Advances in Technology Innovation, vol. 4, no. 4, 2019, pp. 222-233

Development of a Cost-effective Design of a P-V Ventilated Greenhouse Solar Dryer for Commercial Preservation of Tomatoes in a Rural Setting

Ebangu Orari Benedict[1,2,*], Dintwa Edward[1], Motsamai Seraga Oboetswe[1]

[1]Department of Mechanical Engineering, University of Botswana, Gaborone, Botswana
[2]Department of Biosystems Engineering Gulu University, Gulu, Uganda

Received 28 March 2019; received in revised form 16 May 2019; accepted 09 July 2019

Abstract

Commercial preservation of agro-produce by solar drying entails using large-scale dryer units that are generally not affordable by potential users in a rural setting. The objective of this study was to design a photo-voltaic greenhouse solar drying unit with air convection powered by a photovoltaic system as part of a research study to develop a cost-effective commercial solar dryer for the preservation of tomatoes in a rural setting. The design methodology involved. First, the determination of thermophysical properties of local tomatoes and predicting its drying model. Second, determination of design parameters; design equations, design conditions and assumptions, and psychrometric analysis. Third, application of the design parameters under the climatic conditions of Botswana to produce the embodiment of design with the drawings and specifications for a solar hot air dryer unit of 2000 kg batch-load of wet tomatoes. This drying unit is integrated into a solar collector with a cost-friendly thermal energy storage system to store solar energy during the day for use after sunset for better performance.

Keywords: commercial preservation, thermo-physical properties, embodiment of design, thermal energy storage system

1. Introduction

The discussion on applicable methods to alleviate the high global postharvest losses, 30-50 %, that negatively impact on the agro-produce value chain is on-going [1]. Recent research work has focused on using renewable energy technologies for drying of agro-produce as the preservation method to reduce postharvest losses [2-3]. Solar dryers have therefore increasingly become popular especially on account of their relative costs of investment and operation [4-7]. However solar dryers are scarce in Botswana despite the endowment with abundant sunshine [8]. This study aims at developing a suitable solar dryer for use in Botswana to preserve fruits and vegetables, particularly tomatoes. Drying of tomatoes for commercial purpose in a rural set up requires the use of tunnel or greenhouse types of solar dryers. In this paper, the design of a forced convection solar dryer ventilated by fans operated by a photo-voltaic system is presented. Various designs of solar dryers for the preservation of fruits and vegetables have been reported in the literature [9]. Experiments were carried out on solar drying of pineapple using a solar tunnel dryer, the version of the original Hohenheim type solar dryer in Bangladesh [10]. This dryer had a transparent polyethylene covered flat plate collector and a drying tunnel. Hot air was supplied to the drying tunnel using fans operated by a solar module. However, the tunnel dryer design had limited batch capacity for large scale commercial drying of products.

Design innovations have been made aimed at increasing the capacity and efficiency of solar dryers. A solar dryer with reverse flat-plate collector absorber to receive concentrated solar irradiation at a higher temperature to increase the efficiency of the dryer was developed [11]. The geometrical construction and manual tracking of the sun rays were the major challenges

---

[*] Corresponding author. E-mail address: benebangu@yahoo.com
Tel.: +267-76675111

of this technology. A solar dryer comprising a flat plate collector that used mirror reflectors to enhance the capture of solar irradiance at the solar heater unit of a mixed-mode greenhouse dryer was designed and constructed [12]. The dryer was tested by successful drying of bananas and tomatoes. However, to track the sunshine, the mirrors needed to be continuously adjusted during the day and this presents a labor intensive activity. A large scale polycarbonate covered greenhouse / tunnel type solar dryer using forced convection air flow was developed [13]. It was tested for performance and it did demonstrate the potential for drying chilli, coffee and banana. This dryer design had the potential to be developed to dry, at large scale, tomatoes and other horticultural products if auxiliary energy source was incorporated into the dryer system to enable drying without interruption. Janjai [14], developed and tested at field level a large-scale solar green-house dryer with a loading capacity of 1000 kg of fruits or vegetables. This greenhouse dryer had a parabolic shape and was covered with polycarbonate sheets. The dryer was backed up by the use of LPG gas energy source and its ventilation fans were powered by photo-voltaic, P-V, module. It was used to dry bananas, coffee, chilli, tomatoes, and other fruits and vegetables. The solar greenhouse dryer was easy to construct and was suitable for commercial-scale applications because of the fast drying rate. However, a cheaper source of auxiliary energy than LPG gas could reduce the operational cost of the dryer.

From the reviews of the greenhouse solar dryer technologies, SDTs, summarized in Table 1, great effort has been put to develop greenhouse solar dryers for fruits and vegetables but few designs have been developed and tested for commercial drying of tomatoes in a rural setting where affordability of the technology is a matter of great concern.

Table 1 Summary of Material Properties

Year	Year	Highlights
2016	Hii, et al. [15]	Development and recent trends in greenhouse SDTs
2016	Hawlader, et al. [16]	Solar tunnel greenhouse type of SDT
2017	Sengar and Kothari [17]	Thermal modeling and performance evaluation of arch shape greenhouse for nursery raising
2017	Atalay, et al. [18]	Modeling of the drying process of apple slices: Application with a solar dryer and the thermal energy storage system.
2019	Badaoui et al. [19]	Experimental and modelling study of tomato pomace waste drying in a new solar greenhouse: Evaluation of new drying models
2019	Román-Roldán, et al. [20]	Computational fluid dynamics analysis of heat transfer in a greenhouse solar dryer “chapel- type” coupled to an air solar heating system

Thermo-physical properties of the material to be dried define the boundary conditions for the drying process. Density, specific heat capacity, heat conductivity, thermal diffusivity, moisture content are the properties of tomatoes were assessed from the literature and also determined by laboratory experiments. The experiments were necessary because although the tomato varieties prevalent in Botswana are of Mexico native origin, Solanum Lycopersicum, their properties could vary due to climatic and ecological conditions The six common varieties grown in Botswana are Money Maker, Expresso, Heinz 1379, Zeal, Zest, and Six Pack. The farmers in Botswana have ranked the Zeal variety as the best variety [21].

2. Design Methodology

The design methodology considers the conceptual design of a phot-voltaic air fan ventilated dome-shaped design of a greenhouse solar dryer for large scale drying of tomatoes. Hence the thermo-physical properties are determined in the first step. The design equations and design calculations are discussed in the second step and the embodiment of design is handled in the final step. The flow diagram of the design process is depicted in Fig. 1.

2.1. Determination of thermophysical properties of tomatoes

The experimental setup for determination of moisture content was in respect of an oven drying method used to determine the moisture content of sliced tomatoes. The oven dryer apparatus (Carbolite-Gero GmbH Co., KG 30-3000 ℃) was used to dry the tomato samples. It was set to operate at a temperature of 105℃, and the air in the oven was set to ventilate at 1.1 m/s. A calibrated electronic balance type: Snowrex LV-6B was used for measurement of weight.

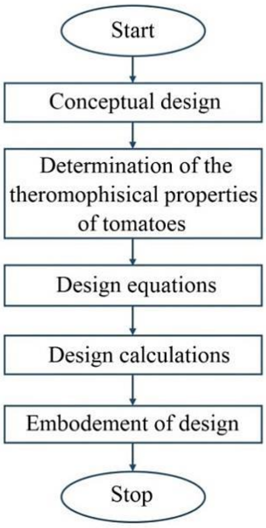


Fig. 1 Flowchart of the design methodology

2.2. *Experimental procedure*

Tomato samples of the Zeal variety that is most prevalent in Botswana were procured from Gaborone supermarkets and used as the material for determining the moisture content of the tomato for drying. The tomatoes were first washed with running water. No chemical pre-treatment of the samples was done. A vegetable cutting knife was used to cut the tomato samples to half- slices of about 25 mm diameter. These slices were weighed and placed inside the oven dryer.

The oven-method procedure of the hot air oven method according to ACAC 1990 for determination of moisture content of sliced tomato was followed. The initial weight of each tomato-slice sample with its containment was recorded after determining the weight of the empty container. Then the instant weights of each sample were recorded on an hourly basis while drying in the oven. The decreasing masses of the sample slices were monitored to a final stable weight by means of a calibrated digital balance. The end of drying was reckoned by uniform constant weight readings. Weight loss was determined at 60-minute intervals during drying. Visual inspection of color and texture was relied upon to confirm the dried status of the tomato slices [22].

2.3. *The design equations*

Moisture content was calculated as the ratio of weight loss during the drying period with the weight of the wet or the dry weight of the sample. The value of moisture content usually expressed in percentage, %, or in decimal values, was thus presented either on a wet basis, wb, or dry basis, db. The value of moisture content usually expressed in percentage, %, or in decimal values, was thus presented either on a wet basis, wb or dry basis, db. The moisture content, wet-basis, and moisture content dry-basis were evaluated [23] by

$$M_{wb} = \frac{W_o - W_d}{W_o} \tag{1}$$

$$M_{db} = \frac{W_o - W_d}{W_d} \tag{2}$$

where W_o is the weight of the wet material and W_d is the weight of the dry material. The relationship between M_{wb} and M_{db} can be given by two expressions of moisture content of agricultural materials as follows

$$M_{db} = \frac{M_{wb}}{1 - M_{wb}} \tag{3}$$

$$M_{wb} = \frac{M_{db}}{1+M_{db}} \tag{4}$$

The moisture content at time t during drying, M_t , is evaluated by [22].

$$M_t = \left[\frac{W_t}{W_o} * (M_i + 1) - 1 \right] \tag{5}$$

where M_i is the initial moisture content, db , W_t is the instant weight of the sample, W_o is the initial weight of the sample. The moisture ratio M_R is a function of time that rationally defines the moisture content of the drying process. Since M_f is relatively negligible in comparison to M_i and M_t . M_R is approximately given as the ratio given by [23].

$$M_R = \frac{M_t - M_f}{M_i - M_f} = \frac{M_t}{M_i} \tag{6}$$

The mass of the moisture to be removed from the food product is calculated by Berichte [24]

$$m_w = \frac{m_p (M_i - M_f)}{100 - M_f} \tag{7}$$

where, m_p , is the initial mass of the product to be dried, m_w is the mass of water to be removed from the wet material, M_i is the initial moisture content, % dry basis, M_f is the equilibrium or final moisture content, % dry basis.

Latent heat of vaporization was calculated by [25].

$$L_V = 4.186 * 10^3 (597 - 0.57 T_{pr}) \tag{8}$$

where L_V is the latent heat of vaporization of water and T_{pr} is the drying temperature in °C of the material to be dried.

The quantity of heat energy required for drying a given quantity of food materials can be approximated using the basic energy balance equation for the evaporation of water was given Norton and Sun by [26]

$$Q = m_w L_V + m_a C_{pa} (T_1 - T_2) \tag{9}$$

where L_V =latent heat of vaporization of water in kJ/kg, m_w is the mass of water evaporated from the food item, m_a is the mass of drying air, $(T_1 - T_2)$ is the difference between initial and final temperatures of the drying air respectively, in Kelvin, C_{pa} is the specific heat capacity of drying air at constant pressure kJ/kg K.

The enthalpy h of air was approximated [27] by

$$h = 1006.9T + w(2512131.0 + 1552.4T) \tag{10}$$

where T is the temperature of drying air, °C, and w is the humidity ratio of water vapor, in one kg of dry air.

The amount of water in food and agricultural materials affects the quality and perishability of the material. The indicator for perishability of the material is a_w the water activity. It is the level of availability of moisture to support degradation like microbial action. The water activity is evaluated as [28]

$$a_w = \frac{p}{p_o} \tag{11}$$

where p is the partial pressure of water above the material surface and, p_o is the partial pressure of pure water under the same conditions as the food.

The water activity can also be evaluated using the empirical formula [29] by

$$\frac{E_{RH}}{100} = \alpha w = 1 - \exp[-\exp(0.914 + 0.5639 \ln M_{db})] \tag{12}$$

where M_{db} is the moisture content dry basis in kg water vapor/kg pure water and, E_{RH} is the relative humidity of the air surrounding the food at which the material neither gains nor loses its natural moisture and is in equilibrium with the environment.

The average drying rate d_r for drying the food was evaluated by [26]

$$d_r = \frac{m_w}{t_d} \tag{13}$$

where m_w is the mass of moisture removed from the food and t_d is the drying time in hours.

The mass flow rate, m_a of the air needed for drying, is given by [26]

$$m_a = \frac{d_r}{(w_f - w_i)} \tag{14}$$

where d_r is the average drying rate, w_i is the initial humidity ratio, kg H2O/kg dry air, w_f is the final humidity ratio, kg H2O/kg dry air.

The volumetric airflow rate V_a in m3/hr is evaluated by

$$V_a = \frac{m_a}{\rho_a} \tag{15}$$

The total useful thermal energy of the drying air, E in Joules, required to evaporate the water is given [30] by

$$E = m_a (h_f - h_i) t_d \tag{16}$$

where the air mass flow rate is m_a in kg/hr, h_i and h_f are the final and initial enthalpy of drying air and ambient air respectively in J/kg of dry air and, t_d is the drying time in hours

The dryer area was calculated from the equation by [31]

$$E = A_d I_\eta \tag{17}$$

where the area of the dryer cover is A_d in m2, I is the total incident radiation on the greenhouse dryer surface during the drying period, and η is the dryer efficiency which is between 30-50% [32].

The vent area A_v was determined by the ratio of the volumetric flow rate of air inside the dryer V_a to wind velocity V_w by

$$A_v = \frac{V_a}{V_w} \tag{18}$$

2.4. Psychrometric chart

Thermodynamic parameters were obtained by use of psychrometric calculator developed from Psychrometric charts that describe the thermodynamic process of hot air drying [33]. The most common dehydration processes use hot air as the drying medium as the air delivers heat to the product in order to evaporate moisture. The properties of air, most easily understood by psychrometric relationships are critical to understanding the process of evaporation. The dry air can be visualized as a gaseous solution of dry gases in constant proportions and water vapor in varying amount. At least two properties of air must be known in order to use the chart to characterize the drying air. Amongst the properties of air that are critical to drying are absolute humidity, enthalpy or heat content, specific volume, and relative humidity. The thermodynamic changes that take place in a solar dryer include heating depicted line A-B of Fig. 3 whereby there is a rise in temperature from TA to TB at constant absolute humidity. The relative humidity reduces from hA to hB. This is followed by the heating phase depicted by line B-C whereby the air picks up moisture from the product and the temperature drops from the drying temperature attained by air inside the dryer TB to exit temperature TC. In this process, the relative humidity increases from hB to hC. The humidity ratio will increase from HB to HC. The initial enthalpy, hA, will change to hC at C'.

Table 2 Psychrometric values of drying air

Item	Temperature-dry basis in °C	Relative Humidity in %	Enthalpy in kJ/kg	Humidity Ratio in kg/kg	Specific volume in m^3/kg
Ambient temperature	24	55	53.70	0.0116	0.9695
Solar collector outlet air	45	21.09	82.36	0.0143	0.913
Dryer outlet air	37	50.0	89.28	0.0202	0.890

Table 3 Design conditions and assumptions

S/No	Items	Condition and assumption
1	Location: Botswana, Gaborone, University of Botswana	Elevation:1005 m, 24.56 0S, 25.92 0E
2	Material for drying	Tomato
3	Drying period using solar energy exclusively, t_d, the average bright sunshine hours in a day	30
4	Loaded mass, m_p kg/batch	2000
5	Initial moisture content, Mi, %, w_b, measured in the laboratory	96
6	Final moisture content, Mf, %, w_b, evaluated using Equation 1 at a_w=0.55	12
7	Average ambient air temperature, Tam ^{0}C	24
8	Average ambient relative humidity, RH, %	44
9	Maximum allowable temperature, Tprmax, ^{0}C	60
10	Maximum allowable product temperature, Tpr, ^{0}C	45
11	Specific heat capacity of tomato slices Cpp, kJ/kg	4.080
12	Average incident solar radiation, in MJ m^2/day	21.6
13	Wind speed, Vw, km/h, from Gaborone weather forecast	6
14	Collector efficiency. η =25-50 % [32]	30
15	The thickness of half sliced tomato, m	0.03

The changes in the drying air are evaluated by the assistance of the psychrometric chart/calculator. This thermodynamic data is given in Table 2. These parameters are used in the design process.

The assumption was made that there was no heat loss between the collector and drying chamber; the solar collector outlet temperature was assumed to be equal to the dryer inlet temperature. The conditions and assumptions for the design calculations are given in Table 3.

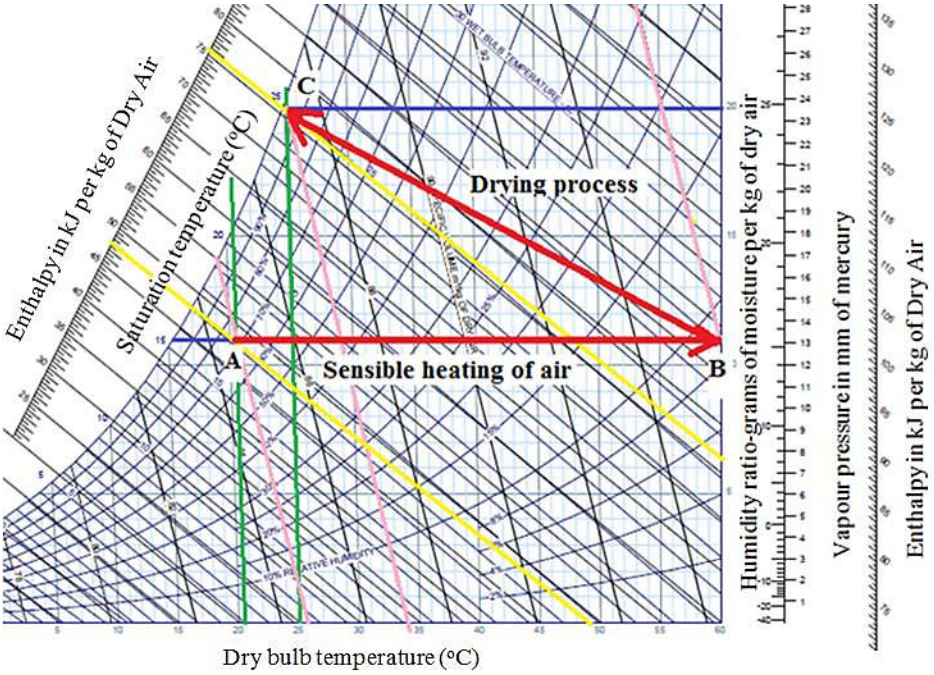


Fig. 3 The principle of the psychrometric chart

3. Results and Discussions

3.1. The tomato thermo-physical properties of tomatoes

The thermophysical properties were determined in respect of moisture content, density, specific heat capacity, heat capacity and conductivity for the Zeal tomato variety. Table 4 gives the results of weight measurements during oven drying.

Table 4 Weight of tomato samples during oven drying

Expired hours	W1, g	W2, g	W3, g	W4 average, g	M (t)	MRexp
0	63	61	66	63.3	24.01	1
1.05	48	36	50	44.7	16.64	0.69
2.08	32	34	38	34.7	12.69	0.53
3.17	28	30	34	30.7	11.11	0.46
3.95	25	28	30	27.7	9.93	0.41
4.7	22	24	27	24.3	8.61	0.36
5.69	17	21	24	20.7	7.16	0.3
6.75	14	17	20	17.0	5.71	0.24
7.05	9	13	16	12.7	4	0.17
7.95	4	10	12	8.7	2.42	0.1
8.86	3	6	8	5.7	1.24	0.05
9.11	3	7	7	5.7	1.24	0.05
9.72	3	7	7	5.7	1.24	0.05

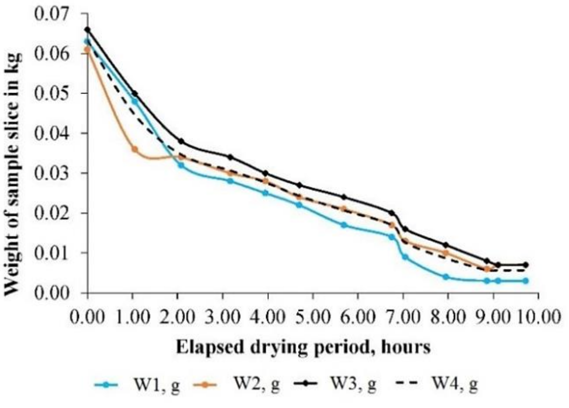


Fig. 4 Determination of the initial moisture content of tomato samples

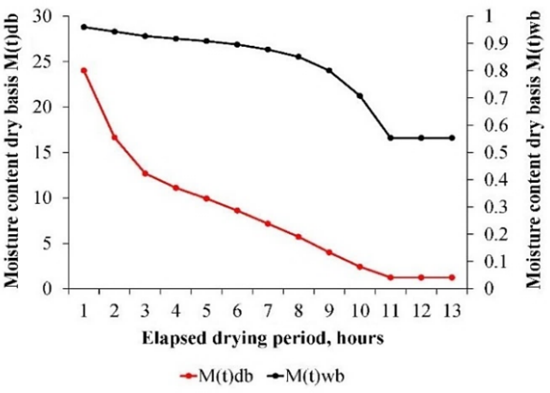


Fig. 5 Moisture content Mt, db and Mt, wb, wet and dry basis

The results depicted in Fig. 4 shows the curves of reducing weight for samples of tomato drying samples. The initial moisture content, wet basis, wb, was determined using Equation 2 as 87%, 90%, and 96%, and for tomato samples Sample TS1, Sample TS2, and Sample TS3, respectively. The moisture content for the local Botswana tomato in this study was taken as 96% as it was the highest value from the samples that were analyzed.

Mass of tomato was measured using a weighing digital scale and volume was determined by displacing water from a calibrated flask by the tomato sample. Hence the density of the local Zeal variety tomato was determined. Fig.5 depicts the moisture ratio M_t , w_b , and M_t , db , calculated from the average weight measurements of the oven drying process using Eq. (5), The moisture content wet basis was determined using Eq. (3).

Fig. 6 shows the Moisture ratio determined from the tomato oven drying experiment using the approximate Eq. (6). By use of Excel curve fitting solver, the predicted moisture ratio for this drying process was modeled as curve Expon MRexp.

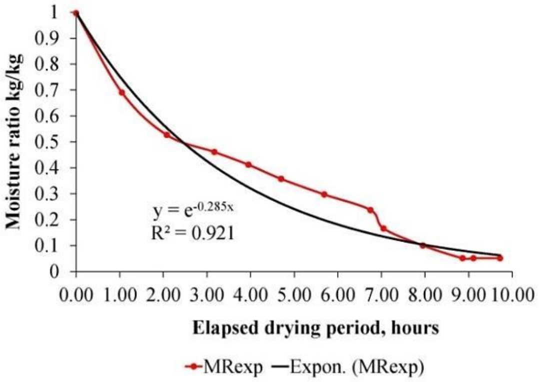


Fig. 6 MRexp determined from experiment and the fitted MRpred

The moisture ratio model is given in Table 5 for oven drying of tomato slices at 105℃ and air velocity of 1.1 m/s was derived by curve fitting model of Excel software, is the Newton model with regression coefficient R^2=0.921.

Table 5 Tomato Moisture ratio model

Model formula $MR = \exp(-kt)$	k	R^2	Model
$MRpred = \exp(-0.285t)$	0.285	0.921	Newton

Specific heat capacity and thermal conductivity were obtained from the literature [34, 35]. The thermophysical properties of the Zeal tomato used in this study are given in Table 6.

Table 6 Properties of the round ripe red Zeal tomato grown in Botswana

Weight in gram^s	Volume, cm^3	Density, kg/m^3	Specific heat capacity, kJ/kg ℃	Thermal conductivity, W/m K	Diffusivity in m^2/s*e-7	Initial moisture content, %	Final moisture content, %
132	130.1	1014	4.080	0.59	1.44	96	12

3.2. Design assumptions and calculations

The results of calculations done on the basis of equations given in section are summarized in Table 7. The parameter of interest is the top area of the solar energy interface. By the determined value of the area, the researcher was able to proceed to complete the design based on priorities for the design concept and other engineering design parameters and procedure and to give specifications of the components and materials to be used.

Table 7 Design assumptions and calculations

S/no	Description	Equation	Value
1	Mass of water to be evaporated from 2000 kg of fresh tomatoes, and 50 kg for prototype, mw. in kg	Using Equation 4.5	1795
2	Latent heat of vaporization in MJ	Using Equation 4.6	2.390
3	The energy required for evaporating water from the product, in MJ	Using Equation 4.7	4.562

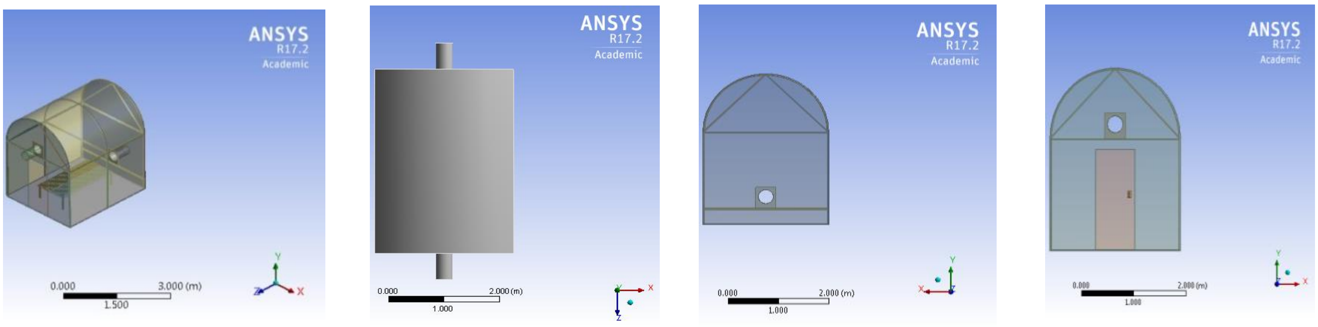
Table 7 Design assumptions and calculations (continue)

S/no	Description	Equation	Value
4	Equilibrium Relative Humidity, in % ERH=*aw**100%	Using Equation 4.10	55
5	Initial humidity ratio, wi	From psychrometric chart/www.psychrometric-calculator.com.	0.0143
6	Final humidity ratio, wf	From psychrometric chart/www.psychrometric-calculator.com.	0.0202
7	Enthalpy, hi, initial enthalpy of ambient air, kJ/kg/kgda	From psychrometric chart/www.psychrometric-calculator.com.	82.36
8	Enthalpy, hf of final moist air kJ/kg/kgda	From psychrometric chart/www.psychrometric-calculator .com.	89.28
9	Average drying rate mdr for td=10 hours per day for 3 days, kg/hr	Using Equation 4.11	59.85
10	Airflow rate, ma, kg/hr	Using Equation 4.12	10144.07
11	Volumetric air flow rate, VA in m^3/min	Using Equation 4.13	141.0
12	Total useful energy, E in MJ	Using Equation 4.14	2105.909
13	Greenhouse top area Ad m2	Using Equation 4.15	324.98
14	Greenhouse with floor area Af m2 of dimensions of about 13 m widths by 25m length	Af=Ad	325
15	The linear air flow rate in m/s	Conversion of Va over the flow area	0.007
16	The vent area Av m2 when wind velocity Vw is 6 km/h	Using Equation 4.16	1.41
17	The diameter of a cylindrical vent D m	D=2*SQRT Av/π	1.34

3.3. *Design features and material specifications*

Table 8 Specifications of major items of the designed Greenhouse dryer

S/No	Item Description	Specification
1	Polyethylene ultra violet resistant cover	Clear 2-3 mm thick film
2	Horizontal floor area	325 m^2.
3	The volume of greenhouse dryer	1035 m^3
4	Drying table for tomato slices	Plastic mesh on an aluminum frame
5	Photovoltaic, P-V unit	100-Watt, 100 Ah solar battery
6	Air fan unit	150 m^3/min
7	Inlet/Outlet ducts diameter	Aluminum 1340 mm



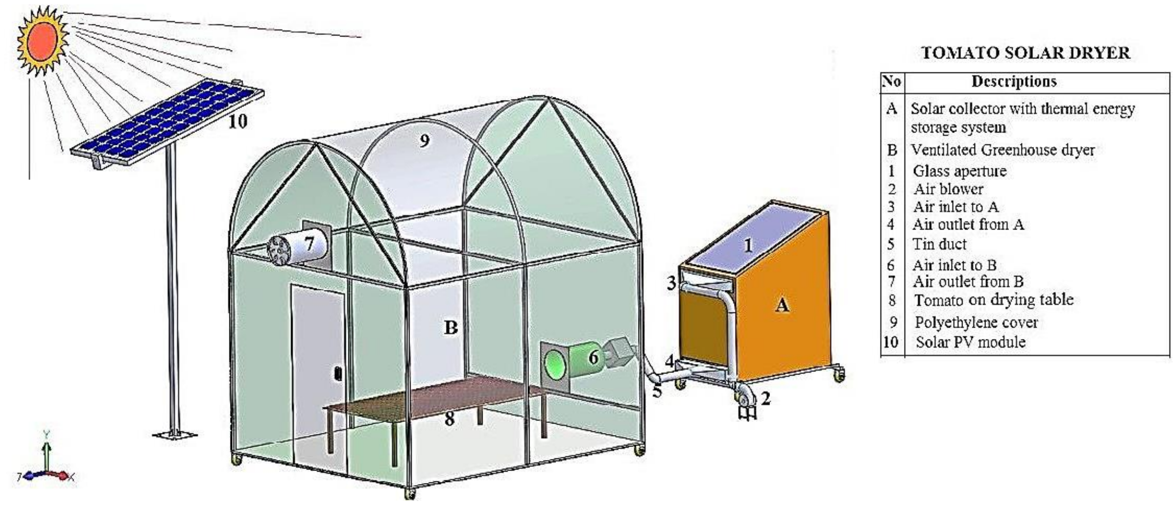
(a) The isometric drawing (b) Top view (c) Back view (d) Front view

Fig. 7 Drawings of the design of the ventilated Greenhouse dryer showing the different views

The final drawings of the ventilated greenhouse solar dryer were prepared using Solid Works software and ANSYS Modeller 17.2. Centrifugal blow fan is fitted at the inlet and the exhaust fan of the same rating is fitted at the outlet to exit the drying air. These fans are powered by a photovoltaic system, not shown in the drawing. The dryer base is covered with checked aluminum plate, painted black and is insulated from the ground. Inside the dryer is the drying rack where half-sliced tomatoes for drying are laid. The greenhouse is covered by polyethylene ultra-violet film and entry to the inside of the dryer is accessed by opening the door in the front side. The design drawings are given in Fig. 7. The major components are listed in Table 8.

3.4. *Cost-effectiveness of design*

The final design of the greenhouse solar dryer is to be integrated with a solar collector with a thermal energy storage system to enable the drying process to continue after sunset. Sensible heat storage, SHS, systems are relatively simple and relatively of lower cost compared to chemical or latent thermal energy storage systems [36]. Solid sensible heat storage system using granite rock as the thermal storage material has been identified for use in the design of the thermal energy storage system. In comparison with latent and thermo-chemical optional thermal energy storage systems, the use of sensible rock thermal energy storage system is the most cost-effective as regards technical, cost and environmental criteria. The classification of the SHS system using rock material that is low cost, ready availability, negligible maintenance, and operational cost would result in a relatively low-cost solar collector. When the solar collector with the TES system is integrated into the greenhouse unit, the technology becomes cost-effective to fulfill the main objective of commercial drying of tomatoes even after sunset in a rural setting. Fig. 8 depicts the schematic drawing of the design of the greenhouse solar dryer with the proposed solar collector.



TOMATO SOLAR DRYER

No	Descriptions
A	Solar collector with thermal energy storage system
B	Ventilated Greenhouse dryer
1	Glass aperture
2	Air blower
3	Air inlet to A
4	Air outlet from A
5	Tin duct
6	Air inlet to B
7	Air outlet from B
8	Tomato on drying table
9	Polyethylene cover
10	Solar PV module

Fig. 8 Schematic design drawing of the P-V ventilated greenhouse solar hot air tomato dryer

3.5. *Design materials*

In selecting the design materials, consideration of their effectiveness and price was made. The ventilated greenhouse dryer’s cover material was chosen based on suitability to interface with the incident solar radiation, strength and price. Plastic films and sheets are relatively cheaper than glass. Generally, plastics may have long-wave transmittance of up to 0.4 with a maximum temperature of 120℃. For application in low-temperature drying, a maximum of 60℃, the ultra-violet resistant polycarbonate material was recommended but it was scarce in Botswana. Polyethylene ultra-violet resistant film, 2-4mm thickness, was alternatively available in Gaborone and was thus chosen.

The insulation material was required for the base of the dryer. The base comprising of an insulated slab made of polyurethane foam, PUR/PIR that is frequently employed in storage tanks was recommended. The insulation material has an extremely low thermal conductivity of 0.02-0.026W/m K possess excellent mechanical strength, exceptional durability, and moisture resistant. The insulation material was cost-effective and easy to install.

The output of the solar collector was the drying air that flowed to the drying chamber via a duct, Aluminium and galvanized-tin ducts are the two standard most common materials for fabricating ducts because of their high optical reflectance. Aluminum is light-weight, has a low density of about third of other metals. It has a high thermal conductivity of about three times that of steel and can be easily fabricated and installed on-site. However, the galvanized tin duct was relatively cheaper than the aluminium duct and was recommended as the ducting material.

Airflow inside the solar dryer was taken care of by the use of a solar photo-voltaic, P-V module. The solar panel system was incorporated in the design as part of the dryer technology and was used to power the fanning system for a controlled operation depending on insolation levels. A solar battery 0f 100 Ah in the P-V system of one 100 W panel was to be used to store energy in order to save on the high operational cost of using electricity.

4. Conclusions

The following conclusions were made from the development of the design of the solar dryer unit:

(1) The thermo-physical properties of the tomato were determined as Weight: 132 g, Volume: 130.1 cm3, Density: 1014 kg/m3, Specific heat capacity: 4.080 kJ/kg ℃, Thermal connectivity: 0.59 W/m K, Diffusivity: 1.44e-7 m/s2, Initial moisture content: 96% *wb*, and Final moisture content: 12 % *wb*.

(2) The moisture ratio curve for drying tomato slices at a temperature of 105℃ and air velocity of 1.5 m/s, under oven-drying, was fitted to the Newton model with regression coefficient R2=0.921 using Excel software. The drawings of the design of the P-V powered forced convection commercial solar drying unit was produced. Locally procured materials were specified in the design consistent with the objective of producing a cost-effective solar dryer. The solar dryer was designed as a mixed-mode type to operate continuously using direct sunshine during the day and stored solar energy at night to dry tomatoes. The design was done under the assumptions and conditions of Botswana. In the finalization stage of the design process, all the parameters were applied to produce the embodiment of design with the design drawings and specifications of the ventilated greenhouse solar dryer unit. This unit will be integrated into the solar collector with a solar energy storage system for use after sunset.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

The authors of this paper acknowledge Mobility to Enhance Training of Engineering Graduates in Africa, METEGA for funding of the Post Graduate study program at the University of Botswana under which this study was made possible.

References

[1] W. H. Organization, “The state of food security and nutrition in the world 2018: building climate resilience for food security and nutrition,” Food & Agriculture Organization of the United Nations, 2018.
[2] M. Güne, B. Blywis, F. Juraschek, and P. Schmidt, “Concept and design of the hybrid distributed embedded systems testbed,” Freie Universität Berlin, Technology Rep., 2008.
[3] C. Gordon and S. Thorne, “Determination of the thermal diffusivity of foods from temperature measurements during cooling,” Journal of Food Engineering, vol. 11, no. 2, pp. 133-145, 1990.
[4] C. Cheapok and P. Pornnareay, “Introducing solar drying in a developing country: the case of Cambodia,” Proceedings of World Renewable Energy Congress (WREC), pp. 2198-2201, 2000.
[5] A. Esper, K. Lutz, and W. Mühlbauer, “Development and testing of plastic film solar air heaters,” Solar & Wind Technology, vol. 6, no. 3, pp. 189-195, 1989.
[6] H. C. Kaymak, I. Ozturk, F. Kalkan, M. Kara, and S. Ercisli, “Color and physical properties of two common tomatoes (lycopersicon esculentum Mill.) cultivars,” Journal of Food Agriculture and Environment, vol. 8, no. 2, pp. 44-46, April 2010.
[7] A. Fudholi, K. Sopian, M. H. Ruslan, M. Alghoul, and M. Sulaiman, “Review of solar dryers for agricultural and marine products,” Renewable and Sustainable Energy Reviews, vol. 14, no. 1, pp. 1-30, January 2010.
[8] W. Weiss and J. Buchinger, “Solar Drying,” AEE INTEC Publication, A-8200 Gleisdorf, Feldgasse, vol. 19, 2012.
[9] S. Lahsasni, M. Kouhila, M. Mahrouz, L. Mohamed, and B. Agorram, “Characteristic drying curve and mathematical modeling of thin-layer solar drying of prickly pear cladode (opuntia ficus indica),” Journal of Food Process Engineering, vol. 27, no. 2, pp. 103-117, June 2004.
[10] B. Bala, M. Mondol, B. Biswas, B. D. Chowdury, and S. Janjai, “Solar drying of pineapple using solar tunnel drier,” Renewable Energy, vol. 28, no. 2, pp. 183-190, February 2003.
[11] R. Goyal and G. Tiwari, “Parametric study of a reverse flat plate absorber cabinet dryer: a new concept,” Solar Energy, vol. 60, no. 1, pp. 41-48, January 1997.

[12] M. Hossain, K. Gottschalk, and B. Amer, "Mathematical modelling for drying of tomato in hybrid dryer," Arabian Journal for Science and Engineering, vol. 35, no. 2, pp. 239, October 2010.

[13] M. G. Green and D. Schwarz, "Solar dryer plans," 2014.

[14] S. Janjai, "A greenhouse type solar dryer for small-scale dried food industries: development and dissemination," International Journal of Energy and Environment, vol. 3, no. 3, pp. 383-398, January 2012.

[15] C. Hii, C. Law, and M. Cloke, "Modeling using a new thin layer drying model and product quality of cocoa," Journal of Food Engineering, vol. 90, no. 2, pp. 191-198, January 2009.

[16] M. Hawlader, M. Uddin, J. Ho, and A. Teng, "Drying characteristics of tomatoes," Journal of Food Engineering, vol. 14, no. 4, pp. 259-268, 1991.

[17] S. Sengar and S. Kothari, "Thermal modeling and performance evaluation of arch shape greenhouse for nursery raising," African Journal of Mathematics and Computer Science Research, vol. 1, pp. 1-9, 2008.

[18] H. Atalay, M. T. Çoban, and O. Kıncay, "Modeling of the drying process of apple slices: application with a solar dryer and the thermal energy storage system," Energy, vol. 134, pp. 382-391, September 2017.

[19] O. Badaoui, S. Hanini, A. Djebli, B. Haddad, and A. Benhamou, "Experimental and modelling study of tomato pomace waste drying in a new solar greenhouse: Evaluation of new drying models," Renewable energy, vol. 133, pp. 144-155, April 2019.

[20] N. I. Román-Roldán, A. López-Ortiz, J. F. Ituna-Yudonago, O. García-Valladares, and I. Pilatowsky-Figueroa, "Computational fluid dynamics analysis of heat transfer in a greenhouse solar dryer "chapel-type" coupled to an air solar heating system," Energy Science & Engineering, 2019.

[21] Baliyan, S. P. M., Shesha Rao. (2013). Evaluation of Tomato Varieties for Pest and Disease Adaptation and Productivity in Botswana. International Journal of Agricultural and Food Research.

[22] Purkayastha, M. D.,Nath, A.,Deka, B. C. and Mahanta, C. L. (2013). Thin layer drying of tomato slices. Journal of Food science and Technology, vol. 50, no. 4, pp. 642-653.

[23] M. G. S. Green, "Solar drying technology for food preservation," GTZ-GATE, January 2011D. Brooker, "Mathematical model of the psychrometric chart," Transactions of the ASAE, vol. 10, pp. 558-560, 1967.

[24] B. A. Berichte, "Experimental studies and mathematical modelling of solar drying system for production of high quality dried tomato," pp. 1-173, 2007.D. Jain and P. B. Pathare, "Study the drying kinetics of open sun drying of fish," Journal of Food Engineering, vol. 78, no. 4, pp. 1315-1319, February 2007.

[25] S. Youcef-Ali, H. Messaoudi, J. Desmons, A. Abene, and M. Le Ray, "Determination of the average coefficient of internal moisture transfer during the drying of a thin bed of potato slices," Journal of Food Engineering, vol. 48, no. 2, pp. 95-101, May 2001.

[26] E. Akoy, M. Ismail, A. Ahmed, and W. Luecke, "Design and construction of a solar dryer for mango slices," Proceedings of International Research on Food Security, Natural Resource Management and Rural Development-Tropentag. University of Bonn, Germany.

[27] V. Puri and R. Anantheswaran, "The finite-element method in food processing: a review. Journal of Food engineering," vol. 19, no. 3, pp. 247-274.

[28] C. Hii, C. Law, and M. Cloke, "Modeling using a new thin layer drying model and product quality of cocoa. Journal of Food engineering," vol. 90, no. 2, pp. 191-198.

[29] J. Hernandez, G. Pavon, and M. Garcıa, "Analytical solution of mass transfer equation considering shrinkage for modeling food-drying kinetics," Journal of Food Engineering, vol. 45, no. 1, pp. 1-10, July 2000.

[30] D. Jain and P. B. Pathare, "Study the drying kinetics of open sun drying of fish," Journal of Food Engineering, vol. 78, no. 4, pp. 1315-1319, February 2007.

[31] D. Wray and H. S. Ramaswamy, "Novel concepts in microwave drying of foods. Drying Technology," vol. 33, no. 7, pp. 769-783.

[32] M. Sodha, N. Bansal, A. Kumar, P. Bansal, and M. Malik, "Solar crop drying," CPR press., Boca Raton, Florida, USA, 1987.

[33] D. Brooker, "Mathematical model of the psychrometric chart," Transactions of the ASAE, vol. 10, pp. 558-560, 1967.

[34] P. Greidanus and M. A. Verhoeven, "Product data of tomatoes," Sprenger Instituut, Wageningen 0169-3638, 1986.

[35] G. Giovanelli, B. Zanoni, V. Lavelli, and R. Nani, "Water sorption, drying and antioxidant properties of dried tomato products," Journal of Food Engineering, vol. 52, no. 2, pp. 135-141, April 2002.

[36] B. Amer, M. Hossain, and K. Gottschalk, "Design and performance evaluation of a new hybrid solar dryer for banana," Energy conversion and management, vol. 51, pp. 813-820, 2010.