Design of a Small-Scale Solar Maize Dryer

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Abstract

Maize is the most widely grown cereal crop in Zimbabwe. At harvest, the content of moisture in maize is usually above 25 % which is undesirable for safe storage throughout the year. The acceptable moisture content for prolonged storage of maize is about 12.5 %. Most farmers in Zimbabwe use the traditional way of drying maize by exposing it to the sun for a prolonged period. The drying period can span up to three months using these traditional methods. This delays the delivery of the grain to the market as well as the quality of the product resulting in post-harvest losses. This paper is a documentation of the project that was supported and sponsored by the Southern African Solar Thermal Demonstration Initiative (SOLTRAIN) to design a small-scale solar grain dryer for maize in Zimbabwe. Drying experiments were conducted in the laboratory to determine the drying parameters that were used in the design. An optimum drying temperature of 60 °C was determined against a drying time of 6 hours to reach the acceptable moisture levels using a drying vessel of a capacity of 1.5 tonnes and a collector area of 48 m^2 using flat plate air collectors. The control system of the dryer was also developed

Keywords: Solar drying, grain drying, flat plate air collectors, drying chamber

1. Introduction

The main goal of this project was to improve the quality of the maize whilst reducing waste associated with the drying process by making use of renewable solar thermal energy. This undertaking drives towards the achievement of Sustainable Development Goal 7 which calls for the provision of clean and affordable energy. The present common maize drying techniques in Zimbabwe are monotonous, time-consuming as far as productivity is concerned (Lambert et al., 2018). The developments that have occurred over the years use non-renewable energy sources (Meyer and Greyvenstein, 1992). These are not readily accessible in Zimbabwe, and they also compromise the natural environment. There is need to spare time, reduce labour, enhance the quality of dried maize with a better clean drying technique. Many farmers suffer post-harvest losses as well as delayed marketing of grain due to the current natural drying techniques (Herald,2016). Hence the need to develop a simple grain dryer that is usable at a small-scale level.

2. Experimental Setup

Experiments were conducted to analyse the effect of temperature on drying rate and moisture content in order to determine and optimise the drying parameters for drying grain. A Thermotec 40 litre laboratory oven was used for the experiment which has a temperature range of 0-150°C and constant airflow rate of 1.5m/s. Three temperature levels were selected according to the Taguchi Design of Experiments that are 40 °C, 50 °C and 60 °C. The mass of the grain was recorded at 5 min intervals until the moisture content of grain reaches the desired 12.5%. A stopwatch was used to measure the drying time for the various experiments. The results of the experiments are as shown in Fig 1 and Fig 2.

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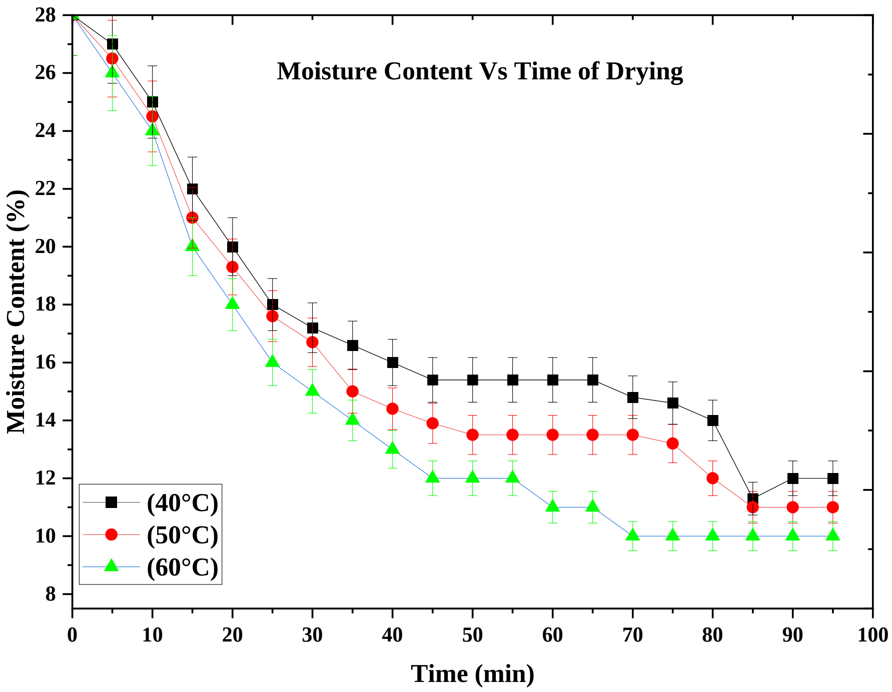

Fig.1. Moisture Content Vs Time of Drying Maize at Varying Temperatures

Fig 1 shows the variation of moisture content and drying time for the three temperature levels, while Fig 2 shows the drying rate against the drying time.

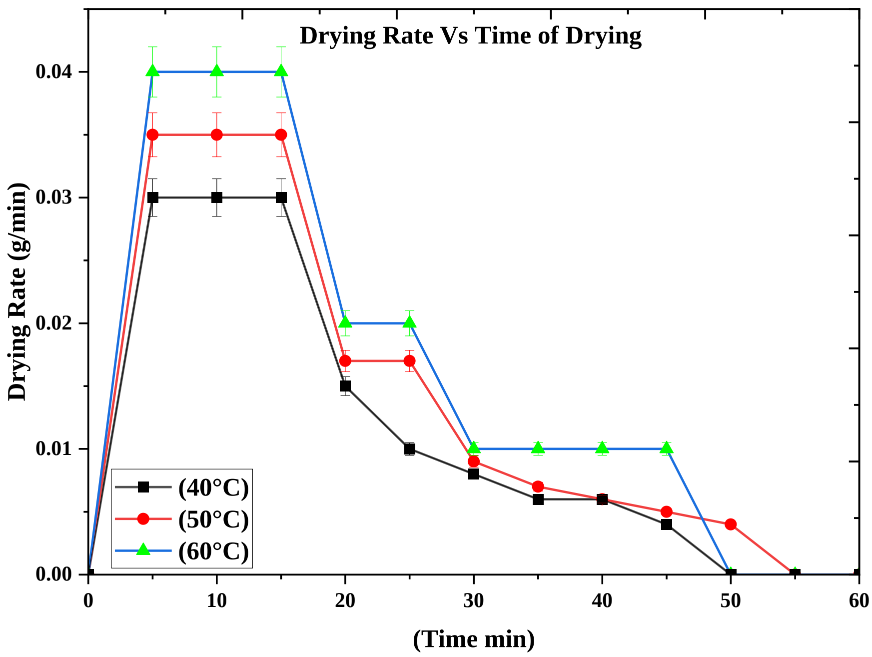

Fig.2. Drying Rate Against the Drying Time

By applying the large is better, the optimum values can be deduced from the graphs. It was concluded that dryer is sensitive to temperature more than the other parameters. Initial mass and drying period needed not be too large and too small for effective drying to take place.

3. System Design

A maize dryer was designed with a capacity of drying 1500 kg of maize from 25 % to 12.5 % moisture content in 8 hours, using a collector efficiency of 33.2 %, and a 30 % pickup efficiency as well as 30 % system efficiency. The system efficiency is within the range of efficiency for forced convection dryers, that is, 20-30 % (Fuller, 2012). The design was made up of two different systems. The first system is the heating system process that uses the flat plate solar collectors (Bala and Janjai, 2012). A dehumidifier to control the humidity and temperature of air was also included. The second system consists of the grain handling circuit for efficient drying of grain. All the electrical components were designed to be powered by an external solar photovoltaic system. Fig 3 shows the schematic of the heat collection, heat storage and drying chamber layout design. The major design considerations for the maize dryer system include the solar collector unit sizing, design of ductwork, drying chamber sizing, dehumidifier sizing, photovoltaic system sizing and the control system sizing. The solar collector design followed guidelines from Duffie and Beckman (2006) as well as Tan and Charters (1970).

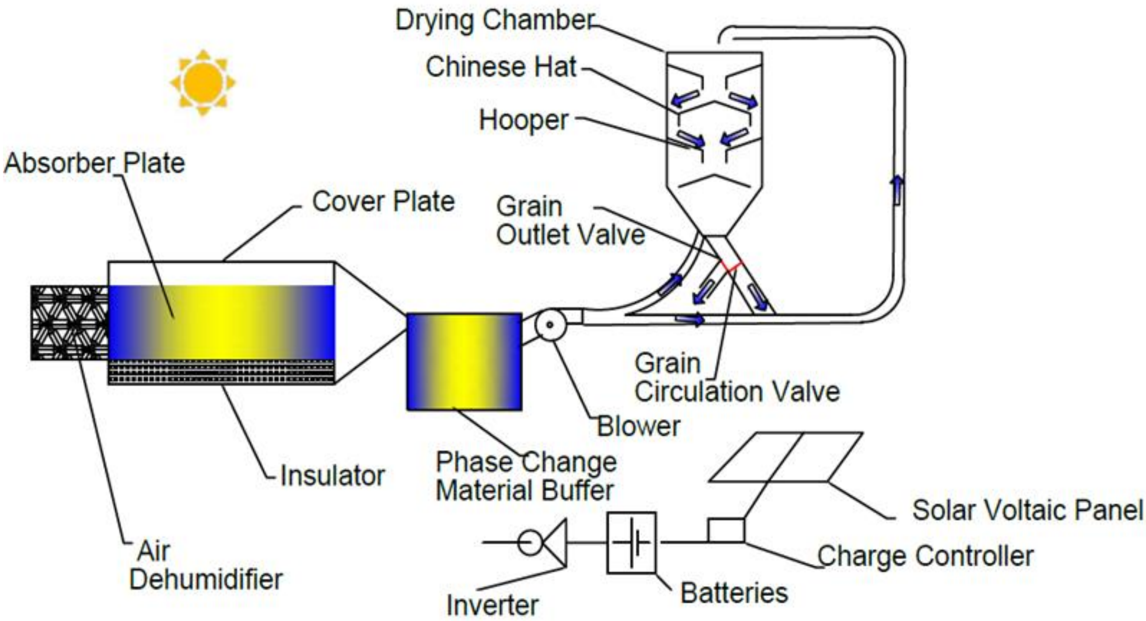

Fig.3. Maize Dryer System Layout

3.1 Design of a Solar Collector Unit

The drying heat load, Q_{load} determines the area of a solar heat collector. The heat load is determined by the amount of grain to be dried, its initial and final moisture contents, and the time required to complete the drying operation. 1500 kg of maize at 25 % moisture content needs to be dried to 12.5 % in 8 hours. The initial amount of moisture in the grain, w_i , is:

$$m_i = 25\% * 1500kg = 375\ kg \tag{1}$$

and the dry matter weight, m_{dm}, is:

$$m_{dm} = 1500\ kg - 375\ kg = 1125kg \tag{2}$$

The final amount of moisture in the grain, m_f, at 12.5 percent moisture content, is found from the relationship:

$$12.5\ \% = \frac{m_f}{m_f + m_{dm}} kg$$

Hence,

$$m_f = \frac{12.5\ \% * 1125\ kg}{0.875} = 160.71kg \tag{3}$$

The amount of moisture to be removed, m_w, is therefore:

$$m_w = 375\ kg - 160.71\ kg = 214.29kg \tag{4}$$

The total heat energy required to evaporate the water and dry maize to the required moisture content for the total drying process is calculated using Equation 5.

$$Q_{load} = m_p C_f (T_f - T_i) + m_w h_{fg} \tag{5}$$

Where:

- m_p = mass of a maize, kg
- C_f = average specific heat capacity of the maize, 1.552 kJ/kgK
- T_f (65 °C) and T_i (28 °C) is the final and initial temperatures of air respectively, ℃
- m_w = is the mass of the water to be removed during drying, kg
- h_{fg} = latent heat of vaporisation, kJ/kg. (2304 kJ/kg from steam tables)

$$Q_{load} = 1500\ kg \times 1.552\ kJ/kgK \times (65 - 28)℃ + 214.29\ kg \times 2304\ kJ/kg \qquad (6)$$

$$Q_{load} = 332.792\ MJ$$

If a conservative collector efficiency of 30% is considered, and an average irradiation of 800.48 W/m^2 for Mashonaland Central in Zimbabwe is used, the useful heat gain in the collector, q_u, is:

$$q_u = 30\% * 800.48\ {}^{W}/_{m^2} = 240.14\ {}^{W}/_{m^2} \qquad (7)$$

Assuming that radiation is available 8 hours a day, hence, using 8 hours of operation, the total collector heat gain, q_{ut}, is:

$$= 240\ {}^{W}/_{m^2} * 8\ h = 1920\ {}^{Wh}/_{m^2}\ or\ 6.916\ kJ/m^2$$

Therefore, the total area of a bare plate solar heat collector, A_c, is given by Equation 8.

$$A_c = \frac{Q_{load}}{q_{ut}} \qquad (8)$$

$$A_c = \frac{Q_{load}}{q_{ut}} = \frac{332.79}{6.916} = 48m^2$$

The average drying rate for the drying system is calculated using Equation 9:

$$\dot{m}_{dr} = \frac{m_w}{t_d} \qquad (9)$$

Where:

- t_d = total time to reach the equilibrium moisture, sec

$$\dot{m}_{dr} = \frac{214.29\ {}^{W}/_{m^2}}{8\ h \times 60\ min \times 60\ s}$$

$$\dot{m}_{dr} = 7.44 \times 10^{-3} kg/s$$

The mass flow rate of air required for the drying process is evaluated using the Equation 10:

$$\dot{m}_a = \frac{\dot{m}_{dr}}{(W_f - W_i)} \qquad (10)$$

Where:

- $\dot{m}_{dr}$, is the average drying rate, kg/hr;
- W_f; W_i are final and initial humidity ratio, ${}^{kgH_2O}/_{kg\ (dry\ air)}$ (Determined from Psychrometric Charts)

$$\dot{m}_a = \frac{7.44 \times 10^{-3}\ kg/s}{(0.20579 - 0.024226)\ {}^{kgH_2O}/_{kg\ (dry\ air)}}$$

$$\dot{m}_a = 0.041\ kg/s$$

Power required for the drying process is calculated using Equation 11:

$$Power, P = \frac{Q_{load}}{t_d} \qquad (11)$$

$$P = \frac{332.792 \times 10^6\ J}{8\ h \times 60\ min \times 60\ s}$$

$$P = 1.156 \times 10^4 W$$

3.2. Design of Ductwork

The air return system requires sizing of ducting for efficient circulation of steam. To design ducting system, a proper fan needs to be selected, evaluation of volumetric flow rate, fan horse power and the determination of the duct area. The equations to design the maize dryer ductwork include:

The volumetric flow rate required for the drying rate is evaluated as follows in Equation 12.

$$V_a = \frac{\dot{m}_a}{\rho_a} \quad (12)$$

Where:

- $\dot{m}_a =$ is the mass flow rate of air, kg/s
- $\rho_a =$ density of air at 65°C = 1.0447 kg/m^3

$$V_a = \frac{0.041\ kg/s}{1.0447\ kg/m\text{^}3}$$

$$V_a = 0.0392\ m^3/s = 79.68\ cfm$$

Fan horsepower is then evaluated using Equation 13.

$$Fan\ HP = \frac{Air\ Flow \times Static\ Pressure}{6320 \times Fan\ Efficiency} \quad (13)$$

$$Fan\ HP = \frac{79.68\ cfm \times 469.74}{6320 \times 0.85}$$

$$Fan\ HP = 6.70511 HP \approx 5\ kW$$

Most fans have efficiency ranges between 70% and 85%. Having a working temperature of 65°C = 149°F and approximating 469.74 inches from the static pressure.

The average velocity of heated air is 200fpm (1.016 m/s) (Ashrae, 2010). The duct area for the pipe system that transport heated air from thermal energy storage tank to drying chamber is determined as shown in Equation 14.

Therefore, the duct area is calculated as;

$$Duct\ Area\ = \frac{Air\ Flow(cfm)}{velocity(fpm)} \quad (14)$$

$$Duct\ Area\ = \frac{79.68\ cfm}{200\ fpm}$$

$$= 0.394 ft^2$$

3.3 Drying chamber sizing

To size the drying chamber, knowledge of amount on maize to be dried per batch as well as the volume of maize is vital. Also, the volume of the screw conveyor in the chamber is considered by addition of 30% volume of the volume of maize. The total volume is 1500kg of maize which occupies an approximate f 1.93m^3 space. With a 1.5m height, the radius of cylinder is calculated using the relationship in Equation 15.

$$Radius, r = \sqrt{\frac{V}{\pi h}} \quad (15)$$

Where,

- V = Volume of drying chamber, m^3
- h = height of drying chamber, m

$$Radius, r = \sqrt{\frac{1.3 \times 1.93\ \mathrm{m}^3}{\pi \times 1.5\ m}}$$

$$= 0.72\ m$$

3.4 Dehumidifier Sizing

Assuming that the initial humidity of moist air is 80% relative humidity, the desired relative humidity is 50%, the atmospheric room temperature and pressure is 28 °C and 760mmHg respectively. The size of the dehumidifier is obtained by use of Equation 16.

$$Dehumidification\ capacity\ per\ hour, kg/hr\ = (H_{a1} - H_{a2})V_r \qquad (16)$$

Where:

- H_{a1} = is present absolute humidity of air, mmHg
- H_{a2} = is desired absolute humidity of air, mmHg
- V_r = Volume of room to be dehumidified, i.e., solar collector volume ($9\text{m} \times 9\text{m} \times 0.5\text{m} = 40.5\text{m}^2$)

The present absolute humidity of air (H_{a1}) in mmHg is given by Equation 17 as:

$$H_{a1} = \frac{P_i \times M_w}{(P - P_i)M_{wdry}}\ mmHg \qquad (17)$$

Where:

- P_i = Partial pressure of water at given relative humidity, mmHg
- P = Atmospheric pressure of water at given relative humidity, mmHg
- M_w = Molecular weight of water, g/mol
- M_{wdry} = Molecular weight of dry air, g/mol

From Equation 17 H_{a1} and H_{a2} were determined as follows:

$$H_{a1} = \frac{P_i \times M_w}{(P - P_i)M_{wdry}} = \frac{22.61\ mmHg \times 18\ g/mol}{(760 - 22.61)mmHg \times 29g/mol} = 0.019mmHg$$

$$H_{a2} = \frac{P_i \times M_w}{(P - P_i)M_{wdry}} = \frac{14.13\ mmHg \times 18g/mol}{(760 - 14.13)\ mmHg \times 29g/mol} = 0.0118mmHg$$

This implies that using Equation 16, the dehumidification capacity would be:

$$(0.019 - 0.0118)mmHg \times 40.5\ \text{m}^2 = 0.293\text{kg/hr}$$

3.5 Photovoltaic System Design

The sizing of the photovoltaic system was done in 5 steps. The steps included estimating the electrical load, battery sizing, solar array sizing, inverter sizing, and charge controller sizing.

(i) Estimating the Electric Load

The biggest load in the design is the blower fan of 5 kW, followed by dehumidifier load estimated to be 0.28 kW. Other loads include LED lights of 30 W and microcontroller of 20 W. The blower is run intermittently during the drying process as the dryer also takes advantage of the natural convection process. It is estimated that the blower runs for an hour cumulatively during the day. The other components will operate for about 8 hours a day. A combined daily energy demand of 10 kWH was used in the design to also cater for system efficiencies.

(ii) Battery Sizing

The battery capacity is determined by the daily energy demand, the system voltage and the depth of discharge. A 12 V system, for a 10-kWH daily energy demand and depth of discharge of 50 % yields a battery capacity of about 1 700 AH. This capacity is based on one day operation. The battery capacity could be increased to give more days of autonomy, but since the solar dryer is not expected to work without radiation, therefore it is prudent to use one day of autonomy to minimise costs.

(iii) Array Sizing

The solar PV array is sized by considering the daily load demand, the peak sun hours and the system efficiency.

The location for which the dryer should be utilised has about 6.5 hours of sunshine. Considering system efficiency of 95 % between the charge controller and the array, the size of the array should be 1619 W. The selection of the panels will depend on the available solar panels on the market.

(iv) Inverter Sizing

The inverter is sized to take both linear and non-linear loads. The capacity of the inverter is should be oversized to allow for a higher power draw at equipment start-up. In this design the inverter should be able to cater for the 5 kW motor and 330 W additional components for lights, controller and dehumidifier.

(v) Charge Controller Sizing

The charge controller should be sized according to the maximum current flowing in the circuit. The maximum power from the solar generator is 1619 W and with a system voltage of 12 V the maximum amperage is around 135 Amps. The current can be reduced by increasing the system voltage to 24, 36 or 48 Volts.

3.6 Control System Design

Process control is the active changing of the drying parameters based on the results of process monitoring. The monitoring sensors measures actual values of parameters and displays them on an HML. The drying chamber will have two humidity sensors (at top and bottom) which works to measure the humidity in the dryer.

When the difference in humidity is measured and is found to be more or less the same, the buzzer system rings to alert the operator to close circulation valve. The operator will then open the offloading valve to take a sample of maize only and check if the moisture content has reached desired level. If the humidity difference between the two sensors is not within threshold, the maize offloading valve is closed whilst the circulation valve is open to allow grain circulation.

The temperature sensors measure current temperature and they shut down the blower when the temperatures in the drier are not within threshold. In the design of the control system, an Arduino controller is used to control the system automatically.

4. System Flow

The system flow can be explained by two different systems. The first system is the heating system process that uses the flat plate solar collectors, dehumidifier to heat air to required temperatures. The second system consist of the grain handling circuit for efficient drying of grain.

4.1 The Heating Circuit

The heating circuit is made up of the flat plate solar collector, dehumidifier, PID controller. The heat energy is collected by the flat plate solar collector and stored in the heat storage tank. From the heat storage tank, there is a valve to regulate the amount of heat energy passing through. As heat passes through the valve, it is then blown to grain at required temperatures for drying.

The drying chamber has temperature sensors to check the current temperatures of the heat transferred to maize. The valve opening levels are controlled by use of PID controller. The PID controller sends a voltage pulse depending with the calculated error. Therefore, the valve is either partially opened or closed as it allows heat to pass through to compensate for the disturbances.

4.2 Grain Handling Circuit

The grain handling system is made up of the drying chamber with hoppers and Chinese hats, valves and two blowers. Grain is loaded into drying chamber by blowing it to the top after which the blower is switched of. As grain falls through the opening of the hopper, it receives heat energy from the heated air and in doing so it starts to dry gradually.

After passing through the top hopper, grain is channeled (by means of Chinese hats) to the constructed gaps between the inner surfaces of the drying chamber and Chinese hats and in doing so increases the holding time of grain in the chamber. From the Chinese hats, grain continue falling down to the conical shaped bottom of the drying chamber by means of gravity.

The tip opening of the conical shaped bottom of the drying chamber has a pipe which collects grain that falls on it. This pipe is Y shaped with single valves for each. One pipe is for grain discharge after drying and the other is for circulation of grain to be blown back to the top chamber hopper such that the process repeats itself until grain reaches the required moisture content.

5. Results

The designed dryer has a capacity of drying 1 500 kg of maize from 25% to 12.5% moisture content in 8 hours. The solar dryer has a collector efficiency of 43.2%, and a 30% pickup efficiency as well as 30% system efficiency. The system efficiency is within the range of efficiency for forced convection dryers, that is, 20-30 %. The collector efficiency is within the range of 30-40 % for the given collector area. This implies that the project is economically feasible and a desirable option.

A working prototype which is shown in Figure 4 was fabricated. The prototype was made up of a flat plate solar collector, heat storage tank, a blower, a drying chamber, as well as the control unit. A flat plate solar collector was made up of a glass cover plate, anodic aluminum absorber plate and a wooden insulator plate. The drying chamber, as well as the heat storage tank, were made of a galvanized metal sheet. Control system was made up of Arduino Mega microcontroller connected to two DHT temperature and humidity sensors and a DSB 108 temperature sensor. A buzzer and an LED light with two colors green and red showing comprised the control system.

Fig.4.Fabricated Prototype

6. Conclusion

The project consists of the design of a solar thermal dryer for use by A1 communal farmers in Zimbabwe. It gives an understanding of harnessing solar energy for the benefit of the farmers thereby increasing the efficiency of drying grain during harvest period. The design can dry 1.5 tons per day on a normal sunny day. This will go a long way in reducing post-harvest losses and farmers can deliver their grain to the market at a faster rate thereby improving their cash flows compared to natural drying.

7. Acknowledgements

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