Development and Performance Evaluation of a Mixed-Mode Solar Yam Dryer for Niger State, Nigeria

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Solar drying is a potential decentralized thermal application of solar energy particularly in the developing countries. It is differentiated from direct sun drying by the use of equipment to collect the sun‘s radiation in order to harness the radiative energy for drying applications. A natural convection, low cost mixed-mode solar yam dryer was developed, and its performance evaluated. The design is based on energy balances and on an hourly-averaged radiation data reduction procedure for tilted surfaces. The dryer combined both direct and indirect type of solar dryers. It was made up of separate glass solar collector, thermal storage system and the drying cabinet. The thermal store was fabricated from wood with pebbles painted black arranged inside and was placed inside the drying cabinet for heat evolution during off-sun hours. The dryer was designed for a maximum food load of 60kg. It was tested on zero-load condition for the first five days. Afterwards, yam products were dried for fifteen days. A maximum collector temperature of 99oC was recorded, and the highest drying temperature was 69.1oC. An average daily thermal efficiency of 66.95% was obtained. The incorporated thermal storage system was evaluated; it has an average efficiency of 65%. Analysis showed that the system performed better than direct and indirect dryers with efficiency values of 56.5% and 61.5% respectively. It also reduced the drying time of yam by 50% against what was obtained in direct sun drying. Exegetic analysis of the dryer has shown that the system is effective and efficient from energy point of view. And physical organoleptic evaluation was employed to test the colour, odour, texture and durability of the products, which all proved to be satisfactory.

Keywords: Development, Mixed-Mode, Performance Evaluation, Solar Energy, Yam Dryer.

Introduction

The present governmental administration of President Muhammadu Buhari change mantra entails diversification especially from the mono-commodity of oil and gas to that of agriculture (Zubairu, *et al.,* 2014). This became necessary in the face of dwindling oil revenue and continuous increase in glut at the labour market (Ogochukwu, 2016). Niger state is purely an agrarian state and can creatively engage agriculture to revive and better her economy. One of the crops that do well in Minna area of Niger state is yam (Fu *et al.,* 2011). Yam farmer suffer heavy crop losses and money in the post-harvest period, during which the harvested yam crops are stored (Olayemi *et al.,* 2011). Those who have no storage facilities suffer more losses through food spoilage, and to avoid such they rush their crops to the market immediately after harvesting. This often results in the flooding of the market and attendant fall in prices.

In developed countries, most foods are preserved through canning and refrigeration. Chemical preservatives are also employed for storage over a long period. These methods are very effective but require sophisticated equipment that are often expensive (Floros *et al.,* 2010). Hence, the need for the development of cost-effective means of food preservation, for which solar energy can play a significant role. Direct sun drying is cost-effective but labour intensive and with little or no control over the drying rate, leaving the products to either be under-dried over dried.

The major cause of wastage or spoilage in food is the growth of micro-organisms. Physiological changes in foods and other chemical reactions such as oxidation also contribute to deterioration (Hammond *et al.*, 2015). These short-comings can be overcome by drying the food products under controlled conditions of temperature and humidity, which results in rapid drying at a safe moisture level and ensures good quality (better nutritional values and germination characteristics) of the products; that can be accomplished using solar dryers whose source of energy is the sun (Prakash *et al.*, 2016). Most of the developing countries lie within the tropics and enjoy abundant sunshine throughout the year. The employment of solar dryer would be a viable option of food preservation in these areas in which the greatest post-harvest losses of foodstuff occur, and they can least afford such losses (Condori *et al.*, 2001).

Drying is a process of removing moisture to a safe level. The equilibrium moisture content is defined as the moisture content in equilibrium with the relative humidity of the environment. The equilibrium moisture content is divided into, static and dynamic. While the static is used for food storage process, dynamic is used for drying process (Masud & Nazrul, 2015). In the main agricultural countries, drying comprises the reduction of moisture from about 17-30%w/w to values between 8 and 15%w/w, depending on the grain. The final moisture content for drying must be adequate for storage (Bolin & Salunkhe, 1982). However, it should be noted that water should be removed in such a way that dehydrated products can easily be rehydrated to regain their structure (Jasim, 2011).

Certain variety of food products are not supposed to be dried by sun drying because they lose certain basic desirable characteristics (Jairaj *et al.,* 2009). Solar drying is an alternative option to conventional sun drying and hot air drying for several reasons, mainly due to the unlimited and renewable source of solar radiations, which can be harvested by using appropriate solar collector system. This eliminates the use of fossil fuels and reduces environmental impact due to consumption of non-renewables (Green & Schwarz, 2012). The benefits of solar drying with respects to sun and hot air drying have been discussed in many literatures (Garg, 1982; lmre & Palaniappan 1996; Jianu & Rosen; Murthy, 2009; Abdullah & Gatea, 2011).

Drying process has been experimentally studied and analyzed to simulate and design solar dryer for various agricultural products (Panwar *et al.*, 2012.). A wooden solar dryer with no heat storage and recirculation was developed (Youcef-Ali, *et al.*, 2004). The solar collector was made of offset plate fins. The design was made of a mesh, wooden cabinet, and a forced convection was used in the chamber. An improvement in the efficiency of the system was observed on testing. Other solar dryer designs with various modifications such as auxiliary conventional heater, chimney and other forms of energy which has resulted in increased dryer efficiency, lower labour cost and continuous production have been reported have been studied (El-Shiatry, *et al.*,1991; Madhlopa, *et al.*, 2002; Kumar, 2016; Mokhtarian, *et al.*,2016 and Caliskan, 2017).

Most of the designs reported earlier have not been by the small scale farmers, either because the final design and data collection procedures are frequently inappropriate or the cost has remained inaccessible and the subsequent transfer of technology from researcher to the end user has been anything but effective (Berinyuy, 2004). Hence, a mixed -mode solar yam dryer for small scale farmers is designed, fabricated and tested in this study. The design is based on energy balances and the performance analysis was evaluated based on exergy.

Mathem*a*tical *M*odel and A*n*alysis

Yam drying is a process of removing moisture from the yam in order to preserve the yam; it is a complex pr**o**cess that involves a combination of heat and mass transfer. A schematic diagram of yam drying showing both transport of heat and mass is shown below in Figure 1.

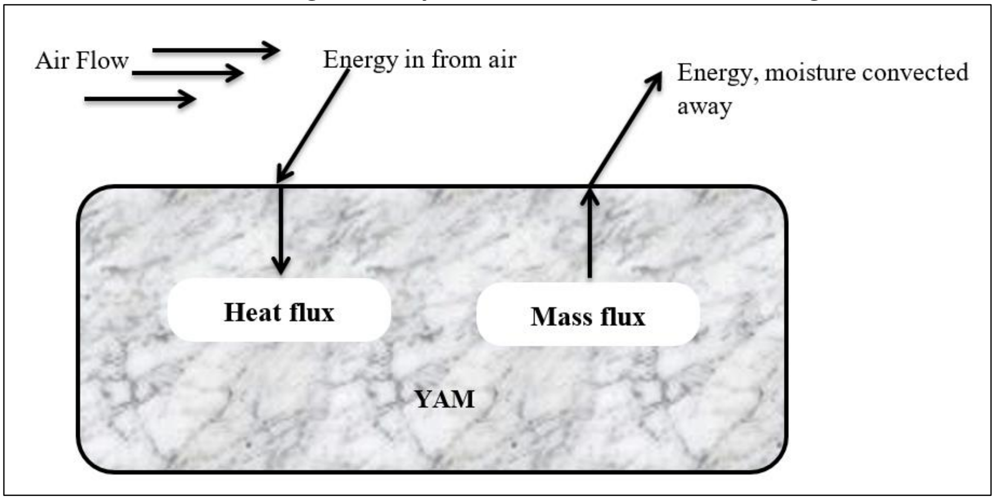

Figure 1: Schematic diagram of heat and mass transfer in yam.

As seen in the diagram, heat is being transferred into the yam from the warm air, while simultaneously being transferred out of the yam via evaporation. This process is expressed using Equation (1) with the heat transfer coefficient (h), the surface area (A), and mass flow (ṁ).

$$hA(T_b - T_\infty) - \dot{m}h_{fg} = \dot{m}C_p(T_b - T_\infty) \quad (1)$$

For the design to function properly by natural convection the material properties and geometry of the heat collector are important when considering the flow of heat. The ideal Tilt angle is found from the known latitude of the location for collecting solar radiation seen in equation (1).

Tilt Angle, ($\beta°$) = Latitude X 0.87 (2)

This produces a desired tilt angle of approximately 12 degrees. We then decided to elevate the tilt angle up to 26 degrees to assist with the flow of heat into the drying chamber. Another task is to contain the heat through the night when there is lower temperatures. Thermal mass will absorb heat energy from the sun during the day and retain heat longer into the night. Materials with high heat capacities such as rock and sand will be utilized as thermal mass. Heat capacity is calculated by the following formula seen in Equation (2). The contributing variables for specific heat are the mass (m), specific heat(C), and temperature difference (T).

$$H = mC(T_1 - T_2) \quad (3)$$

The heat capacity of a thin bed of rock vs. a sheet of steel shows that the rock will be able to hold approximately seventeen times more heat energy. (Hs= 366BTU, Hr = 6,390BTU). Insulation will then be vital in directing and maintaining the heat into the drying chamber. Knowing the thermal resistance can be used to find the effectiveness of the insulation and can be found by Equation (3).

R = L / kA (4)

Thermal resistance (R) is found by the length (L), or thickness of the material, divided by the multiplication of the conductivity (k) and the area (A) of the wall.

Materials and Methods

Material selection

Transparent surfaces

Glass of 5.00mm thickness was selected for the transparent surfaces. The choice is based high transmissivity to visible radiation, low transmissivity to infra-red radiation and stability at the operating temperature properties of glass.

Absorber plate

A good absorber plate should give little resistance to the passage of air. Corrugated galvanized iron was selected for the absorber plate. This has the advantage in most places of being readily available, relatively cheap, durable, have good thermal conductivity, low emissivity, and ease of use.

Thermal storage material

A good sensible thermal storage material has chemical stability, thermal stability, high specific heat and high density. Pebbles apart from having the stated properties can be gotten at relatively low cost and were selected for use.

Thermal Insulators

Thermal insulator is necessary to prevent heat losses. This has to be adequate in thickness and readily available. They should equally have low thermal conductivity, materials such as fibre glass, mineral wool, shaven wood, saw dust and polythene foams are Good thermal insulators. Shaven wood, saw dust, and polythene foams were used for the design.

Drying Cabinet

The drying cabinet houses the food being dried. As such, it must be strong enough to withstand the weight of the food product(s). It must equally be strong to withstand weather (sun and rain) without quickly getting spoilt. In addition, it must have poor thermal conductivity. Wood was chosen for the drying cabinet.

Drying trays

Drying trays holds the food being dried. As such, the tray materials should be perforated to allow for air movement, and moisture drainage. For low cost, perforated iron net strengthened with wood was used. The net made of iron has the advantage of absorbing heat and transferring such heat to the food, thus contributing positively to the drying process.

Equipment description

The dryer is made up of three main parts namely; solar collector, drying cabinet and thermal store. The dryer components and their fabricated sizes are here discussed.

Solar collector

The solar collector was fabricated from corrugated iron sheet (100mm x 96 mm) painted black. It (collector plate) was housed by a wooden box of dimension (100 x 101 x 30 (mm). the lower side of the plate was insulated with polystyrene foam and wood shaves, and the insulation was 13 mm thick. The wooden box has a transparent cover made of glass, 5mm thick of dimension 1000mm x 960mm. There was a space 18mm high between the plate and the glass where incoming air was heated and passed through two pipes into the drying cabinet.

Drying cabinet

The drying cabinet's frame was fabricated from wood of size 25.4mm x 50.8mm. It has the roof (1000 x 960) mm covered with glass, inclined at 7.25o (the latitude of Minna). The Eastern side was also covered with glass of dimension (1000 x 920) mm, while the other sides (West, South and North) were covered with plywood. The bottom of the cabinet was covered with planks. The pipes from the solar collector were passed through the southern side into the cabinet, and the northern side has the door. The upper part of the northern side has holes frilled to act as exhaust outlet for spent air. The inner part of the cabinet was divided into four for the frying trays, it was painted white so as to reduce heat loss (the white surface will reflect the heats trapped inside the cabinet), and the outside was painted black to aid heat absorption into the system.

Experimental procedures

The dryer was tested over a period of twenty (20) days between February and March, 2017, using yam as specimen. During the testing period, the thermal storage system was kept in the cabinet, closed during the day and opened in the night for heat retention measurements. The parameters were measured between 09:00 and 18:00 hours (local time) each day. The incident solar radiation intensity was measured by a solarimeter. The humidity-temperature meter was used to measure the relative humidity and ambient temperature. The plate temperature and dryer's temperature were measured by mercury-in-glass thermometers. The weights of the dried products were measured using a weight balance and the moisture contents determined by the gravimetric method.

Unload testing

The dryer was tested on no-load for five days. The parameters were measured and recorded hourly. It was assumed here that the available energy is equal to the useful energy as no product was dried and no control experiment was set up.

Load testing

The dryer was tested on load for a total of six (6) days with yam. The products were weighed at the start and end of the experiment to determine the moisture content. The temperatures of the drying cabinet were taken at two points (lower and upper chambers) and the average value recorded. The thermometers were suspended in the chamber through small holes on the Western side of the cabinet. Control experiment was also set up in the open (direct sun drying) for the product. Figures 1 and 2 show the experimental set ups and the corresponding control (sun dried yam products).

Heat Retention test

Heat retention tests were carried out during the nights. These were to monitor the heat storage system incorporated into the dryer. The transparent cover of the thermal store remains closed during the day and opened in the night. The temperature of the drying chamber and ambient temperature were measured hourly. Relatively humidity of the chamber and open air were equally measured and recorded.

Figure 2: Testing with Yam

Figure 3: Control Test for yam

Figure 4: Yam samples showing grown moulds.

Results and Discussion

This section discusses the observations and results obtained from the performance evaluation tests. The results are presented in tabular, graphical, and photographic forms

Unload testing

The dryer was tested on no-load to make sure that it was in line with the design, and to be able to make amendments where necessary, to ensure good performance. During this test, a maximum collector temperature of 78.8oC was recorded at an ambient temperature of 35.0oC on 5 – 2 – 17. The dryer's temperature then was 69.1oC (almost double the ambient temperature) with an efficiency of 71.61%. The highest thermal efficiency during the period was 76.10%. During the test, the available energy was assumed equal to the useful energy, as no product was dried. As shown in Figures 4-6, the energy per unit area is close to the solar insolation. This shows that the dryer was able to convert most of the absorbed incident solar energy to useful energy, and this increases with increase in solar insolation. The temperature profile (Figures 7-9) revealed that the solar collector and the dryer cabinet responded well in increasing the temperature far above ambient. An average efficiency of 64.21% was obtained during the period.

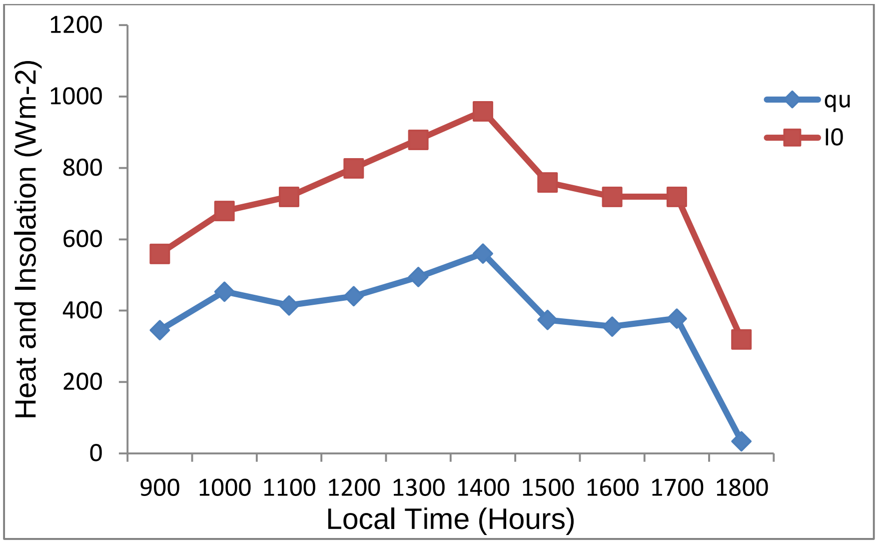

Figure 5: Heat and insolation profile showing hourly variation for 02-02-17 on no-load

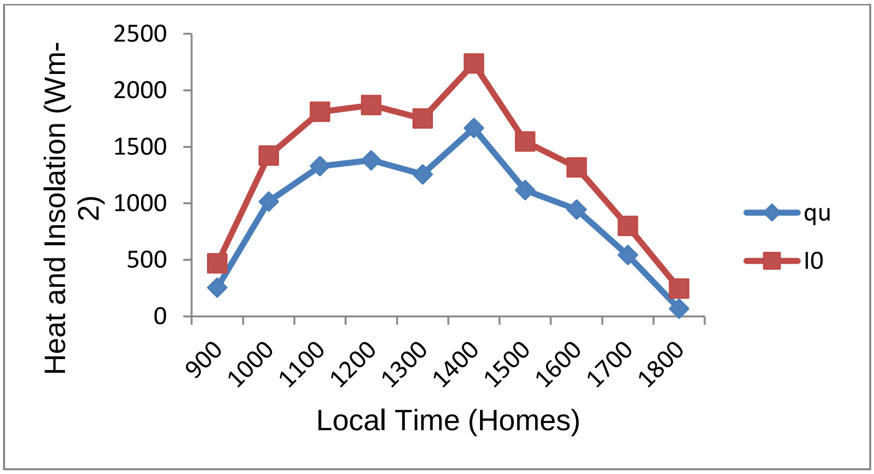

Figure 6: Heat and Insolation Profile Showing Hourly Variation for 04-02-17 on No-Load

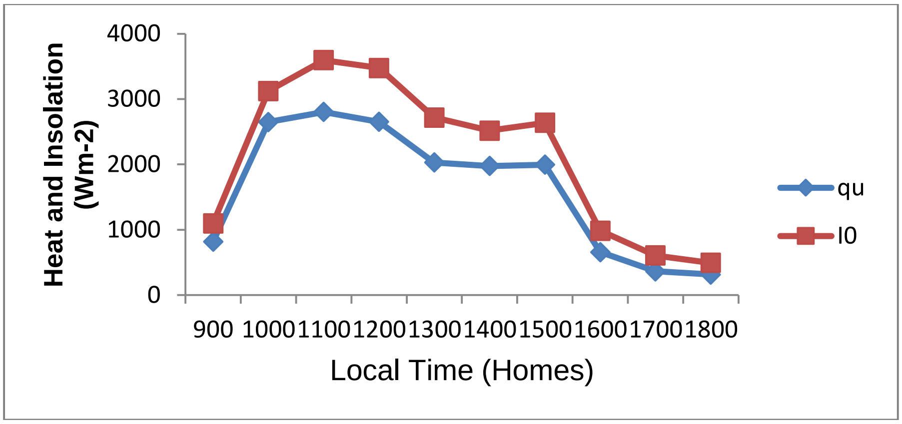

Figure 7: Heat and solar insolation profile showing hourly variation for 06-02-17 on no-load.

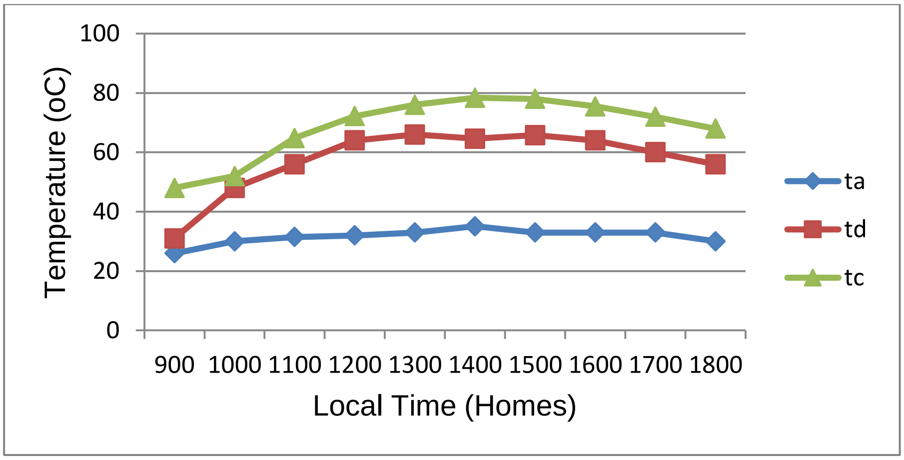

Figure 8: Daily Temperature versus Local Time for 02-02-17 on No-Load

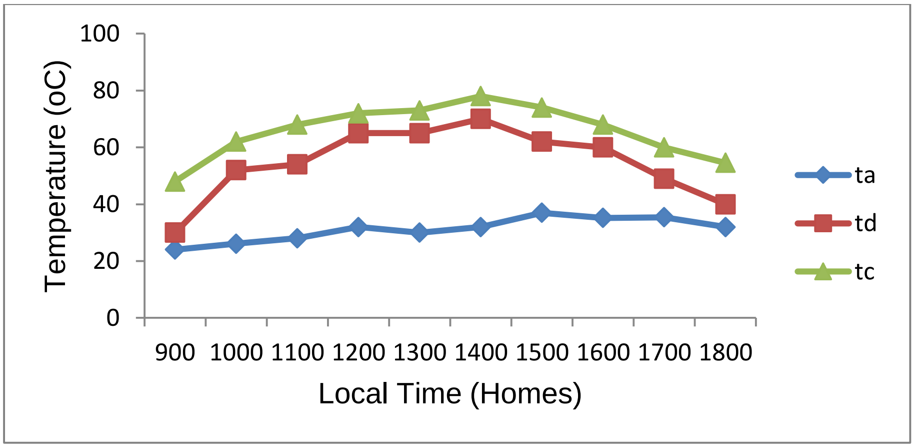

Figure 9: Daily Temperature versus Local Time for 04-02-17 on No-Load

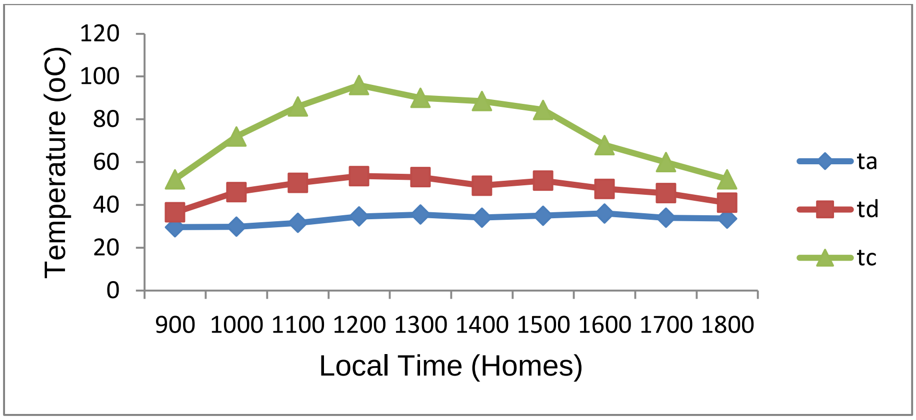

Figure 10: Daily Temperature versus Local Time for 06-02-17 on No-Load

Load testing with yam

The dryer was subjected to test with yam between 22nd and 27th February, 2017. Two trays, each loaded with 60.00kg of sliced yam were used with one kept inside the dryer, and the other kept in the open air. Moisture contents were determined on a daily basis, using the weight at the start and close of experiment. The yam kept inside the dryer got dried to the required moisture content level of 12% at the end of the fifth day, while that in the open air took five additional days to dehydrate to the same moisture level. Apart from taking longer days, many pieces of the yams started growing moulds and undesirable colouration of the products was observed. Figure 4 shows some of the products with grown moulds. A temperature of 98oC was recorded by the solar collector on 23 – 2 – 17 and 27 – 2 – 17 at ambient temperature of 35oC and 35.4oC respectively. The drying cabinet's temperatures were 50.5oC and 58.5oC for the two days with efficiencies of 69.63% and 65.94% respectively. The system worked efficiently in converting the absorbed solar energy to useful energy. The yam was dried from an initial moisture content of 80% to a final moisture content of 12%. An average daily efficiency of 68.75% was obtained during the period.

Exergetic analysis of the dryer

Total energy is the sum of useful or available energy (exergy) and the unavailable energy (anergy). Figures 11 to 14 show the relationship between Exergetic Efficiency, Thermal Efficiency and Time for no-load condition and the dried products. Figures 10 and 11 for no-load condition show that the dryer is very effective at the energy values obtained. The exergetic efficiency values were almost equal to the thermal efficiency values, justifying the statement that the total energy equal the useful energy on no-load condition as no product was dried. Figures 13 to 14 equally show that the system is effective at the obtained thermal efficiency values. However, the exergetic efficiency was always low in the morning, which implied that the system was not effective very early in the morning. On the whole, the system recorded a highest exergetic efficiency value of 68.53%, and an overall average exergetic efficiency of 52.89%. This average value puts the effectiveness of the dryer on the average.

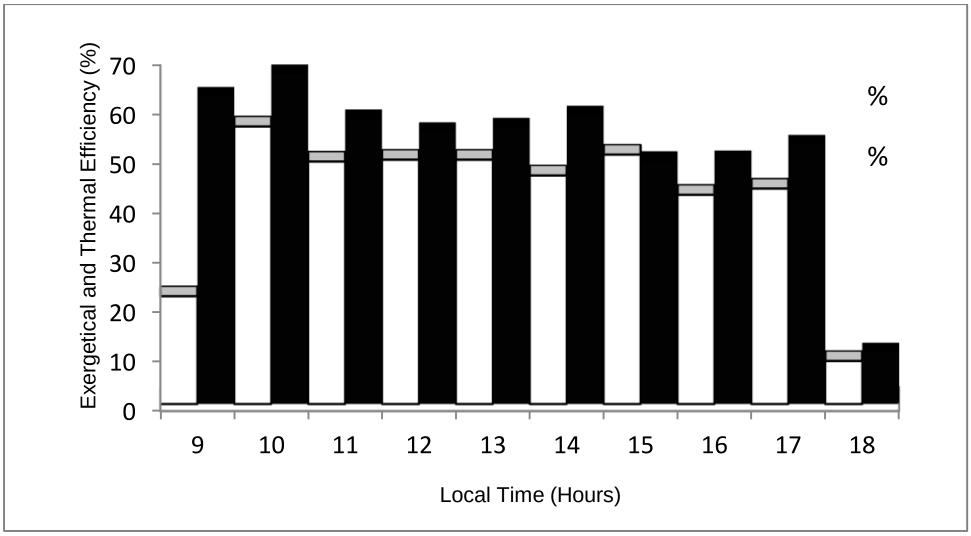

Figure 11: Relationship between Exergetic Efficiency, Thermal Efficiency and Time for 02-02-17

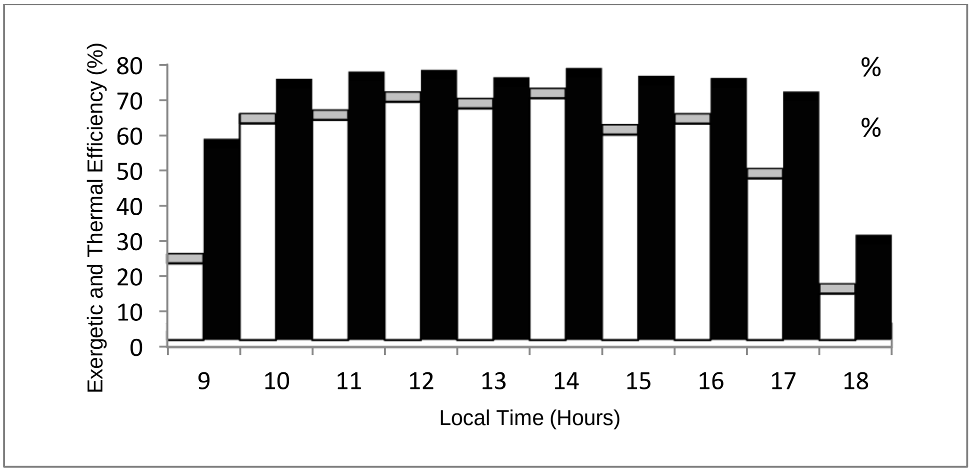

Figure 12: Relationship between Exergetic Efficiency, Thermal Efficiency and Time for 04-02-17

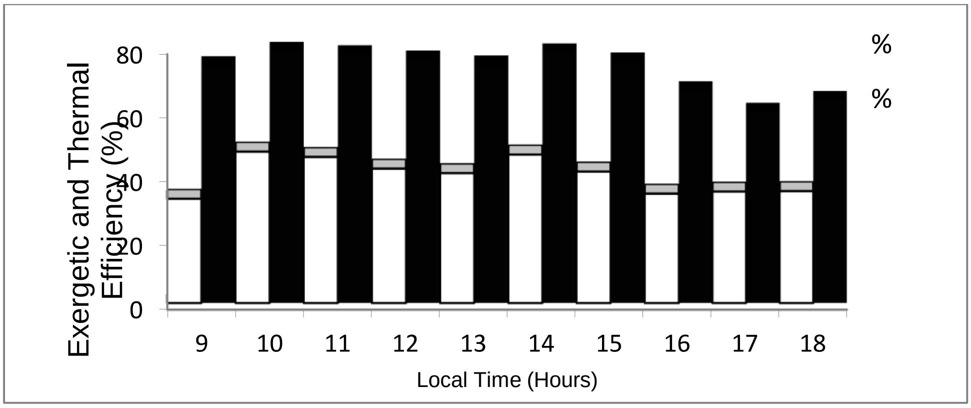

Figure 13: Relationship between Exergetic Efficiency, Thermal Efficiency and Time for 24-02-177 with Yam

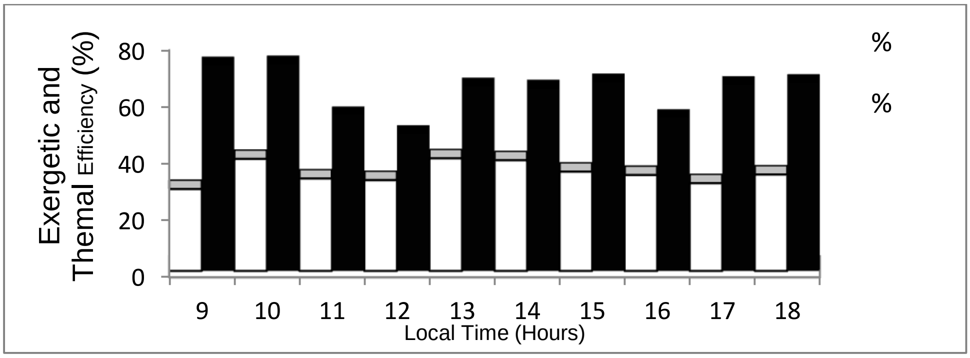

Figure 14: Relationship between Exergetic Efficiency, Thermal Efficiency and Time for 26-02-17 with Yam

Conclusion

A mixed-mode solar yam dryer incorporating a thermal storage system was developed and its performance evaluated. The dryer was tested first on no-load. It was thereafter used to yam slices. The average daily efficiency was 66.95%. It has the highest drying temperature of 69.1oC at an ambient temperature of 35oC, and the highest solar collector temperature was 99oC at an ambient of 33.9oC. These values confirmed that the dryer operates at higher temperature conditions than the ambience, hence, the high efficiency value. On the quality of the dried yam, the dryer turned out a higher quality yam product than those gotten from the traditional sun drying method, as the latter is subject to excessive contamination, dirt and insect infestation. These set-backs were naturally eliminated by the construction and operating conditions of the developed dryer, as the products were not directly exposed to the air. The quality of the product were equally higher than that turned out by the indirect solar dryer, whose products could not thoroughly be dried due to constant power failure, resulting in poorly coloured grains and undesirable flavour.

From exergetic point of view, the dryer is effective in utilizing the available energy, and is more effective than direct sun drying. An overall average exergetic efficiency of 52.89% was obtained. The incorporated thermal storage system also proved itself worthwhile and exhibited the practicability of drying during off-sun hours. The loss in moisture during the night (off-sun hour) concludes that there was dehydration. This concludes that the dryer can be used at any time of the day.

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