgK)
$T1 \text{ and } T2$ = Initial and final temperatures of the drying air respectively (K)

According to Al-Juamily *et al*. (2007), the mass of water evaporated can be calculated using:

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$$Mw = mi\frac{Mi-Mf}{100-Mf} \quad (2)$$

Where

$mi$ = Initial mass of the food item (kg)
$Mi$ = Initial moisture content (% dry basis)
$Mf$ = Final moisture content (% dry basis)
Also, the mass of drying is expressed as:

$$ma = [(Ti - Tf)(\frac{WwL}{Cp\rho a})] \quad (3)$$

Where

$ma =$ Mass of drying air (kg)
$Ww =$ Quantity of water to be removed
$L =$ Latent heat of vaporization
$\rho a =$ Density of air (kg/m$^3$)

The quantity of water to be removed can be calculated from Equation (4).

$$Ww = wg\frac{Mi-Mf}{100-Mf} \quad (4)$$

Where

$wg =$ Quantity of the product to be dried

The moisture content of the product can be determined from Equation (5) (Chung *et al*., 2010):

$$Md = 100\%(W - d)/d \quad (5)$$

Where

$Md$ = Moisture content on dry basis
$W$ = Wet weight
$d$ = Dry weight

Also to calculate the rate of drying the following equation is used:

$$Wdr = Ww/td \quad (6)$$

**Collector efficiency**

The thermal efficiency of a collector is defined as the ratio of useful energy gain by the air to solar radiation incident on the absorber of solar collector (Al-Juamily *et al*., 2007).

$$\eta = Qg/AcIt \quad (7)$$

Where:
$Qg =$ Heat gain by the air from the absorber (W/m$^2$K)
$Ac =$ Area of transparent cover (m$^2$)
$It =$ Total incident solar radiation (W/m$^2$)
Joe (1980) defined the total incident solar energy as:

$$Qs = Qa + Qr + Qc \quad (8)$$

Where:

$Qr =$ Rate of radiation losses from absorber (W)
$Qa =$ Rate of convection and conduction losses from absorber (W)
$Qc =$ Rate of useful heat by the absorber (W)

Bukola and Ayoola (2008) found that the three heat losses terms are usually combined into one term given as:

$$Ql = Qco + Qcv + Qr \quad (9)$$

Where

$Ql =$ Rate of losses from the absorber (W/m$^2$K)

Duffie and Beckman (1974) reported that the rate of the losses as:

$$Ql = UlAc(Tc - Ta) \quad (10)$$

Where

$Ul =$ Overall heat transfer coefficient of the absorber
Also, the heat transferred per unit time is:

$$Qg = macp(Tc - Ta) \quad (11)$$

Where

$ma$ = Mass of air leaving the collector per unit time (kg/s)

The rate of heat absorption by the collector is defined as follows (Tiwara, 1978):

$$Qab = (\tau\alpha)Io \quad (12)$$

Where

$Io =$ Incident solar radiation (W/m$^2$)
$\tau =$ Transmittance
$\alpha =$ Absorptance

**Solar air heater**

The solar absorber of the collector was constructed using 0.55 mm thick corrugated aluminium plate, painted black and is mounted on a box constructed of the same area. The bottom of the absorber was insulated with 19 mm thick plywood also of the same area. To create a greenhouse effect, a single layer transparent glass sheet of 5 mm thickness was placed on top of the absorber. The overall length, width and height of the solar collector are 720, 600 and 250 mm, respectively.

**The drying cabinet**

The drying cabinet structural frame was built from a well-seasoned gmelina wood and 19 mm plywood sheet was used to cover the frame. An outlet vent (chimney) was provided towards the upper end at the back of the cabinet to facilitate and control the convection flow of air through the dryer. The overall length, width and height of the drying cabinet are 1200, 600 and 1800 mm, respectively. The drying trays are contained inside the

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drying cabinet and were constructed with fine chicken wire mesh of a fairly open structure to allow drying air to pass through the food items.

The storage unit is a compartment that is located directly below the trays in the drying cabinet. It contains rock pebbles of 21 mm bed thickness. The heated air passes through the storage where some of the heat energy is stored. During off-sunshine hours, the stored energy is released to the air.

**The orientation of the solar collector**

The solar collector is tilted and oriented in such a way that it receives maximum solar radiation. The best stationary orientation is due south in the northern hemisphere and due north in the southern hemisphere (Bukola, 2008). The tilted angle is $11^0$.

**Drying process description**

The experimental procedure follows as:
The temperature is considered as indicator to measure the real valuable energy obtained from the collector and to determine the efficiency of the system.

Air was supplied to the system by the five air circulation units. The airflow rate was controlled by adjusting to 0.027, 0.054, 0.0162, 0.0108 and 0.0135 $m^3/s$ i.e., each air circulation unit can produce 0.027 $m^3/s$ airflow rate. In natural mode, the air circulation units were removed and the natural flow of air occurs in to the solar collector unit.

The vegetable products were washed and sliced to about $1/6^{th}$ of the original size and loaded on the trays, and then the door of the drying cabinet is closed. In case of the forced mode system, the air circulation unit was started. In the case of natural mode system, the air circulation units were removed from the system.

**Dryer performance evaluation**

During the testing process, the ambient air temperature, the collector, inlet, outlet and storage unit and the drying cabinet were measured by laboratory type mercury bulb thermometer at regular interval of two hours between the hours of 0800 and 2400 local time. The dryer was loaded with vegetable product and its weight was measured at the start and at two hours interval thereafter.

The performance of a solar dryer is determined by the amount as well as the rate of moisture it can remove from the products (Mohammed, 2008). Knowing the initial weight and the final weight at point when no further weight loss of the product was attained, the weight loss was used to calculate the moisture removed in kg water/ kg dry matter at intervals as the vegetable dried. The moisture content was determined using the weight loss method with the aid of a sensitive balance with range of 0-500 g.

**RESULTS AND DISCUSSIONS**

Figure-1 showed the variation of temperatures with time for the mixed-mode systems. Figure-2 to Figure-6 showed the drying curve of tomato, onion, pepper, okra and spinach using the forced and natural convection systems. The temperature reading at two hours interval was recorded for the forced convection system while for natural convection system; the reading was carried out at an interval of three hours. The temperature measurement recorded consist that of ambient air temperature, the solar collector unit, the inlet, the heat storage and the outlet are all in degree centigrade.

The system is hottest about midday when the sun is usually overhead. The temperatures inside the dryer and the solar collector were much higher than the ambient temperature during the most hours of the daylight. The temperature of the storage unit was higher as from 1600 hours for six hours than that of the other units. This is an indication of energy release by the rock pebbles and therefore, energy gain by the air during off-sunshine hours.

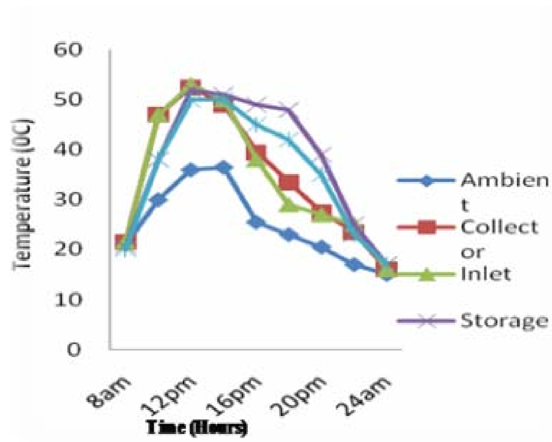


**Figure-1.** Variation of temperatures with time.

The Figure-2 to Figure-6 showed the drying rate by weight loss of the product with time. It is the drying curve for tomato, onion, pepper, okra and spinach. Knowing the initial weight and the final weight at point when no further weight loss of the product was attained, the weight loss was used to calculate the moisture removed in kg water/ kg dry matter at intervals as the vegetable dried.

The heat absorbed by the collector was 60.62 $W/m^2K$ and equals the heat absorbed by the heat storage system. Sensible heat storage system (gravels) was used of bed of 3/4 inch - 3 inch rock; the useful heat was 48.9 $W/m^2K$. The useful heat was utilized during the night hours for about six hours for drying.

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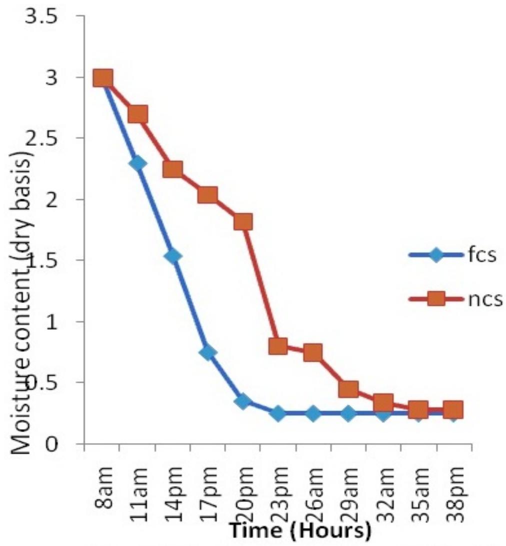


Figure-2. Drying curve of tomato for fcs and ncs.

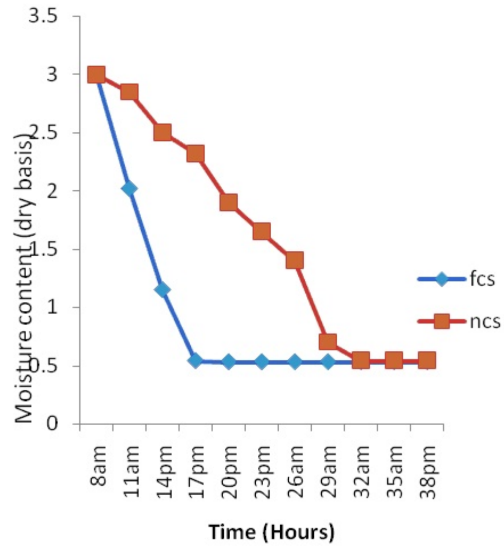


Figure-4. Drying curve of pepper for fcs and ncs.

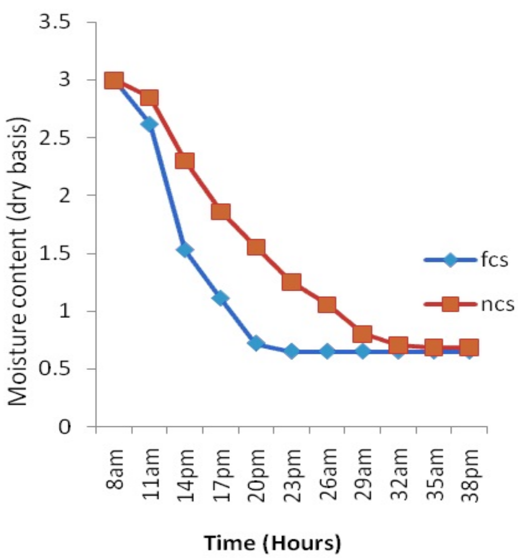


Figure-3. Drying curve of onion for fcs and ncs.

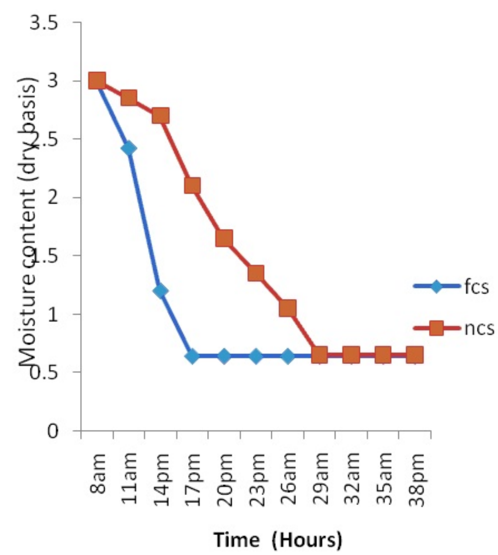


Figure-5. Drying curve of okra for fcs and ncs.

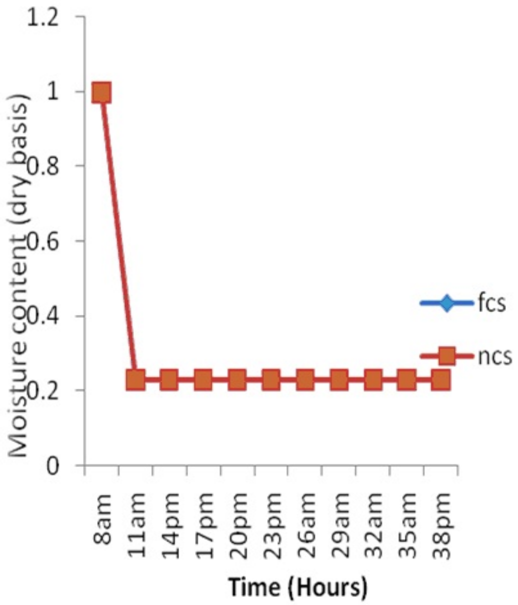


**Figure-6.** Drying curve of spinach for fcs and ncs.

## CONCLUSIONS

A forced and natural mode solar vegetable dryer was designed and constructed with locally available materials such as corrugated aluminium sheet, wire mesh, plywood, steel pipe and transparent glass, incorporated with a heat storage system to ensure drying during night hours. The various airflow rates produced by each air circulation unit were 0.027$m^3$/s. The five air circulation units have the collective airflow rate of 0.0135 $m^3$/s. Temperature measurement at noon for the ambient temperature, collector unit, inlet, storage and outlet were $36^0$C, $53^0$C, $52^0$C, $52^0$C and $44^0$C, respectively.

When using the forced convection mode, the drying time of tomato, onion, pepper, okra and spinach were 14 hrs, 15 hrs, 12 hrs, 11 hrs and 1 hr while the rate of drying were 0.20 kg/h, 0.020 kg/h, 0.21 kg/h, 0.22 kg/h and 0.77 kg/h, respectively. When using the natural convection mode, the drying time of tomato, onion, pepper and spinach were 24 hrs, 27 hrs, 25 hrs, 21 hrs and 2 hrs while the rate of drying were 0.12 kg/h, 0.08 kg/h, 0.09 kg/h, 0.11 kg/h and 0.39 kg/h, respectively.

The forced convection system has higher airflow through the solar collector and drying chamber hence, it has higher drying capabilities compared to the natural convection system. Also, the airflow rate can be controlled as needed, not as in natural mode whose airflow rate is depending on ambient climatic conditions. However, forced convection mode requires a source of motive power for the operation (battery) which is an added cost.

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