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Design, Construction and Performance Evaluation of A Mixed-Mode Solar Dryer

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ABSTRACT
This paper presents the design, construction and performance evaluation of a 100 kg capacity cassava mixed-mode solar dryer, incorporating a black painted conical chimney to serve as an additional absorber. The constructed dryer was tested with 10%, 25% and 50% load dryer capacity for drying of cassava chips. The peak and minimum solar collector outlet air temperatures as observed during the period of the experiment were 81°C and 14°C respectively. The average dryer temperature was found to be 40.9 °C. The average weight loss were 0.52 kg, 1.01 kg and 1.56 kg per hour for initial total load capacities of 10%, 25% and 50% respectively. The average drying efficiencies of the various load capacities were found to be 15.3%, 26% and 40% respectively. The solar radiation received through the glass, used for the covering of the drying chamber sides contributed about 25% of the total energy used for the drying process.

KEY WORDS: *Cassava, mixed-mode, loss, wind speed, conical chimney*

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I. INTRODUCTION

The postharvest loss from agricultural products in temperate geographic locations like Zaria is really an issue of concern. The practical use of the energy from the sun, electricity or fossil fuels for the purpose of drying agricultural products will go a long way in reducing post-harvest loss. Drying is an ancient phenomenon that existed from the earth's creation, but the technological research work into the concept of drying process started around mid-twentieth century. Drying process play a very important role in the preservation of agricultural products [1]. Drying simply put, is a simultaneous heat and mass transfer process consisting of the removal of water in moisture form, by evaporation from the surface of a substance under consideration.

Traditional open air sun drying process is one of the oldest, simplest and widely practiced by local farmers in the rural areas. The process requires relatively low capital investment, large drying area, is time consuming, and is generally unhygienic. Mechanised dryers, which are of recent being preferred to the traditional open air sun drying process, are much faster in drying process, use less drying area, but require a substantial quantity of fossil fuels or electricity to operate which makes it energy intensive. Solar drying is an improved drying process, because studies undertaken so far have clearly indicated that while the initial cost of solar dryers are high, the life time cost of drying is only a third of the dryers based on conventional fuels [2].

In most of the developing countries, use of fossil fuels for drying agricultural products has not been practically feasible due to unaffordable costs to majority of the farmers [3]. The solar drying process harnesses the free and inexhaustible needed energy without any pollution, thereby removing the carbon dioxide (Co_2) emissions and preventing other products of combustion of fossil fuels from precipitating on the earth as acid rain. The use of solar energy for drying agricultural products in the tropics is quiet feasible, since at least six (6) hours of sunshine are received every day at 500-800 W/m^2 of radiation per hour resulting in about 185 W/m^2 /day of insolation [4]. Solar dryers may be classified into two major groups' namely; active and passive solar energy drying systems. They can further be divided into three distinct sub-classes namely; integral (direct), distributed (indirect) and mixed-mode solar dryers. A mixed-mode solar dryer combines aspects of direct and indirect types, a separate collector preheats an incoming airflow and then direct sunlight adds heat to the airflow and the product as well. Among the different types of natural convection solar dryers, the mixed-mode type has been demonstrated to be superior in speed of drying [5].

Nigeria is currently the world's largest producer of cassava accounting for over 70 % of the total production in West Africa and about 40 % of the global annual production [6]. The mean moisture content of cassava root is about 62.8% [7]. The losses are estimated after harvest to be more than 50%, with 23.3% major losses occurring during processing, 13.6% losses during harvest and 8.5% losses at handling [8]. Nigerian government is currently promoting large scale production of cassava roots either as flour, pellet or chips. Cassava chips are pieces of dried irregular slices of cassava which vary in sizes but not exceeding 5-6 cm in length [9]. The optimum drying temperature of cassava products was found to be 52^0C [10].

However, a dryer utilizing the energy in the sun for use by rural farmers for drying of agricultural products will be designed, constructed and tested. This work will focus on increasing the solar radiation received by using glass to cover the drying chamber sides and improving the airflow rates in the drying chamber by incorporating a back painted conical chimney. Fresh cassava chips samples will be used to evaluate the performance of the cassava mixed-mode solar dryer.

II. DESIGN THEORIES

2.1 Solar intensity on collector surface

Total solar radiation coming from the sun to the earth surface can be used for generating electricity for heating of water, air and other materials. The global solar radiation incident on a collector surface is usually in the form of beam (direct), diffuse (sky) and solar radiation reflected from the ground and the surroundings. The direct solar radiation is the radiation that comes directly from the sun to the earth surface in a bright and clear day. The diffuse solar radiation comes indirectly from the sun after reflection and scattering by the atmosphere and ground. The intensity of solar radiation on a collector surface is affected directly by the changes in location of the sun.

The total solar radiation, I_T on a surface of an arbitrary orientation as given in [11] is:

$$I_T = I_b\ R_b + I_d R_d + \rho R_r \left(I_b + I_d\right) \tag{1}$$

Where, I_b is beam radiation (W/m^2), I_d is diffuse radiation (W/m^2), R_b is beam radiation conversion factor, R_d is R_d is diffuse radiation conversion factor, R_r is reflection radiation conversion factor and ρ is reflection coefficient of the grounding.

2.2 Collector overall heat loss

The overall heat loss can be determined by considering the thermal loss from the collector to the surroundings by conduction, convection and radiation. The heat loss to the surrounding from the plate through the glass cover as top loss, from the plate through the insulation as back loss and the side of the collector casing as edge loss. The overall heat loss coefficient, U_L , is the sum of the top, back and edge loss coefficient and is given by [12],

$$U_L = U_T + U_b + U_e \tag{2}$$

Where, U_T is top loss coefficient (W/m^2 K), U_b is back loss coefficient (W/m^{2}K) and U_e is edge loss coefficient (W/m^{2}K)

2.3 Energy absorbed by the collector

The rate of useful energy gain by the collector under steady state condition is proportional to the rate of useful energy absorbed by the collector minus the amount of energy lost by the collector to its surroundings. The useful energy gained by the collector will be transferred to the medium passing through it. Therefore, useful energy is given by [13].

$$Q_u = m_a C_p \left(T_o - T_i\right) \tag{3}$$

Where, m_a is mass of air (kg), C_P is specific heat at constant pressure (J/kg), T_i is inlet fluid temperature, T_o is outlet fluid temperature.

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. Therefore, the actual useful energy gain, Q_u , is determined by multiplying the collector heat removal factor F_R by the maximum possible useful energy gain and the expression is known as the "Hottel Whillier -Bliss equation given by [13]:

$$Q_u = F_R A_c \left[I_T (\tau\alpha) - U_L (T_i - T_a) \right] \tag{4}$$

Where, F_R is collector removal factor, A_c is collector surface area (m^2), T_i is inlet temperature (^{0}C), T_a is ambient temperature (^{0}C), τ is transmittance of glass cover and absorber plate and α is absorbtance of glass cover and absorber plate.

2.4 Solar collector area

The solar collector surface area can be deduced by considering equations (3) and (4), and assuming that collector inlet air temperature, T_i, and the ambient air temperature, T_a, are approximately equal, we obtain the collector area, A_c as:

$$A_c = \frac{m_a C_p (T_o - T_a)}{F_R [(\tau\alpha) I_T]} \tag{5}$$

Where, $A_c = Lb$ (collector area), *b*=collector breadth and *L*= collector length

2.5 Natural ventilation flow

Natural ventilation is the process of drawing a relatively denser air from the bottom of a duct and exhausting a less dense air through the top of the duct without using a mechanical system, or a passive strategy using both wind and temperature differences to ventilate spaces. A well designed chimney with additional height with all air passages increase the air pressure differential. The solar chimney will be designed to capture solar radiation to increase the heat of the air at the top and thereby increasing the difference in temperature between the incoming and the out flowing air. The increase in natural convection that occurs from these measures enhances the drawing of air through the system. The natural ventilation due to the chimney effect is given by the expression from [14].

$$V_{exit} = \sqrt{gH \left(\frac{T_{avch} - T_a}{T_{avch}} \right) \Big/ \left(1 + \left(\frac{A_2^2}{A_1^2} \right) \right)} \tag{6}$$

Where, V_{exit} is air velocity at the chimney exit (m/s) , H is the height between collector inlet and the chimney exit (m), T_{avch} is the average drying chamber temperature , T_a is the ambient temperature, A_1 is the collector inlet area (m^2), A_2 is chimney exit area (m^2)

2.6 Air Mass Flow on the Absorber Plate

The mass flow rate of air on the absorber plate can be determined by considering the average air speed of the location (Zaria town), the breadth of the collector and the air gap height between the absorber plate and the collector glazing. Thus, volumetric flow rate of air, $\dot{V}$, is given by the expression.

$$\dot{V} = V_a h b \tag{7}$$

Where, V_a is ambient air velocity, *h* is air gap height, *b* is collector breadth

Density of air, ρ_a , is given as mass per unit volume.

Therefore, the mass flow rate of air, m_a , will be given by the expression

$$m_a = \rho_a \dot{V} \tag{8}$$

2.7 System Drying Efficiency

Drying efficiency is defined as the ratio of the energy required to evaporate the moisture inside the product to the energy supplied to the dryer. Total heat in this case of solar dryer is the available solar radiation upon the collector surface supplied to the dryer. The system drying efficiency is calculated from [15]:

$$\eta_{sys} = \frac{WL_v}{tA_c I_T} \tag{9}$$

Where Where, W = *m*oisture evaporated, L_v = latent heat of vaporisation of water, t = time

2.8 Exergetic Efficiency

Exergy is a measure of the maximum amount of work or potential which can be produced by a system or flow of matter to cause change, as a consequence of not being completely in stable equilibrium relative to the reference environment, and it is expressed mathematically as follows [16]:

$$\text{Inflow exergy}, H_{Xin} = C_p\left[\left(T_{inav} - T_a\right) - T_a \ln\left(\frac{T_{inav}}{T_a}\right)\right] \tag{10}$$

$$\text{Outflow exergy}, H_{X\,out} = C_p\left[\left(T_{outav} - T_a\right) - T_a \ln\left(\frac{T_{outav}}{T_a}\right)\right] \tag{11}$$

$$\text{Exergy loss}, H_{XL} = H_{Xin} - H_{Xout} \tag{12}$$

$$\text{Exergetic efficiency,} \qquad \eta_X = \frac{H_{Xinav} - H_{Xlossav}}{H_{Xinav}} \tag{13}$$

Where, T_a is ambient temperature, T_{inav} is mean collector inlet temperature, T_{outav} is mean collector inlet temperature, H_X is exergy, H_{xav} is average exergy, H_{Xin} is average exergy inflow, H_{XL} is exergy losses, $H_{Xlossav}$ is average exergy losses, H_{Xout} is average exergy outflow.

2.9 Design Considerations

The following considerations were made in the design of the cassava mixed-mode solar dryer:

1) The layout of the drying chamber to house the samples to be dried;
2) The method of loading and offloading the samples;
3) Variation in ambient temperature, relative humidity, wind velocity at the location;
4) Availability of solar radiation; and
5) The amount of moisture to be removed from a given quantity of fresh samples.

III. MATERIALS AND METHODS

3.1 Description of the cassava mixed-mode solar dryer

The cassava mixed-mode natural convection solar dryer was constructed at the Nigerian College of Aviation Technology, Zaria and operated at the Department of Mechanical Engineering, Ahmadu Bello University, Zaria. The dryer consists of three main sections coupled together. These are: solar collector, drying chamber and conical chimney. Figure 1 shows the sketch of the whole assembly of the cassava mixed-mode solar dryer.

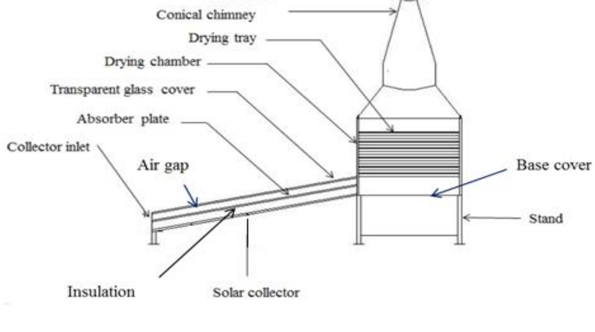

Figure 1: Sketch of the cassava mixed-mode solar dryer.

The first section is a solar collector system, with dimensions of 3000 mm long x 1200 mm wide x 188 mm high, consisting of an absorber plate, a single glass cover, insulation and back cover. The main framework of the solar collector system was constructed with 19.1 mm and 25.4 mm plywood. A flat gauge 12 galvanized iron sheet painted black was used as collector absorber plate because of its high solar radiation absorption, high thermal emissivity, protection from corrosion, ease of maintenance and long life. The single layer of a transparent clear glass cover with thickness of 4 mm is applied on the top surface of the collector. The collector was insulated with 65 mm thick sawdust and 35 mm thick glass wool from the bottom respectively. During the test, air flows through the netted space between the glass cover and the absorber plate. As the air passes through, it gets heated before going up the drying chamber by buoyancy. The distance between the glass cover and the absorber plate is 50 mm. A transverse section of the collector is shown in Figure 2. The solar collector system was placed facing south and was tilted at the Zaria latitude of 11.10 ^{0}N [17] from the horizontal.

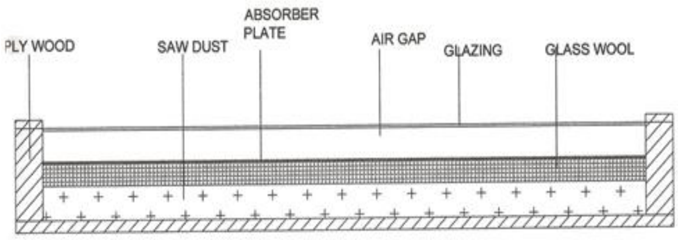

Figure 2: A transverse section of the solar collector system

The second section is the drying chamber, made of 38.1 mm x 38.1 mm x 4 mm angle iron, with volume of 1200 mm x 1500 mm x 1228 mm. The drying chamber comprises of a module, bottom cover and external walls. The module is divided into two, left wing and right wing, each wing of the module consists of ten (10) levels of trays with two (2) trays on each level. The trays are placed at a vertical distance of 7 cm apart. The effective dimension of one tray is 1492 mm x 538 mm x 25.4 mm, and was made from 25.4 mm x 25.4 mm x 2 mm angle iron. A schematic view of the drying chamber is shown in Figure 3.

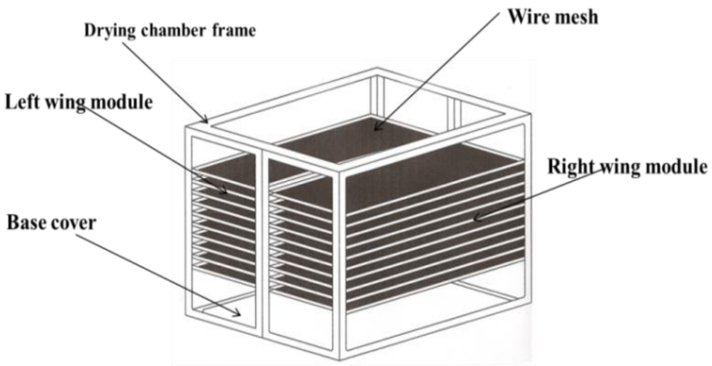

Figure 3: Schematic view of the drying chamber

A wire mesh is also riveted to the base of all the frames of the trays. Each drying tray can conveniently contain about 3 kg of fresh cassava chips at a time, with enough spacing in between to allow airflow through. All the trays can be easily reached by an average man of height (1.62 m). The bottom is covered with a base board made of plywood which is also painted black. For the purpose of loading and offloading the drying trays, two access doors of dimension 1228 mm x 600 mm each, was constructed at the rear of the dryer. The external walls of the drying chamber with exception of the top and bottom were all covered with 5 mm thick clear glasses to eliminate the requirement for insulation, but rather to increase the overall solar radiation received by the drying samples. The glasses were secured to the dryer walls by screwing 19.1 mm black pipes along with rubber seals on the drying chamber frames. The rubber seals are there to prevent leakages between the glass covers and the dryer frames. The whole drying chamber sits on a structural support stand made of 50.8 mm x 50.8 mm x 6.35 mm angle iron. The third section is the conical chimney also painted black with dimension of 1500 mm x 1200 mm x 2000 mm. It was constructed from gauge 18 flat mild steel plate, to increase the speed of airflow at its exit and also decrease the relative humidity of the air around it. A mild steel plate was used for the construction of the conical shaped chimney considering its relative low cost. The chimney also contains a constructed exhaust hood to prevent rain or water from entering the drying chamber through the upper part.

3.2 Experimental setup and procedure

This setup in Figure 4 was used to evaluate the performance of the solar dryer by monitoring the moisture loss and the drying rates of samples to be placed in the left and right wing module of the drying chamber. The instruments and components used were as follows: A digital thermometer, two (2) digital hygrometers, two (2) digital anemometers, six (6) T- type copper/constantan thermocouple wires and two (2) upload weighing scales. The temperatures at six (6) different points were taken using a digital thermometer. The temperatures measured are for ambient air, collector air inlet, collector absorber plate, collector air outlet, drying chamber and chimney air outlet. The relative humidity of the drying chamber (inside) and the atmospheric air (outside) were recorded in percentage using two (2) digital hygrometers. The wind speed of the chimney outlet air and ambient air was measured using one (1) national geographic TM wireless wind chill and humidex thermometer and one (1) hand held cup anemometer wind direction respectively. The weight of each drying sample placed on a tray was obtained by using an upload weighing scale calibrated in kilogrammes. The energy received from the sun on the solar collector as incident global solar radiation expressed in Watts per square metre, for Zaria location data, was obtained from the weather data generation of the Weather Analytics Incorporated in the United States of America.

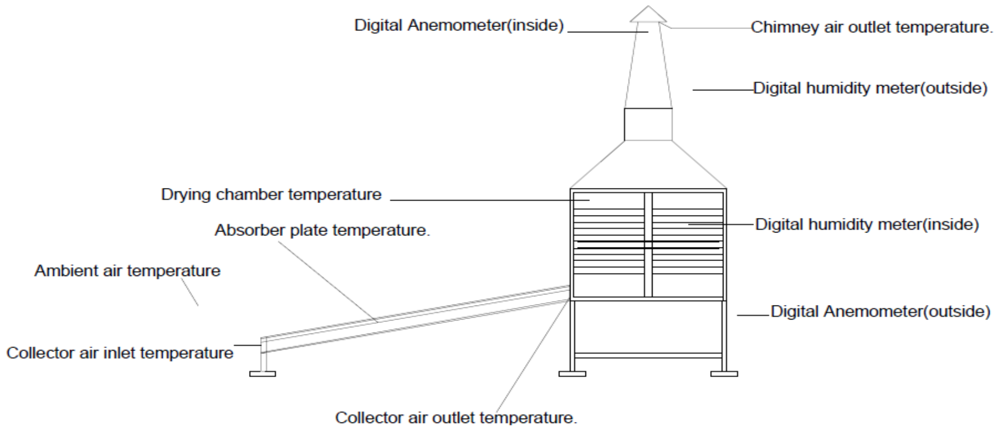

Figure 4: Schematic view of the cassava mixed-mode solar dryer showing measurements points

In order to analyze the performance of the cassava mixed mode solar dryer measurements at two hours interval were taken between the hours of 07:00 and 19:00. The harvested cassava roots were peeled and sliced into chips of uniform disk of 5 mm thickness using a clean stainless steel table knife. The cassava chips of various load capacities tested were 10% placed on five (5) trays, quarter (25%) placed on ten (10) trays and half (50%) placed on twenty (20) trays.

IV. RESULTS AND DISCUSSION

4.1 Solar collector performance

From the hourly variation of temperature against time for an eight (8) day drying test, the peak and minimum temperatures of air at the solar collector outlet as observed were 81^{0}C and 14^{0}C respectively and are shown in Figure 5 and Figure 6 respectively. The average collector air outlet temperature was found to be 52.63^{0}C, which is in agreement with [10]. The average dryer temperature was found to be 40.9^{0}C.

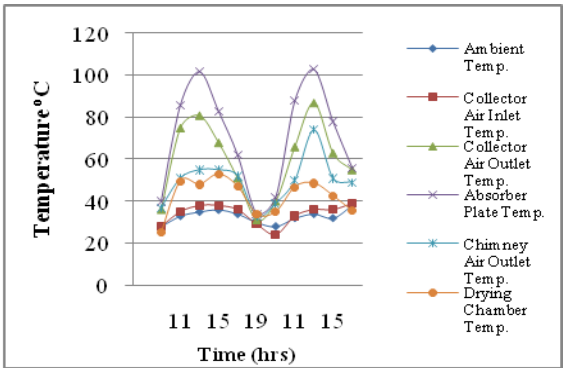

Figure 5: Variation of temperature against time for 10% load capacity on 11/03/2011

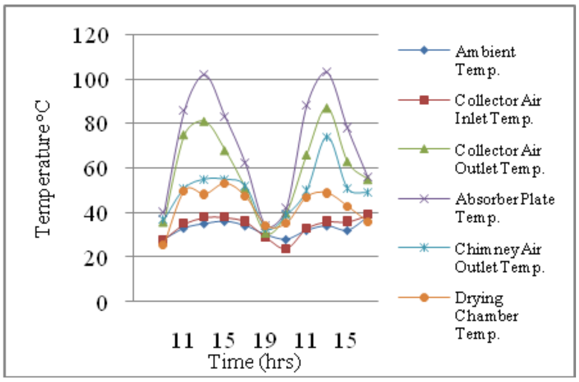

Figure 6: Variation of temperature against time for half load capacity on 18 & 19/03/2011

4.2 Airflow rate

The wind speed as measured with the anemometer placed at the chimney exit read zero throughout, this implies that the wind speed in the dryer was not significant enough, even with the incorporation of a conical chimney to increase the speed of airflow at the dryer exit. But the chimney exit velocity was found to 1.41 m/s.

4.3 Drying Efficiency

The average weight loss per hour for 10%, quarter and half load capacities were found to be 0.52 kg, 1.01 kg and 1.56 kg respectively. In figure 7, the drying efficiency increased as the load of samples was increased in the dryer. The average drying efficiencies of the various load capacities were found to be 15.3%, 26% and 40% respectively.

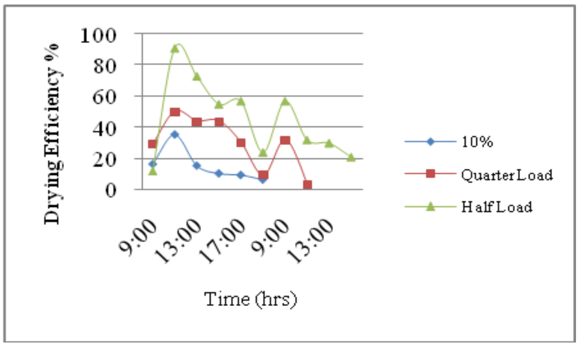

Figure 7: Variation of dryer efficiency against time

4.4 Exergetic Efficiency

Figure 8 shows the variation of exergy inflow, outflow and loss against load capacity and as observed their respective values increased with increase in loading and began to decrease beyond 10% load, with a minimum average recorded at half load. The average exergetic efficiencies for the various load capacities were found to be 39%, 45% & 34.5% respectively, shown in Figure 9.

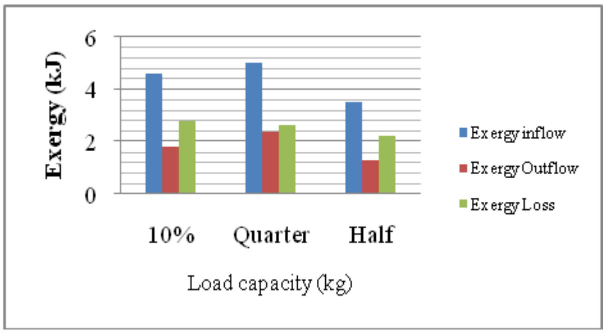

Figure 8: Variation of exergy inflow, outflow and losses against load capacity

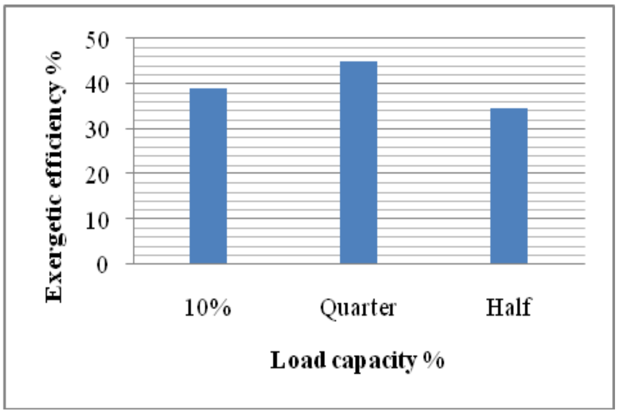

Figure 9: Variation of exergetic efficiency against load capacity

V. CONCLUSION

The following conclusions can be drawn.

1) A cassava mixed-mode solar dryer was designed, constructed and tested and on an average it takes 2 days to dry a batch of cassava chips sample.
2) Drying rate varies with coordinate position of trays; it decreases from the bottom tray up to a minimum at the middle tray and starts increasing up to the top tray.
3) The average percentage moisture removed (wet basis), collector efficiency and exergetic efficiency for half drying capacity were 8.76%, 40% and 34.5% respectively.

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