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DEVELOPMENT OF AN INDIRECT FORCED CONVECTION SOLAR DRYER FOR CASSAVA CHIPS

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ABSTRACT

Solar drying has been widely applied as a preservative measure for agricultural/food materials, as a system which combines cost-effectiveness (coupled with other advantages) with efficiency. This work presents the design, construction and preliminary testing of an indirect forced convection solar dryer. The system was constructed using locally available materials at a total cost of ₦40,550. The calculated collector area is $0.32\,m^2$, fan ratings is 20 CFM; 24 VDC; 1.4 A. Photovoltaic Panel rating is 15 W, while battery rating is 24 VDC. It was tested under no load (for temperature variations) and load (for temperature, relative humidity and moisture content variations) conditions. The equipment was used to dry cassava *(Manihot spp)* chips in order to study the effect of the enhanced airflow on the drying rate of the product. The drying test was carried out in two replications. The duration of each test was 0800hr to 1800hr. At no load maximum temperatures of 60℃ and 48℃ were obtained in the collector unit and drying cabinet respectively on 04/05/2014 when the ambient temperature was 35℃. Under load condition maximum temperatures of 57.5℃ and 50℃ were obtained in the collector unit and drying cabinet respectively on 10/05/2014 when the ambient temperature was 36.4℃. During second replication the relative humidity in the drying cabinet varied from 58% to 78% while the ambient relative humidity varied from 70% to 90%. In a day with maximum ambient temperature of 6.4℃, the dryer efficiency was calculated as 53.2 , the dryer capacity was 116.3g/hr and drying time of cassava chips in the forced convection solar dryer was 10 hours, as opposed to 2-3 days drying of crops in natural convection solar dryers as reviewed in this work.

KEYWORDS: Design, preliminary testing, forced convection, indirect, solar dryer, cassava chips

1. INTRODUCTION

In food processing, drying can be defined as a Unit operation which involves the removal of moisture from an agricultural/food material until the moisture content is in equilibrium with the surrounding air. Drying serves as a preservative measure, as it helps to lower the moisture content and water activity of the produce, thereby inhibiting the growth of microorganisms (Alonge and Adeboye, 2012). Alonge and Adeboye (2012) stated that preserving dried food by removing enough moisture from the food can prevent decay and spoilage. Drying is essential as it facilitates crop handling by reducing weight and improving resistance to attacks by some pests and insects (Yohanna and Umogbai, 2010). The drying process involves simultaneous heat and mass transfer. Successful drying depends on enough heat to draw moisture without cooking the food, dry air to absorb the released moisture and adequate air circulation to carry off the moisture. The key is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the food (Alonge and Adeboye, 2012). Drying must therefore occur at a temperature that is not too high, to prevent surface hardening (at very low humidity) and not too low, to prevent growth of microorganisms before the product is dried. In the nutshell, the drying air must be constantly monitored by velocity, temperature and humidity to ensure quick and effective drying that does not alter the aesthetic and nutritional quality of the product (Mabrouk, 2012). The agro-processors and food industries employ several methods in product drying. Sanni *et al.* (2012) lists the commonly employed drying systems as Open sun drying, Cabinet dryers, Flash dryers, Solar cabinet Dryers, Rotary dryers and a combination of Solar and Indirect heating of the drying room, which can be described as a hybrid drying system.

Solar drying could be employed in the drying of cassava chips instead of open air and uncontrolled sun-drying or electrical/ mechanical drying. Open air drying comes with its attendant problems as product is unprotected from rain, wind-borne dirt and dust, infestation by insects, rodents and other animals. Also products may be seriously degraded to the extent that sometimes become market valueless and inedible, with the attendant adverse economic effects on domestic and international markets (Ogheneruona and Jusuf, 2011). The disadvantage of electrical/mechanical drying borders on the high cost and limited availability. Solar drying is effective in that it is economical, readily available and also avoids the problems associated with open air drying.

When drying a crop like cassava which is known to possess a high spoilage rate, conversion of the raw product into dried form must take place in an efficient, cost-effective system capable of completely drying the product within one day. This is particularly necessitated by the fact that if the product is subjected to intermittent drying, bacterial organisms could germinate and grow, and cause spoilage overnight. For cost effectiveness and other advantages, solar drying is the best choice. However, conventional solar dryers, most of which operate by natural convection are not satisfactory at achieving complete drying within one day. Cassava products are said to be ‘‘completely dry’’ when the moisture content is reduced from the initial value of 67-75%Wb to an acceptable limit of 14%Wb (Ogheneruona and Jusuf, 2011). To achieve this, forced airflow, generally termed ‘Forced Convection’ drying needs to be investigated. Forced convection drying here involves incorporating a fan in the design to give the hot air delivery needed for complete drying of the material within one day. This is the opposite of natural convection drying which depends on density differentials to move heated air. Further since the system is solar equipment, the source of power must also be solar. A photovoltaic ‘voltage generator’ needs then be incorporated into the design to generate the voltage needed to power the fan. Finally, Ogheneruona and Jusuf (2011) stated that the optimal drying temperature for cassava products is 52°C. Regulation of drying temperature within the optimum would be impossible with a direct solar dryer, thus an indirect solar dryer is what is required here.

Photovoltaic technology involves the direct conversion of sunlight into electrical energy, using solar panels or arrays. The advantages of this source of energy is that it is an inherently clean source of energy, produces no noise , smoke, acid rain, water pollutants, CO_2 or nuclear waste because it relies on the power of the sun for its fuel (Anon., (2012). The history of photovoltaic technology goes back to the year 1839, when Becquerel discovered the Photovoltaic effect. A semiconductor age began about 100 years later. After Shockeley had developed a model for PN junction, Bell Laboratories produced the first solar cell in 1954; with 5% efficiency (Quaschning, 2011). When light shines on a PV cell, it may be reflected, absorbed, or refracted. The absorbed light generates electricity if it possesses a ‘threshold energy’ needed to release electrons (Anon., 2013).

The objective of this work was to develop a forced convection dryer for crops.

2. MATERIALS AND METHODS

2.1 Design Concept/Consideration

An indirect forced convection solar dryer was designed and fabricated using low-cost materials. The effectiveness of the forced convection drying was measured by subjecting the dryer to test using cassava chips. The size of the dryer was fixed based on investigations using the design capacity. The following were considered for the design of the indirect forced convection solar dryer as adapted from Alonge and Oniya (2012), Ogheneruona and Jusuf (2011) and Babagana et al (2012).

2.1.1 Technical Design Considerations

The technical design considerations for the dryer include the following: The mass of cassava chips to be dried (taken as 2kg); the initial and final moisture contents of the cassava; the daily sunshine hours for the selection of total drying time; amount of moisture to be removed from the 2kg of wet product to bring the moisture content to a safe level in the drying time; the mass and volumetric flow rate of air (kg/hr; m^3/hr) needed for complete drying over the drying time (to be supplied by the fan i.e., for fan selection); the daily solar radiation to determine the energy received by the dryer per hour and hence determine; the area of the flat plate collector , (considering also; the average ambient temperature for Uyo meteorological area; the transmittance of the transparent glass cover; the absorptivity of the collector material; and the useful energy gain of the system); the Brake Horsepower (BHP) of the fan for rating of photovoltaic module (PV module selection); the watt-peak of photovoltaic which will supply the needed BHP; The dimensions of the drying chamber (to handle the design 2kg of cassava chips), and of the solar heater that will accommodate the fan size and the solar collector (of area designed); and the angle of inclination of the solar collector to the horizontal for optimum efficiency.

2.1.2 Sanitary Design Considerations

For ease of cleaning, the food contact surfaces (trays) are made of tin-coated wire meshes. Also the trays are removable to ease dislodging of any accumulated dirt. The non-food contact surface (wood) is covered with grey Formica and sealed with Porte sealant to prevent absorption of water and entry of insects and flies. The fan air inlet and outlet air vent are covered with fine nets to prevent the entry of tiny bodies, such as insects and flies.

2.1.3 Economic Considerations

For the lowest possible cost, the dryer is constructed with locally available materials. The plywood is thick enough to eliminate any need for additional insulation. The capacity of the photovoltaic is selected to supply just the needed power to the fan. The fan is also selected to supply just the needed air flow rate.

2.2 Design Analysis

The design is divided into two areas typical of food engineering design: solar cassava chips drying process design and solar cassava chips drying equipment design.

2.2.1 Process Design

- **Basis:** Process type: Batch; Weight of feed: 2kg Cassava Chips; Initial moisture content : 72% $^{w}/_{w}$ (wet basis); Final moisture content : 14% $^{w}/_{w}$ (wet basis); Ambient air temperature: 32°C for Uyo meteorological area (Augustine and Nnabuchi, 2010); Dryer temperature : 52°C
- **Material Balances:** The quantum of moisture to be removed to reduce the product moisture content to the safe level was determined using the material balance equation:

Total Material Balance (TMB): Total Input = Total output

$$F + H_a = V + D \qquad 3a$$

Where; F = Weight of wet cassava chips, $^{kg}/_{batch}$; D = Weight of dried cassava chips, $^{kg}/_{batch}$; H_a = Weight of heated air, $^{kg}/_{batch}$ and V = Weight of exhaust air saturated with water vapour, $^{kg}/_{batch}$.

- **Desired Drying Rate:** This was determined using:

$$R_d = {}^{Q}/_{t} \qquad 3b$$

Where; R_d is the desired drying rate; Q is mass of moisture removed and t is required drying time.

- **Energy Balances:** The mass flowrate of air required to achieve the desired drying rate was determined using the overall energy balance equation:

- **Total Energy Input = Total Energy Output**
  Energy in Raw cassava chips + Energy in heated air = Energy in Dry cassava Chips + Energy in Water vapour

$$F\,\left({}^{kg}/_{batch}\right) C_{pf}\ {}^{kJ}/_{kg°C}\,(52-t_d)°C + H_a\left({}^{kg}/_{batch}\right) C_{pa}\ {}^{kJ}/_{kg°C}\ (52-t_d)°C$$

$$= \ D\left({}^{kg}/_{batch}\right) C_{pp}\ {}^{kJ}/_{kg°C}\ (52-t_d)\,°C + Q\left({}^{kg}/_{batch}\right)\{\Delta h_{lv} + \Delta h_{vv}\}\,{}^{kJ}/_{kg} \qquad 3(c)$$

Where: $Q\,{}^{kg}/_{batch}$ = Mass of moisture to be removed = $1.35\,{}^{kg}/_{batch}$; $C_{pf}\ {}^{kg}/_{batch}$ = Specific heat capacity of wet chip;

$C_{pa}\ {}^{kJ}/_{kg°C}$ = Specific heat capacity of air; $C_{pp}\ {}^{kJ}/_{kg°C}$ = Specific heat capacity of dried chips; $\Delta\, h_{vv}\ {}^{kJ}/_{kg}$ = Enthalpy of vaporisation of vapour and $\Delta h_{lv}\ {}^{kJ}/_{kg}$ = Enthalpy of liquid.

- **Volumetric Flow rate of Air Required**

$$V_a = \frac{H_a\,{}^{kg}/_{hr}}{\rho(air)\,{}^{kg}/_{m^3}} \qquad 3\ (g)$$

Where, $\rho(air)$ = Density of air at 52°C (325K) and atmospheric pressure and H_a is mass flowrate of air.

2.2.2 Equipment Design

The equipment design involved the following: Fan selection, Photovoltaic panel selection, solar air heater design and drying cabinet design.

- **Fan Selection:** The fan type considered for the design was vane axial fan for technical reasons**.** The volumetric flow rate of the fan as calculated is $10cfm$; but for the purpose of selection an *overdesign factor* of 2 was introduced. The duct Static pressure was estimated as $0.0249KPa$. These data were used to select the correct fan for the job from NIDEC fan catalogue.
- **PV Panel Selection:** For size considerations, a photovoltaic panel of ratings 12VDC; 15W was selected to be used with a 24VDC Deep Cycle Battery already charged to full capacity. This supplies a voltage of 24VDC across the fan terminals for maximum capacity.
- **Solar Air Heater Design:**
- The **area of the flat plate solar collector** was determined using equations 3c and 3d given by (Mumah, 1995)

$$\boldsymbol{Q_u = H_a C_{pa}(T_2 - T_1)} \qquad \textbf{3c}$$

$$\boldsymbol{Q_u = A_C[T\alpha I_T - U_L(T_{pm} - T_a)]} \qquad \textbf{3d}$$

Where: H_a is Mass flow rate of air, T_1;T_2 are ambient and dryer temperature respectively; I_T = Total incident solar radiation on the collector cover $KJ/_{hr.m^2}$; $\boldsymbol{T\alpha}$ = Effective transmittance-absorptance product of the collector; $\boldsymbol{A_C}$ = Collector area, m^2; $\boldsymbol{U_L}$ = Collector overall heat loss coefficient, $KJ/_{hr.Km^2}$; $\boldsymbol{T_{pm}}$= Mean temperature of the collector absorber plate; and $\boldsymbol{T_a}$ = Outdoor or ambient air temperature.

- **Inclination of the Collector** $\emptyset$: The angle of inclination of the collector was fixed based on the latitude of Uyo given by Augustine and Nnabuchi (2010) as 5.06[redacted]
- **Other parameters** such as the collector and cabinet dimensions were fixed using simple geometry.

2.3 Equipment Construction and Performance Testing

The equipment was constructed at the Faculty of Engineering Workshop, University of Uyo, Nigeria. Testing of the dryer took place at the vicinity of Food Engineering Laboratory, University of Uyo, Nigeria.

2.3.1 Temperature and Relative Humidity Measurements

The equipment was subjected to temperature tests at no load (4th May 2014) and at loaded condition (5th May 2014 and 9th May 2014).Tests were run from 0600hrs to 1700hrs each day. A Digital thermometer was placed outside to read ambient temperature. Another Digital thermometer was inserted into the drying chamber to read temperature of the cabinet while a mercury-in-glass thermometer was inserted into the solar air heater to read the temperature of the heated air. Also two Wet-and-dry bulb thermometers (psychrometers) were placed each at the inside and outside to obtain Wet and dry bulb temperatures utilized in estimating the relative humidity of the drying cabinet and ambient air respectively, using standard CIBB'S Psychrometric chart.

2.3.2 Drying Tests/Moisture Content Determination

The equipment was tested with cassava chips. The Cassava roots was washed, peeled, washed and sliced into chips of standard sizes (3-5mm) in diameter, using a manual slicer. The sliced chips was then blanched at 70°C for 2minutes to deactivate the enzymes and microorganisms present. 1kg of blanched cassava chips was placed in each tray and loaded into the dryer. The equipment was allowed to start up for 1hr and the fan put on for the equipment to run under forced convection. The drying experiment was conducted in two replications.

Each drying experiment started with the determination of initial moisture content. Samples were taken and analysed for moisture content using the AOAC Standard, involving oven dry method. Weight measurements were carried out using the weighing balance. The moisture contents were determined using the following equation (Alonge and Oniya, 2012).

$$\text{MC (wet basis)} = {(w_2 - w_3)}/_{(w_2 - w_1)} \qquad 3(j)$$

Where; w_1 = weight of empty crucible; w_2= weight of crucible + sample before oven drying; w_3 = weight of crucible + sample after drying

2.2.3 Efficiency and operational Capacity of the Dryer

The efficiency of the convective solar dryer was calculated using Equation 3(k) (Mumar, 1995).

$$E = {M_W L_V}/{(I_T A_C + E_f)} \qquad 3k$$

Where, E = current dryer efficiency, ; M_W= evaporated moisture mass of the product, kg ; L_V= specific latent heat of water vaporization, kJ/kg; I_T= solar radiation energy per collecting area, kJ/m^2; A_C= collector area,m^2 ; E_f = fan energy, kJ

- The operational capacity of the dryer was calculated using equation 3(l)

$$M_W/t_s \qquad 3(l)$$

Where, t_s = time in hours

2.4 Design Features and Construction Details

The Solar Powered air dryer is an innovative technology based on a combination of Solar Thermal and Photovoltaic Technologies. The main parts of the equipment can be divided into three; the Drying abinet, the Solar Air Heater, and the Voltage generator. The drying cabinet has dimensions $900 \times 540 \times 525\, millimeters$ and is fitted with two high strength wire gauze trays of dimension $490 \times 475\, millimeters$; the wire gauze is supported with wood rod. The distance between the trays is $250\, millimeters$. The inside of the dryer is painted black to enhance the absorption and radiation of heat; the effect of which prevents the loss of heat by conduction through the wood. At the front of the cabinet is an access door fitted with a handle for easy opening and closing. The door is specially designed to fit when closed to reduce heat losses. Figure 1 shows the front features of drying cabinet.

Fig. 1: The Dryer Showing the Drying Cabinet.

At the top left hand side of the drying cabinet is an exhaust air vent of diameter $54\, millimeters$ as revealed by the isometric picture of Figure 2. The air vent and fan air inlet are covered with a fine mesh to keep out insects and pests while allowing easy passage of air out of the dryer and into the dryer respectively. Figure 2 also shows the drying cabinet trays in an exploded position with the dried cassava chips.

Figure 2: Internal Features Showing the Dried Cassava Chips.

The solar air heater comprises a flat plate solar collector of area (0.32m^2(690 X 460 millimetres) made from black-painted aluminium. The collector is placed at angle 5.06^{0}C for maximum energy absorption and encased in a wooden box covered with silicate glass of 2.5 millimetres in thickness for green-house effect. Axial to the collector length is a dc axial flow fan, 200 millimetres in diameter. Figure 3a shows the external features of the solar air heater. The circular opening is the fan air inlet; the transparent silicate glass reveals the heat absorber inside.

Plate 3a: Pictorial View Showing the Solar Air Heater and PV

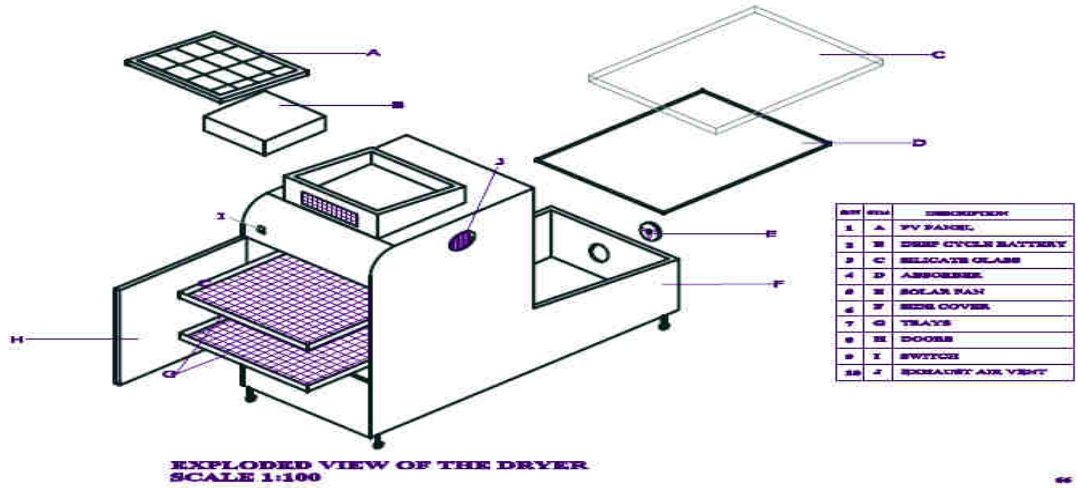

Fig. 3b. Exploded view of the dryer scale 1.100

The Voltage generator comprises a Photovoltaic panel, a horizontally placed deep-cycle battery, and an enclosure with an opening to aerate the battery, as well as wiring. The Photovoltaic panel is connected to the battery which is in turn connected to a breaker (switch) and to the dc fan. The Switch is placed in front of the drying cabinet. Fig. 3b also reveals the solar voltage generator at the top of the drying cabinet. The solar panel is fixed at the top at an angle of 5.06℃.

The body of the dryer is made of plywood of thickness 1.5 centimetrs. The bottom cover of the dryer is made of plywood of the same thickness. The external surface of the dryer is covered with grey Formica for durability and aesthetic reasons. The equipment is mounted on movable casters to allow rolling movement of the equipment. The equipment is designed for Uyo meteorological area and is located North-South during solar drying.

2.5 Working Principles of the Equipment

The Cassava *(Manihot spp)* chips are placed in the perforated wire gauze trays (which are removable), perforations allowing for the rising of heated air through the two trays. Heated air enters the drying chamber from the solar air heater via an opening between the cabinet and the solar air heater. As the heated air rises, the product is dried by transfer of heat from the air to the product and transfer of moisture (mass) from the product to the activated air. The exhaust air mixed with water vapour leaves the cabinet through the exhaust air vent. The heat delivered to the drying cabinet is generated by a solar heat collector made of black-painted aluminium and placed in the solar air heater. The dc axial flow solar fan blows air across the collector to be heated and delivered into the drying cabinet. The fan sucks in air through a specially designed opening equal in diameter to the fan. Power delivery into the dc fan is controlled using the on/off switch located on the drying chamber.

The solar photovoltaic panel generates the voltage, through the photoelectric effect, which in combination with the current flow constitutes the power supply to the dc fan. The Solar panel also charges a deep cycle battery which serves as a backup, ensuring a supply of 24Vdc across the fan terminals. Both solar panel and Solar air heater are inclined in the posterior direction at 5.06℃ and aligned due South for maximum solar energy utilization.

3. RESULTS AND DISCUSSION

3.1 Temperature Variations with Time

The drying equipment was tested under no load and load conditions. Figure 4 shows a typical of ambient, collector and solar drying cabinet air temperatures. From the result obtained under no load test, it is clear that the temperature of the solar collector air is the highest, followed by the cabinet temperature. At an ambient temperature of 35℃, the temperature in the drying cabinet reached its peak for the day at 45℃ while the collector temperature reached its peak for the day at 60℃. One striking observation here is that despite the forced air delivery of the fan, the temperature in the collector area was always higher than the temperature of the drying chamber. It is also safe to candidly state here that the design temperature (52℃.) was exceeded at the collector area on this typically sunny day, but the maximum temperature in the drying chamber was 45℃.

Fig. 5 shows the ambient, collector and drying cabinet temperatures for the first drying replication. The figure shows that even at low ambient temperatures the temperatures in the cabinet and collector are higher, although the difference is not significant. However at very low ambient temperatures, the fan tends to cool the system and the collector and cabinet temperatures continued to fall as observed between 1400h and 1700h.

Fig. 6 shows the variation with time of the ambient, collector and drying cabinet air temperatures, under load (during the second replication). The figure shows that as the ambient temperature increases, both the collector and cabinet temperatures also increase rapidly in such a way that the temperature of the cabinet and collector are always higher than the ambient temperature. The day was a typical sunny day.

3.2 Variation of Relative Humidity with Time

The relative humidity variations for ambient and drying cabinet air are shown in Figure 7. The curve shows that at all time intervals and temperatures, the relative Humidity within the dryer is lower than the relative humidity outside the dryer. This lower Relative humidity in the drying chamber accounts for the ease of mass transfer of moisture from the product to the air. The Graph also shows a rapid increase in drying chamber air relative humidity between 2pm and 5pm.

3.3 Variation of Moisture Content with Time

Fig. 8 shows the variation of moisture content of the cassava chips with time (first replication). Relating the figure to Figure 5 (showing the variation of temperature with time), it can be seen that there was no significant drop in moisture content of the product due to the poor weather conditions (low ambient and dryer temperatures). At the end of the one-day drying period, the product still contained 57% moisture on wet basis. The insignificant moisture loss must also have been due to high air humidity occasioned by the rain. The first replication could not continue the next day as the product was already deteriorated.

Fig. 9 is a drying curve (graphical representation of the variation of moisture content of the cassava chips with time) during the second replication. The moisture content of the product reduced slowly during the early hours of the day, but very rapidly between the hours of 3pm to 5pm, reaching a final moisture content of 14% wet basis at 6pm. Relating the figure to Figure 6, (showing the variation of temperature with time during the same (second) replication), the high moisture reduction rate compared to the first replication occurred due to the relatively high ambient and dryer temperatures. Also, relating this curve to Figure 7 (showing the variations of relative humidity with temperature), it can be seen that the increased moisture loss from the product between 2pm and 5pm caused the relative humidity in the drying chamber to rise rapidly. The results obtained during this second drying test is very close to the design objective; the difference being that while the design calculations was aimed at achieving complete drying (reduction of moisture content to 14% on wet basis) in 9hrs (8:00am to 5:00pm), the drying process achieved the safe moisture content of 14% wet basis in 10hrs (8:00am to 6:00pm).

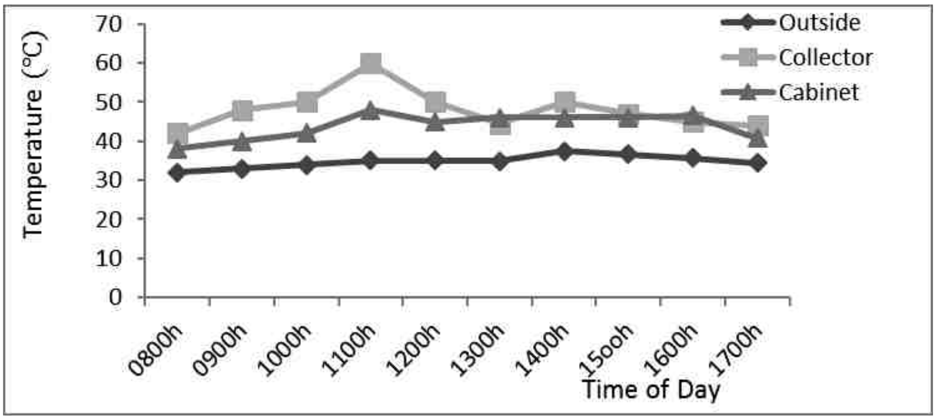

Fig 4: Variation of Temperature with time (no load)

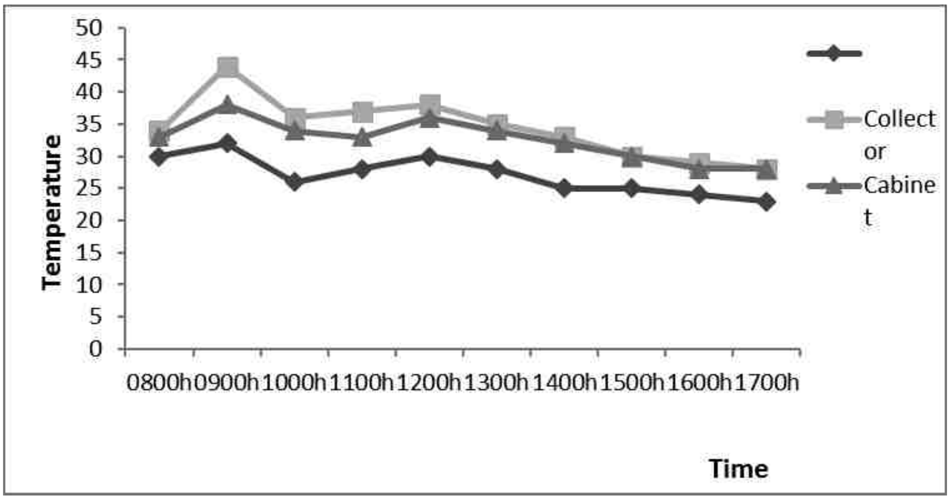

Fig. 5. Variation of Temperature with Time (Under Load; First Replication)

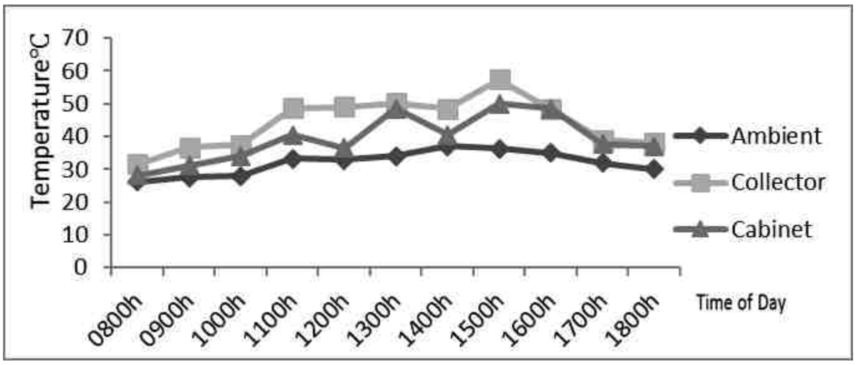

Fig 6. Variation of Temperature against Time (Under Load; Second Replication)

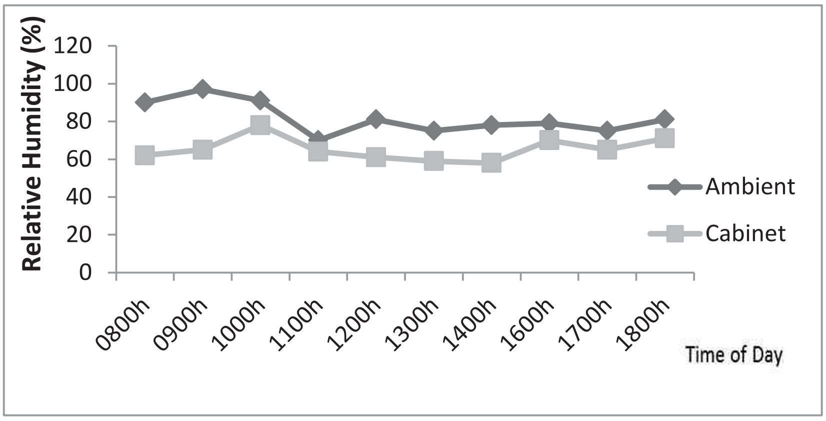

Fig 7. Variations of Relative Humidity with Time (Second Replication)

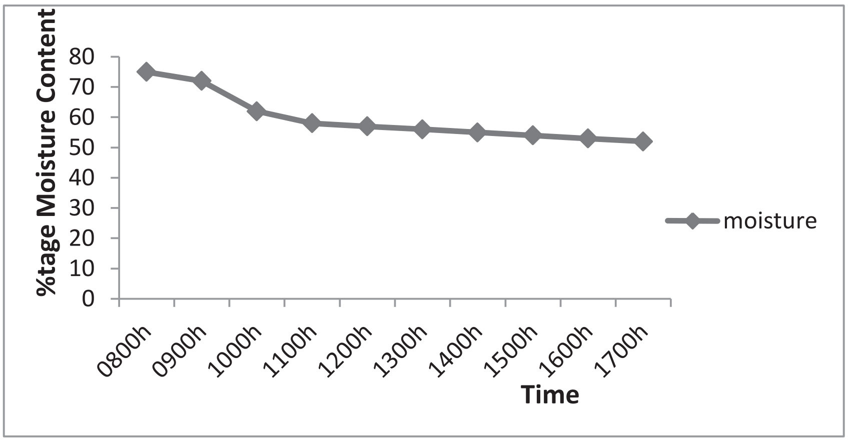

Fig 8. Variation of Moisture Content with Time (First Replication)

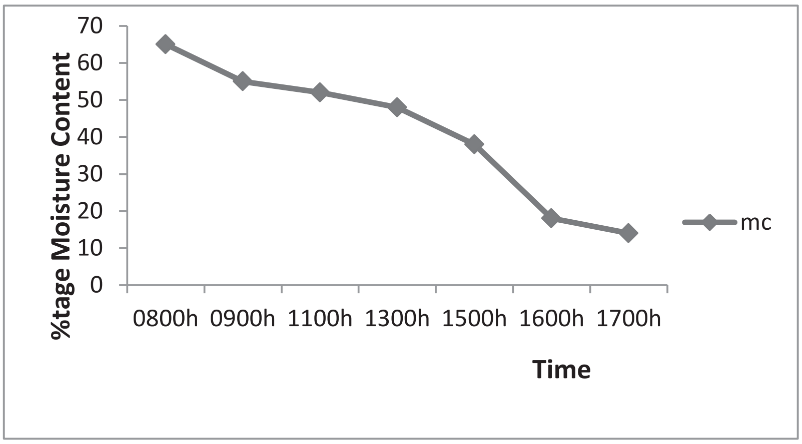

Fig 9. Variation of Moisture Content with Time (Second Replication)

4. CONCLUSIONS AND RECOMMENDATIONS

The essential steps of the engineering design method as well as the heuristics of intelligent designs were followed in design, construction, and performance evaluation of the Indirect Forced Convection Dryer for Cassava Chips. The results obtained fall within regions of acceptability. From the results it could be concluded that:

(i) Forced convection solar dryers can generate temperature significantly higher than the ambient temperatures, provided the intensity of sunlight is sufficient;

(ii) In cases of insufficient intensity of solar radiation, occasioned by poor weather conditions experienced in a rainy season, the fan tends to cool the system, and the collector and drying chamber temperature falls with time;
(iii) As a result of (i) above, the drying rate of product in forced convection solar dryers is significantly high at good ambient conditions;
(iv) As a result of (ii) above, the rate of drying of product in forced convection solar dryers is unimaginably poor at very poor weather conditions and very low solar intensity.
(v) The dryer achieved significant reduction in the relative humidity of air and this accounts for the high drying rate obtained during the second drying replication.
(vi) In a normal day (with high solar insolation), it is possible to dry cassava chips in the forced convection solar dryer to a safe moisture content in just $10 sunshine\ hours$ compared to the 2-3 days product drying obtainable in natural convection drying as reviewed in section 2.7.

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