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Design and Fabrication of an Intelligent Solar-Photovoltaic Hybrid Tunnel Dryer for Tomatoes with Automatic Temperature Control and Air Recirculation.

Achalle Joseph Tambe*, Isaac N. Simate**
**(Department of Mechanical Engineering, University of Zambia, P.O. Box 32379, Lusaka, Zambia)*
*** (Department of Agricultural Engineering,University of Zambia, P.O. Box 32379, Lusaka, Zambia)*

ABSTRACT
The agricultural sector in most developing countries encounters a lot of post-harvest losses of agricultural products due to a lack of appropriate drying and storage facilities for preservation. Though many drying technologies have been developed, there is an increasing demand for automation in drying. Concerning this limitation, this work presents the design and fabrication of an intelligent solar-photovoltaic hybrid tunnel dryer for tomatoes with automatic temperature control and air recirculation. The dryer consists of a solar collector, a drying chamber, axial fans, a solar photovoltaic system, an electric heater, and a control unit. The dryer was first experimented on two no-load experiments to determine the collector efficiency and to check the control unit's operation respectively. Later, it was experimented with a 700g of sliced tomatoes for 9 hours from which an average temperature of 60.33℃, collector efficiency of 67.06%, drying chamber efficiency of 10.24%, drying efficiency of 23.72%, and drying rate of 66.31g/hour were obtained for an average solar irradiance of 0.528$\boldsymbol{kW/m^2}$. The use of the control provided an optimum temperature in the drying chamber for achieving a high-quality product for long-term preservation.
Keywords-Automatic temperature control, Air recirculation,Design and fabrication,Solar-photovoltaic hybrid tunnel dryer, Tomato drying.

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I. Introduction

More than two-thirds of the African population work in small-scale plantations, making agriculture one of Africa's most significant economic sectors, contributing approximately 15% of the continent's gross domestic product [1]. The agricultural commodities produced are usually for both national and international consumption. However, the agriculture sector confronts certain fundamental challenges, such as substantial post-harvest losses brought on by subpar post-harvest management, which calls for careful consideration. To overcome this drawback and seasonal variations in food products, some food preservation methods such as smoking, open-air drying, and frozen storage have been implemented over the past years.

The abundant solar radiation,available year-round, has made open sun drying a key method of food preservation in most African countries from prehistoric times [1]. However, this conventional method of food preservation usually poses some drawbacks to the food. According to Zoukit et al [2], open sun drying renders the agricultural product vulnerable to contamination by pests, bird droppings, dust, insects, and flies. The agricultural product often takes a long time to dry resulting in increased contamination, poor product quality due to intermittent sunshine, and rehydration at night [2]. In addition to this, when drying some agricultural products, for instance, tomatoes, at temperatures far below the optimum temperature, the product will dry slowly, giving time for bacteria or mold to develop [3].

To solve some of the problems faced with open sun drying, solar drying has been the most reliable technology in recent times where the food product is shielded from contaminants. As far as Solar drying is concerned, many technological advancements have been made by several researchers but an important question stays unanswered: How to monitor and automatically maintain the drying temperature for any agricultural product at its optimum temperature and avoid the wastage of heat to the surroundings and rehydration at night? Varma et al [4] designed and experimented with an active solar dryer that had an air recirculation technique for spices such as chilly, turmeric, and ginger. The dryer consisted of a black-painted collector, a drying chamber with trays, and an air recirculation system. Air was drawn in through an air inlet and heated in the collector, and then circulated in the drying chamber for drying. The moist air leaving the spices from the drying chamber was recirculated through a pipe to the collector for reheating to increase its moisture-carrying capacity instead of being expelled into the environment. The dryer was designed for an optimum drying temperature of 60℃ in an ambient air temperature of 30℃. The limitation of this design, though, was the lack of a heat compensator to maintain an optimum drying temperature for periods when the ambient air temperature went below 30℃ as a result of low solar insolation. Another study was done by Vengsungnle et al[5] who designed, constructed, and tested a hybrid photovoltaic-ventilated mixed-mode greenhouse solar dryer for Ganoderma with automatic temperature control. The dryer had suction fans which were connected to relative humidity transmitter sensors that operated the fans when the relative humidity difference inside and outside the dryer changed from the set value. The dryer also had a heater which was powered by a photovoltaic system to supplement heat in the dryer, a lamp that worked with the heater for drying at night, and a control box. Though there was temperature and relative humidity control, this dryer did not have an air recirculation system to recirculate the warm, moist air that exited the product.In yet another study, done by Moussaoui et al[6] on a hybrid solar-electrical forced convection dryer for apple peels, automatic temperature control which was aided by a programmable temperature controller was used. The dryer system consisted of a solar collector for heating ambient air and a heater that acted as a supplementary heat source for the drying temperature to reach the desired value. The heater and the fan were powered from an AC source. Though the system was a hybrid one and the temperature was automatically monitored and controlled to maintain the desired value, the system did not haveexhaust air recirculation.According to Mortezapour et al [7], only a small portion of the thermal energy supplied to hot air dryers is utilized for the drying process; the majority is lost through the dryer walls and exhaust air. Therefore to increase the energy efficiency of dryers, it is, useful to recycle the waste energy associated with the exhaust air. The findings of Sarsavadia[8]have further demonstrated that recycling exhaust air at drying temperatures between 65 and 75℃ can result in a maximum overall energy savings of 70.7%.

Having studied the improvements that can be done to increase the efficiency of solar dryers, it was the objective of this study to design and fabricate an intelligent solar photovoltaic hybrid tunnel dryer for tomatoes with automatic temperature control and air recirculation. The dryer consisted of three major units, the main dryer itself, the automatic temperature monitoring and control unit, and the power supply unit. The main dryer was equipped with an air recirculation path for the recirculation of warm, moist air from the drying chamber to the collector for reheating, and back to the food in the drying chamber for further moisture removal. Axial fans were used for air circulation and helped in the regulation of drying temperature. Moreover, inside the main dryer was an 828W AC-powered electric heater which was the auxiliary heat source for the dryer. The automatic temperature monitoring and control unit (or the control unit) consisted of a microcontroller for automatic monitoring and control of the drying temperature to maintain it at the optimum range for the product. It had a soft-touch LCD panel with a Nextion interface that enabled users to read data and write data to the system. The power supply unit included a solar photovoltaic system and an AC main electricity source. The photovoltaic solar system comprised a solar module, a charge controller, and a battery that powered the fans and the control unit. The main AC power source was used to power the heater. The uniqueness of this dryer was its ability to automatically monitor and control the drying temperature and maintain it at the optimum range for drying an agricultural product without any human help, irrespective of the weather condition and even at night thereby reducing the drying time with a desirable end product quality.

II. Material and Method

2.1. Design of the dryer

The general design architecture of solar tunnel dryers from earlier studies[9][10] was adopted in this work but with the use of an air recirculation path, an auxiliary heat source, and a control unit. The dryer was designed and fabricated based on the quantity of product to be dried. The fabrication and experimentation of the dryer were carried out at The University of Zambia, Department of Agricultural Engineering with coordinates (15.39S, 28.32E). Tomato fruit was the selected product for drying as it experiences a lot of post-harvest losses. A capacity of 700g of fresh tomatoes was selected as the dryer capacity.

The total amount of moisture (M_W) removed is given by Sharma [11].

Moisture removed:

$$M_w = \frac{M_{is}(M_{iwb} - M_{fwb})}{(100\% - M_{fwb})} \quad (1)$$

Where M_w is the amount of moisture to be removed, M_{is} is the initial mass of the sample, M_{iwb} is the initial moisture content (wet basis) and M_{fwb} is the final moisture content (wet basis) with respective values of 95% and 10%. Therefore,

The drying process involves two stages. The first stage is to raise the temperature of the tomatoes to the desired level for which the moisture can be removed.

In this case, the quantity of heat energy required to raise the temperature of the wet sample of tomato to this desired level is given by Mercer [12].

Energy to raise temperature:

$$Q_1 = M_{is} C_P (\Delta T) \quad (2)$$

Where ΔT is the temperature difference between the optimum drying temperature T_{opt} and the average ambient temperature T_{av}.

$$\Delta T = T_{opt.} - T_{av.} \quad (3)$$

For Lusaka, Zambia where the experiment was conducted, $T_{av.} = 20.4$℃[13] and for tomatoes, $T_{opt.} = 60$℃.Snart et al[3] stated the optimum drying temperature for tomatoes should lie between 57.2℃ and 60℃. If dried at lower temperatures, the product will dry slowly, giving a chance for bacteria and mold to grow and if dried at higher temperatures, the outside of the tomatoes cooks or hardens while the interior remains wet.

$C_P = 3.98 KJ/kg$℃ is the specific heat capacity of tomatoes [14].

The second stage involves the evaporation of the moisture from the sample (heat of vaporization). The water starts to evaporate when the sample is warmed up and the quantity of heat neededQ_2 for this second stage is given by Mercer [12].

$$Q_2 = M_w (h_g - h_f) \quad (4)$$

Where h_g is the enthalpy of water in the gaseous state and h_f is the enthalpy of water in the liquid state as obtained from steam tables at a temperature of 60°C and absolute pressure of 0.1994 bar.

$$h_g = 2609.6 kJ/kg \text{ and } h_f = 251.1 kJ/kg$$

$$Q_2 = 0.6611111(2609.6 - 251.1)$$

$$Q_2 = 1559.230556\ kJ$$

Therefore the total heat energy Q_{total} required was finally determined as

$$Q_{total} = 1669.5562 kJ$$

The electric heater power P_E was sized based on the total energy Q_{total} consumed during the drying time. Therefore,

$$\text{From} P_E = \frac{Q_{total}}{Drying\ \ time} \quad (5)$$

WhereP_E is the electrical power.

The drying time of tomatoes from an initial moisture content of 95% wet basis to a final moisture content of 10% wet basis at an optimum temperature of 60℃ with a slice thickness of between 4mm and 8mm is 8 hours [15], giving a P_E for this case as 58W.

The energy generated by an auxiliary heat source must always be greater than the actual energy needed to compensate for losses [16]. In this case, the heater wattage must be stepped up to also have an impact on the energy generated.

Since the drying chamber efficiency of a dryer depends on the temperature of the air entering it,Ononogbo et al [17] found in their design and experiment that the drying chamber efficiency for the hot air dryer with an auxiliary heat source was between 4.23% to 8.07%. Considering an efficiency of 8.07% for determining the actual power rating P_{actual} of the heater implies that

$$P_{actual} = \frac{P_E}{8.07\%} = \frac{58W}{8.07\%} = 718.71W$$

Hence to minimize heat losses from the drying chamber to the environment, and due to the availability of materials, a 240VAC/828W heater, used previously in another project, was adopted and installed inside the dryer to provide electrical heating.

From $P = IV$ (6)

Where $P = 828W$ and $V = 240V$

$$I = \frac{P}{V} = \frac{828}{240} = 3.45A$$

Hence $V = IR$ (7)

$\Rightarrow R = \frac{V}{I} = \frac{240}{3.45} = 69.56\Omega$ resistive nichrome wire

If it was required to raise the ambient temperature from an average value of 20.4℃ to 60℃ with the heater alone. Therefore, the energy require to raise this temperature E is given by:

$E = mC_{pair}\,\Delta T$ (8)

Where m is the mass of air, $C_{pair\ at\ 20.4℃} = 1.006kJ/kgK$ is the specific heat capacity of air, and ΔT is the temperature change.

$m = \rho A h$ (9)

Where A is the floor area of the dryer and h is the dryer height from the floor.

The density of air at 20.4℃, $\rho = 1.202Kg/m^3$

$$m = 1.202 \times 1 \times 0.48 \times 0.3 = 0.1731kg$$

$$E = 0.1731 \times 1.006 \times 39.6 = 6.8959KJ$$

How long it will take to raise this temperature of the air using an 828W heater element was gotten as

$P = \frac{E}{\Delta t}$, where Δt is the time duration.

$$\Delta t = \frac{E}{P} = \frac{6.8959KJ}{0.828KJ/s} = 8.328\ seconds$$

$\Delta t \approx 8.33\ seconds.$

The dryer was made from a frame of square steel tubes covered with a 0.3 mm thick galvanized sheet on its sides and bottom. The outer bottom and sides of the dryer were insulated with a 0.04 m thick Styrofoam to reduce heat losses. To improve the absorption of solar radiation, the collector and drying chamber floor was painted black. A rectangular removable wire tray was installed in the drying chamber for the placement of the food product to be dried. Three suction fans were installed on the shorter sides of the dryer, one exhaust fan, and the other two for air recirculation. The recirculation fans operated on a 100% recirculation basis. They were connected through a 100mm diameter PVC pipe and four bend connectors. Table 1 and Table 2 show the dimensions of the various components which make up the dryer. A 12VDC lamp was installed in the dryer at the roof metal frame which supports the 200μmthick UV-treated polyethylene plastic sheet covering the dryer. The lamp provides light in the dryer if drying is to be conducted at night.

Table 1. Dimensions of the solar tunnel dryer.

s/n	Dryer component	Length (m)	Width (m)	Height(m)	Surface area (m^2)
1	Drying chamber	0.52	0.48	-	0.25
2	Tray	0.52	0.29	-	0.15
3	Dryer legs (20mm*20mm square tubes)	-	-	0.80	-
4	Collector	0.48	0.48	-	0.23

Table 2. PVC pipe dimension for warm, moist air recirculation

s/n	PVC pipe component	Quantity	Length (m)	Diameter (mm)	Arc length h(m)
1	Main Pipe	1	1.00	100	-
2	Bend connectors	4	-	100	0.17

Fig. 1 shows an AutoCad design of the main dryer with its dimensions and fig.2 shows the dimensions of the PVC air recirculation pipe.

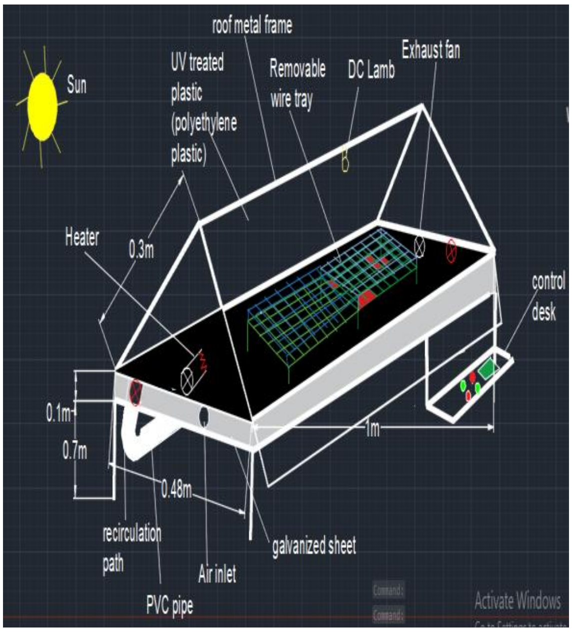

Fig. 1 AutoCad design of the dryer.

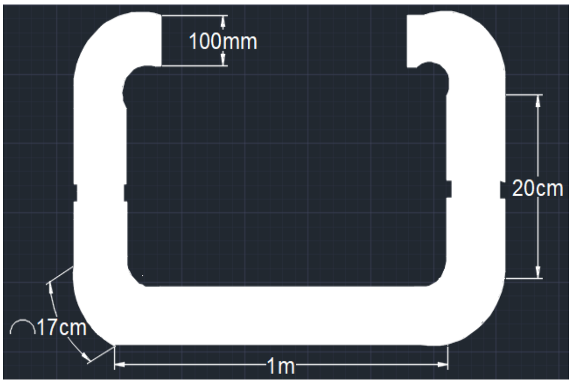

Fig.2 Dimensions of PVC recirculation pipe.

Fig. 3a shows the outside view of the dryer with the recirculation pipe, whereas fig. 3b shows the inside of the dryer.

Fig.3a Outside view of solar tunnel dryer with air recirculation pipe.

Fig.3b Internal view of the solar tunnel dryer.

In order to monitor and control the temperature of the air in the drying chamber at an optimum range, a control unit was designed and fabricated. This unit consisted of an Arduino Uno board that carries the ATMEGA328P programmable microcontroller. The microcontroller acts as the brain of the entire system. The program code which was loaded in the microcontroller was written in an Arduino-integrated development environment, version 1.6.9.0. The microcontroller controls the recirculation fans, exhaust fan, lamp, and heater through 5VDC relay modules based on the temperature in the drying chamber. Connected to the Arduino board was a soft-touch LCD panel with a Nextion interface that enables the user to read data from and write data to the system.The data read include, the ambient air temperature and its relative humidity, the drying chamber air temperature and its relative humidity, and the states of the fans, heater, and lamp whether or not they are on. A DHT22 (Model: AM2302) temperature and humidity sensor was used to measure the ambient temperature and relative humidity of the air entering the dryer and another of the same model was used to measure the temperature and relative humidity of the air just entering the drying chamber. On the LCD screen was a programmed soft-touch power button which was used to switch ON or OFF the entire dryer. The automatic optimum temperature monitoring and control unit as seen in fig. 4a was fabricated with locally available materials which were procured from the local market except for the soft-touch LCD with Nextion interface which was purchased from China. Since the components of this unit operate with 5VDC, the unit was powered by the solar PV battery through a 12V/5VDC voltage stabilizer which converts the 12VDC of the solarbattery to 5VDC. The circuit diagram of the fabricated voltage stabilizer can be seen in fig. 4b

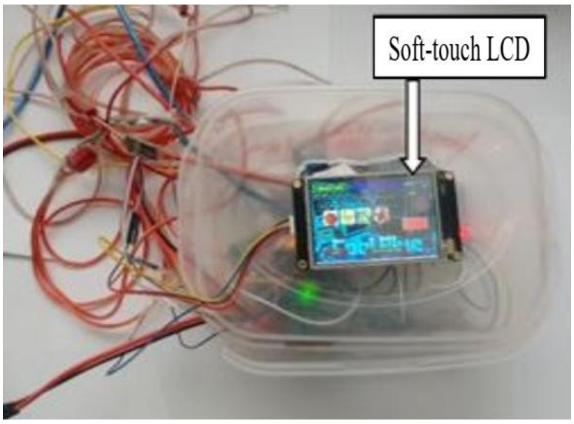

Fig. 4a Fabricated automatic optimum temperature monitoring and control unit.

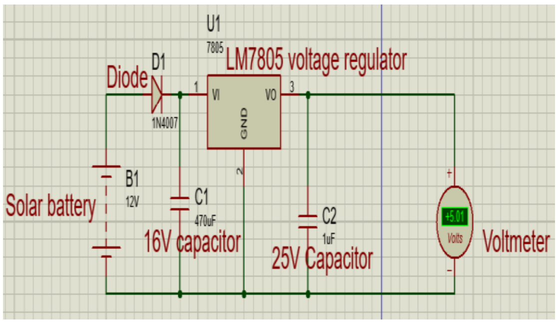

Fig. 4b 12V/5VDC Voltage Stabilizer.

To provide the electrical energy needed by the automatic control components seen in Table 3, a PV system was appropriately sized. The PV module converts solar energy into electrical energy which is stored in the battery with the help of the charge controller. The energy needed by the control unit was accessed from the battery. The sizing of the various components of the PV system was done according to the mathematical models given by Leonics[18].

Battery efficiency = 0.85

Inverter efficiency = 0.90

Sun hour for worst day = 5.5 hours [19].

Panel size = $\frac{82.02Wh}{5.5h} = 14.912W$.

Since all devices used were 12VDC so a system voltage of 12VDC was chosen.

Battery depth of discharge = 0.6

Battery autonomy = 1 day

PV array size (Wh) =

$$\frac{\text{Daily energy (Wh) demand}}{\text{Inverter efficiency} \times \text{Battery efficiency}} \quad (10)$$

$$\text{PV array size (Wp)} = 1.3 \times \frac{\text{Daily PV array Wh)}}{\text{Sun hours}} \quad (11)$$

$$\text{Number of solar panels} = \frac{\text{Array size Wp}}{\text{Panel size}} \quad (12)$$

Battery bank capacity (Ah) =

$$\frac{\text{Daily energy demand} \times \text{Autonomy}}{\text{Inverter efficiency} \times \text{Depth of discharge} \times \text{System voltage}} \quad (13)$$

$$\text{Required charge current} = 1.2 \times \frac{\text{PV array Size}}{\text{Battery Bank Voltage}} = 1.2 \times \frac{\text{Number of panels} \times \text{Panel size (Wp)}}{\text{Battery bank voltage}} \quad (14)$$

From the equations, PV array watt-hour(Wh) = 107.215Wh, PV array watt peak (Wp) = 25.342Wp, From equation 13, the number of solar panels = 1 panel (12V/14.912W monocrystalline) but a 200W panel was chosen since it was readily available.Battery capacity (Ah) = 13.402Ah but a 100Ah battery was chosen since it was readily available, and the required solar charge current = 15.3A. A 30A Pulse Width Modulation(PWM) solar charge controller was chosen since it was readily available. The PV system was installed without an inverter since all the appliances and components required DC voltage to operate except the heater which operated on AC. The optimum tilt angle of a PV module in Lusaka Zambia of 20°was used [20]. The components of the photovoltaic system were procured from the local market and installed following the specifications. The system was ground-mounted as seen in fig. 5.

Table 3. Control Components and energy demand.

Component	Active power (W)	Quantity	Hours of operation (h)	Total active power (W)	Energy (Wh)
Arduino board	0.492	1	7	0.492	3.444
Nextion LCD	2.5	1	7	2.5	17.5
LED	0.088	1	7	0.088	0.616
12V LED Lamb	3	1	7	3	21
Exhaust fan	1.7	1	5	1.7	8.5
Air recirculation fans	1.7	2	7	3.4	23.9
Temperature and humidity sensors	0.005	2	7	0.01	0.07
Buzzer	0.15	1	5	0.15	0.75
Heater fan	6.24	1	7	6.24	6.24
Total					82.02

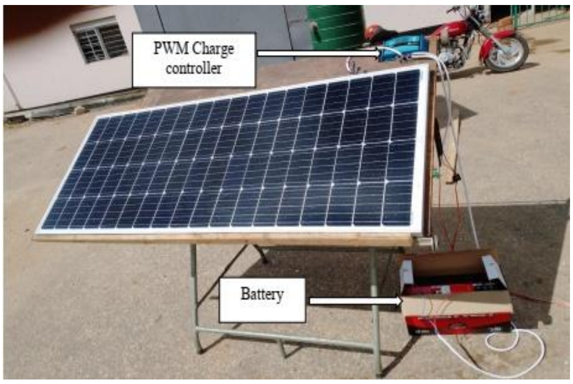

Fig. 5 Ground-mounted PV system.

2.2. The general principle of operation

The dryer was fabricated with the ability to dry three different food products. These were Tomatoes, bananas, and cabbage. But in this study, tomatoes were used as the experimented food product. The entire dryer system comprises a control unit, a renewable energy system, a heating unit, fans, an air recirculation path, and sensors. In the beginning, the operator is required to choose the product to be dried from the soft-touch LCD screen by clicking on the image of the product seen on the LCD screen. When this is done, the system automatically set the drying conditions for that product to be dried at an optimum level (the drying temperature and relative humidity for recirculation). Secondly, the system takes the user to a page that tells the user to start the system by pressing the start button on the screen. When the start button is pressed, the system comes on. The sensors then detect the temperature and relative humidity in the drying chamber and send the data to the controller to display on the LCD. A comparison of the measured values and the set range of values is done by the controller and then an automatic action is performed on the air recirculation fans, heater, and exhaust fan based on the desired set condition. When the automatic action is done, the states of these components are displayed on the LCD. If the temperature of the air just entering the drying chamber is less than the minimum set value, the heater and the air recirculation fans are switched ON while the exhaust fan is switched OFF. When the temperature goes above the maximum set value, the heater and air recirculation fans are switched OFF while the Exhaust fan is switched ON. As this continue, drying occurs at the optimum temperature for that particular product. This monitoring and control were done and the data was displayed on the soft-touch LCD screen at intervals of 1 minute. The Block diagram of the general principle of operation is shown in fig. 6.

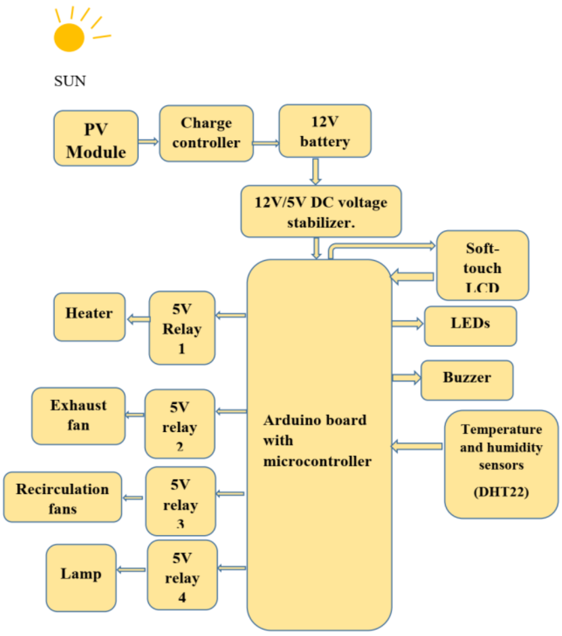

Fig. 6 Block diagram of the general principle of operation.

Three experiments were performed to test the performance of the dryer. The tests were the no-load experiment without the heater, the no-load experiment with the heater, and the load experiment.

2.2.1. No-load experiment without the heater.

This experiment was conducted on the 16th of July 2022 from 11:10 am to 16:40 at the Department of Agricultural Engineering, University of Zambia. This experiment was conducted to experimentally evaluate the collector efficiency. Fig.7 shows the setup of the experiment where the heater was switched OFF, the air recirculation fans were switched ON, and the control unit was just set to read data without any control action. A standard multi-probe Campbell Scientific Inc. data logger (Model: CR 1000) and the control unit were at the same time used to automatically measure from their sensor probes the ambient temperature T_a, and relative humidity R_a of the air which enters the dryer, the air temperature T_o which leaves the collector, and the solar irradiance I_T measured by the solarimeter (Kipp & Zonen Delt BV, Model: CM11). The data obtained by the standard data logger were recorded automatically on a personal computer at intervals of 1 minute while the data of the control unit was displayed on its LCD screen for manual recording by the operator. For experimental purposes,data were collected at intervals of 30 minutes for analysis.The temperature probes of the standard data logger could sense temperatures in the range between -5°C and 95°C, while the DHT22 temperature and humidity sensors could sense temperatures between -40°C to 80°C and relative humidity between 0% RH to 99.9 % RH[21]. The Solarimeter has an irradiance range of $0W/m^2$ to $1{,}400W/m^2$, and sensitivity between 4 and $6\mu V/Wm^{-2}$[22].The velocity of air V leaving the collector to the drying chamber at each interval was recorded, from where the collector efficiency was calculated at each interval using equation 15.

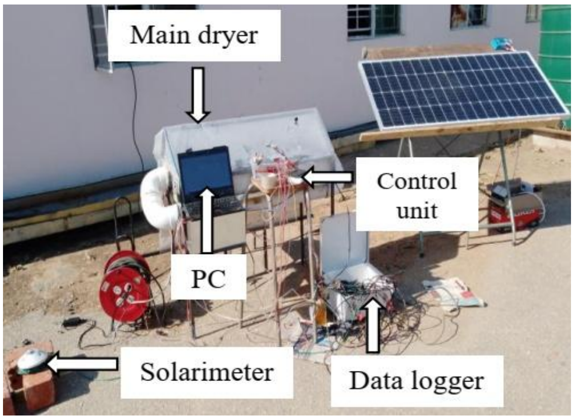

Fig. 7 No-load experimental setup without heater.

2.2.2. No-load experiment with heater and control unit.

This experiment was conducted on the 18th of July 2022 at the Department of Agricultural Engineering, University of Zambia. This experiment aimed to test the ability of the control unit in monitoring and controlling the temperature of the air entering the drying chamber at the set optimum range when no product was loaded in the drying chamber. The experiment was set up in the same manner as seen in fig. 7 but at this time the heater and the control unit were involved. The experiment was conducted for 2 hours on this day from 9:00 hours to 11:00 hours. At intervals of 8 minutes, the corresponding ambient temperature and relative humidity (ambient RH), the temperature of the air entering the drying chamber (dryer temperature or drying chamber temperature) and its relative humidity (dryer RH), and the solar irradiance were recorded.

2.2.3. Determination of the moisture content of the test sample of tomatoes.

This experiment was conducted on the 19th and the 20th of July 2022 at the University of Zambia, Department of Agricultural Engineering. This experiment was conducted to determine the initial moisture content of the sample of tomatoes that was used in the drying experiment. A mass of 300g of freshly bought tomatoes was used. The tomatoes were washed and sliced at a thickness of 5cm and placed on a tray. The initial mass of the tomatoes was recorded using an electronic scale balance (model: PE 3000, accuracy,$\pm 0.1g$). The tray and the tomatoes were placed in an electric convection oven whose temperature was set at 60℃ (the optimum temperature for drying tomatoes)[3]. The tomatoes were left in the oven for a day (24 hours) after which the initial moisture content of the tomatoes was calculated as the mass of water lost divided by the initial mass of tomatoes, and was found to be 95% (wet basis). This moisture content was then considered in the load experiment of section 2.2.4.

2.2.4. Load experiment with tomatoes.

The experiment was conducted on the 21st of July 2022 and was continued on the 22nd of July 2022 at the University of Zambia, Department of Agricultural Engineering. The experimental setup was the same as in fig.7 with the control unit engaged.This experiment was conducted to determine the performance of the dryer such as the, drying chamber efficiency, drying efficiency, and drying rate. This experiment was conducted using 700g of sliced tomatoes. On the first day of this experiment (19th July 2022), the leftover of freshly bought tomatoes in section 2.2.3 were washed and sliced at a thickness of 0.5cm and placed on the removable rectangular tray. Two slices were placed on the sample tray as shown in fig. 8a to ease removal for measurement. The sample tray was placed on the main tray (fig. 8b), and the combination was placed in the drying chamber.

Fig. 8a Sample tray with fresh pieces of tomatoes.

Fig. 8b Combined mass of fresh tomatoes on sample tray and main tray.

The tomato button on the soft-touch LCD screen which carries the image of tomatoes was selected with a click, from where the control unit automatically set the optimum drying conditions as reported by Snart et al [3] for drying tomatoes. The experiment started at 10:42 am from which data was collected at intervals of 1 houruntil when the experiment ended at 16:42. The experiment continued the next day beginning at 9:00am until 12:00 noon when the tomatoes were dried.The total time of drying (from the first day to the second day) was 9 hours.

III. Result and Discussion

Fig. 9 presents the graph of the collector efficiency versus time from the No-load experiment without the heater. From this experiment, an average collector efficiency of 67.06% was obtained for an average solar insolation of 0.721kW/m^2, an average air velocity of 0.135m/s, an average collector air temperature of 42.07℃, and an average ambient air temperature of 26.83℃ was also obtained. The data from the control unit and that from the standard data logger were the same in magnitude. The collector efficiency is defined as the heat gained by the collector as a ratio of the solar insolation falling on it [23].

Collector efficiency:

$$\eta_c = \frac{\dot{m}_a C_p (T_o - T_a)}{A_C I_T} \qquad (15)$$

Where η_c is the collector efficiency, $\dot{m}_a$ is the air mass flow rate, C_p is the specific heat capacity of air (J/kg K), T_o is the temperature of outgoing air from the collector (℃), T_a is the ambient temperature of air (℃), A_C is the collector surface area (m^2), and I_T is the solar insolation (W/m^2).

$$\dot{m}_a = \rho_a \dot{\upsilon} = \rho_a V A x$$

Where: $\dot{\upsilon}$ is the volumetric flow rate of air (m^3/s), V is the velocity of air through the collector, A_x is the cross-sectional area of the collector, and ρ_a is the density of air (kg/m^3).

This average collector efficiency of 67.06% which was obtained using equation 15 lies within the range of 21% to 69% as reported by Nabnean et al [24].

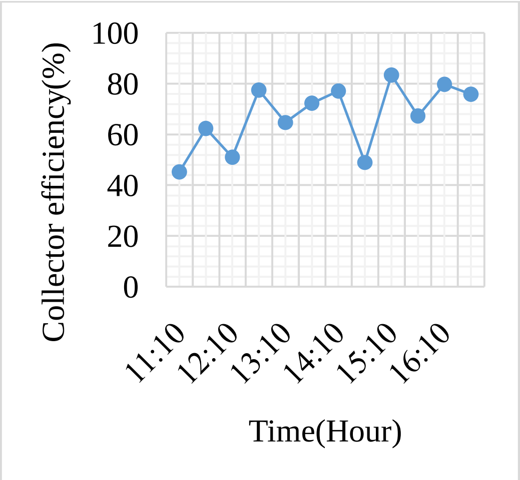

Fig. 9 Collector efficiency versus drying time.

Fig.10 shows the graph of the temperature, relative humidity, and solar irradiance against time from the no-load experiment with the heater and control. During this test, the average temperature of the air entering the drying chamber was 59.951℃,the average solar irradiance was 0.629 kW/m^2, the average relative humidity of the air entering the drying chamber was 5.94%, the average ambient air relative humidity was 35.24%, and the average ambient air temperature was 22.14℃. The temperature inside the dryer was maintained at the desired range by the control unit even during low solar irradiance.

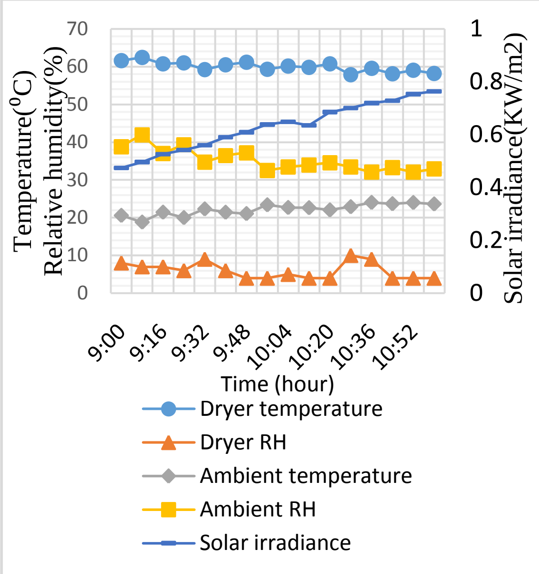

Fig.10. No-load experiment with heater and control.

For the load experiment with tomatoes, a reduction of moisture from 95.0% (wet basis) to a final moisture content of 5.30% (wet basis) was achieved with an average drying chamber air temperature of 60.33℃, average solar insolation of 0.528kW/m^2, an average ambient relative humidity of 38.643%, and an average ambient temperature of 22.71℃. The drying process can be considered to have been at optimum conditions since the achieved average drying chamber air temperature of 60.33℃ could be rounded down to 60℃. Fig.11 shows the dried tomatoes while fig.12 shows a plot of the temperature, relative humidity, and solar irradiance against the time of drying.

Fig. 11 Dried tomatoes (moisture content of 5.30% wet basis).

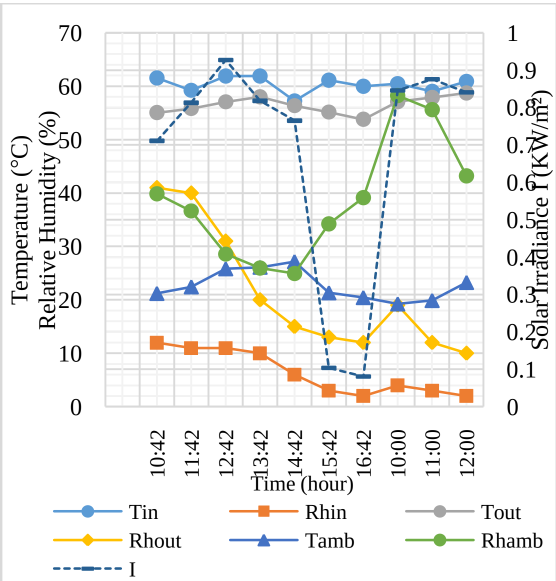

Fig. 12 Temperature, relative humidity, and solar irradiance against the time of drying.

Where *Tin* is the temperature of the air entering the drying chamber, Rhin is the Relative humidity of the air entering the drying chamber, *Tout* is the Temperature of air leaving the drying chamber, *Rhout* is the Relative humidity of air leaving the drying chamber, *Tamb* is the Ambient temperature of the air, *Rhamb* is the Relative humidity of ambient air and, *I* is the Solar irradiance.

At 14:42, the chamber temperature was observed to fall to 57.22℃ due to cloud cover but the control system was able to restore the temperature to its set range within a few seconds.

Fig. 13 and 14 show the graphs of the moisture content and the mass of tomatoes respectively, against time for the 700g tomatoes. It can be seen that both the moisture content and the mass of the tomatoes decrease with drying time. The final moisture content and mass of the tomatoes after drying were respectively 5.30% and 36.98g, respectively.

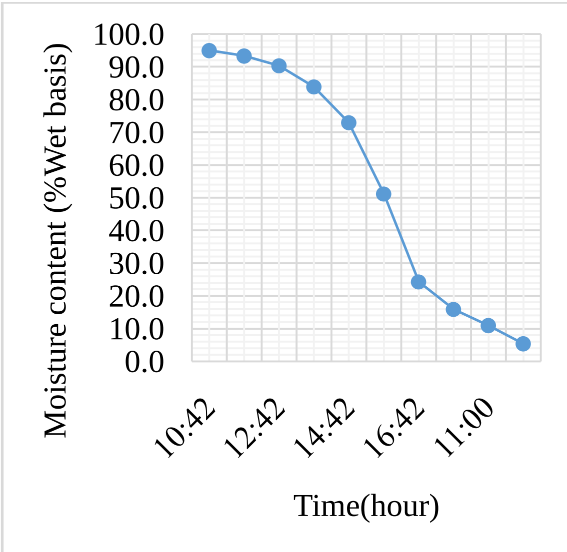

Fig. 13 Moisture content versus time.

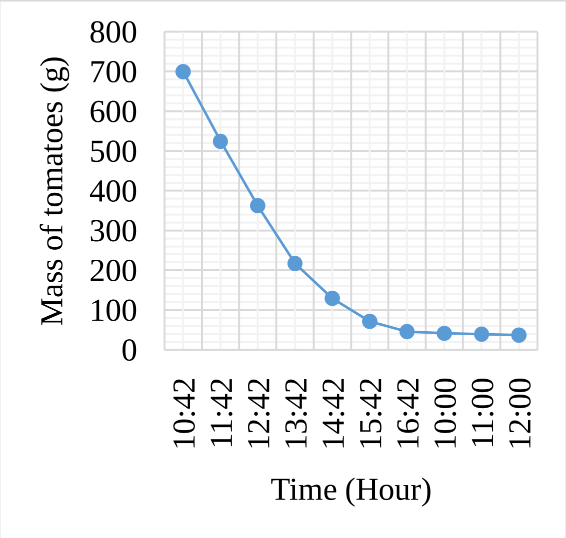

Fig. 14 Mass of tomatoes versus time.

The temperature of the air entering the drying chamber and that of air leaving the drying chamber were used to determine the drying chamber efficiencyusing equation 16[25]. The graph of drying chamber efficiency versus time was plotted as seen in Fig. 15. An average drying chamber efficiency of 10.24% was obtained which is comparable tothe 10% obtained by Nandakumar et al [25] for a hybrid drying system using reflectors.

Drying chamber efficiency:

$$\eta_{dc} = \frac{T_{in} - T_{out}}{T_{in} - T_{amb}} \times 100\% \quad (16)$$

Where T_{in} is the air temperature entering the drying chamber, T_{out} is the air temperature leaving the drying chamber, T_{amb} is the ambient air temperature entering the dryer.

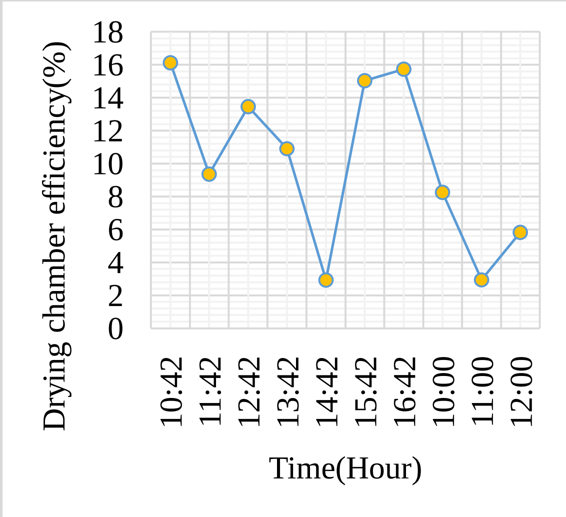

Fig. 15 Drying chamber efficiency against time.

The drying efficiency is the ratio of the thermal energy used to evaporate moisture from the food in the drying chamber to the thermal energy supplied in the dryer as expressed in equation 17.

Drying efficiency:

$$\eta_d = \frac{M_p C_p (T_d - T_a) + M_w L_v}{I A_c t + Q_{heater}} \quad (17)$$

Where M_p is the mass of the tomatoes, C_p is the specific heat capacity of the tomatoes, T_d is the average drying temperature, T_a is the average ambient temperature, M_w is the quantity of moisture to be removed, L_v is the latent heat of vaporization of moisture from the tomatoes, I is the average irradiance, t is the time of drying, Q_{heater} is the heat supplied by the electric heater.

The drying efficiency was gotten as 23.72% which was higher than that obtained byTibebu[26]which was 8.7% throughout the day with the burning of charcoal as a backup heat source in hybrid mode.This efficiency was also slightly higher than that obtained by Kothari et al [27] which was 21% using a mixed-mode solar dryer with air recirculation for drying onion flakes. Nevertheless, further works need to be done to improve the obtained efficiency.

The drying rate is the amount of moisture that evaporates from the food product over a period of time and it isgiven by equation 18.

Drying rate:

$$DR = \frac{dM}{dt} = \frac{M_{it} - M_{f(t+\Delta t)}}{\Delta t} \quad (18)$$

Where M_{it} is the initial product mass at time t, M_f is the final product mass at time $t + \Delta t$. Δt is the time interval for obtaining the rate of mass reduction of the product. It was chosen to be every 1 hour.The drying rate increases sharply from zero at the start of drying to the highest value of 175.6g/hour at the end of the first hour. During this period, moisture is readily available on the surfaces of the tomato slices, hence it is easily removed by the flowing air. After the first hour, the drying rate gradually decreases until it reaches a constant level from 10:00 to 12:00hours. The average drying rate for the tomatoes wasfound to be 66.31g/hour. The final mass of the tomato at the end of drying was measured to be 36.96g with a final moisture content of 5.30%. The total time of drying to reach this moisture content was 9 hours.

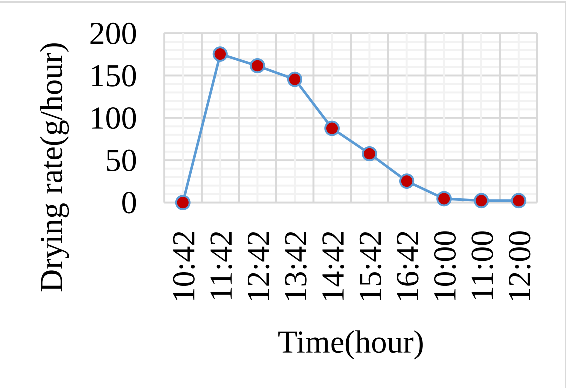

Fig.16 Drying rate versus time graph of tomato.

IV. Conclusion

The design and fabrication of an intelligent solar-photovoltaic hybrid tunnel dryer for tomatoes with automatic temperature control and air recirculation have been presented. With the control system, the dryer was able to dry the tomato at the optimum temperature of 60 ^{o}C, reducing the moisture content of tomatoes to 5.30% in a drying time of 9 hours. The implications of this study are that this solar dryer demonstrates a technology that is able to dry tomatoes within 9 hours resulting in a good quality product that is not exposed to prolonged drying which can allow the product to deteriorate. The high drying rate of this technology means that more quantities can be dried in a shorter period of time compared to other types of solar dryers. Although the experiments were done on tomatoes, the dryer was designed to dry bananas and cabbage as well under optimum temperature conditions, therefore future experiments could consider these products. Future studies could also look at optimizing the electrical energy use and therefore develop a dryer with maximum solar energy contribution but minimum electrical contribution for a given quantity of tomato. Since 240 V AC electrical power may be costly and not readily available, especially in rural areas, other future studies could consider using electrical power from solar PV with battery storage to power the heater.

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