



## ENERGY ANALYSIS AND OPTIMIZATION OF THIN LAYER DRYING CONDITIONS OF OKRA

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### ABSTRACT

This paper presents the energy analysis and optimization of thin layer convective hot air drying conditions of okra slices in a hybrid solar-electric crop dryer based on the specific energy consumption and drying duration using response surface methodology (RSM). Fresh sliced okra samples (*Abelmoschus esculentus*) of 900g batch size were dried from initial to final desired moisture contents of 87.8 to 0.5% (wb) respectively. The Box-Behnken approach of Design Expert 7.0 statistical package was used to illustrate the effects of the varying levels of the drying parameters: drying air temperature (50, 60 and 70°C), air velocity (1, 1.5 and 2ms<sup>-1</sup>) and sample slice thickness (10, 15 and 20mm) on the drying duration and specific energy consumption of okra slices. All responses were fitted into a second order polynomial model and R<sup>2</sup>-values > 0.959 were observed in all treatment combinations. Suitability of the developed predictive response models was verified and validated with statistical analyses of the process parameters, experimental data, normal % probability plots, as well as simulated versus experimental data plots. Results obtained showed that the maximum and minimum mean energy consumptions were 69.02kWh and 2.02kWh, respectively. Regression models of specific energy consumption for each slice thickness were developed and their respective R<sup>2</sup> compared. Thermal utilization efficiency of okra slices were in the range of 11.1 to 38.8%. The energy efficiency varied in the range of 11.2 to 45.6%; whereas the drying efficiency ranged between 28.1 and 49.6%. The desirability index technique was used to predict the optimum drying condition. The best drying conditions of 59.81°C, 2ms<sup>-1</sup> and 10mm air temperature, air velocity and slice thickness, respectively were obtained. The corresponding predicted response values of 94.54mins and 3.54kWhg<sup>-1</sup> were obtained for drying duration and specific energy consumption, respectively. The results from this study make available to food industries the optimized drying conditions for better quality dried okra slices as well as improve the dryer energy efficiency and reduce cost of drying operation.

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### 1.0 Introduction

High energy demand in the food industry has prompted extensive study on the dynamics of drying energy and its consumption for optimal product quality drying, increased energy

efficiency and cost effectiveness. Convective hot air crop drying using artificial dryers requires substantial amount of energy input when compared to other production processes as a result of relatively low energy efficiency of the dryer (approximately 30%), inefficient heat transfer between convective air and food material, large quantity of energy loss through the exhaust air (even as temperature reaches the wet bulb temperature), and increased latent heat of vaporization of water (Beigi, 2016; Kudra, 2012; Raghvan *et al.*, 2005). In most developed nations, the energy consumption for drying operations accounts for 7 – 25% of the nation's total industrial energy demand (Motevali *et al.*, 2014; Akpinar *et al.*, 2005). Convective hot air-drying is regarded as the commonest method for crop drying. There is often limited heat transfer to the inner sections (matrix) of food materials during conventional heating as a result of low thermal conductivity of food materials during the falling rate drying period (Kudra, 2012). Energy efficiency of convective dryers is of great importance since it represents about 85% of all industrial dryers (Devahastin, 2000). Kudra (2012) suggested that partial recycling of exhaust air or heat recovery in addition to the use of multi-stage dryers can improve the overall energy efficiency of dryers. In order to achieve optimal drying conditions and gross reduction in energy utilization, performance of energy analysis is very important.

Energy analysis involves practical quantitative evaluation of the amount of energy required for drying and associated energy losses in the system during drying process. Technical information obtained from energy analysis of convective dryers is beneficial to design of new dryers, optimize the drying conditions, and design heat recovery systems for improved efficiency. From the energy point of view, energy efficiency and specific energy consumption amongst various indices are frequently used to characterize the performance of a convective drying system (Kudra, 2012; Baker and McKenzie, 2005). Dryer performance evaluation through the specific energy consumption seems to be more beneficial in preference to the energy efficiency index as a result of its clearly defined reference point value for an adiabatic dryer, whereas dryer performance assessment through energy efficiency requires knowledge of the maximum energy efficiency, which depends on the product characteristics and drying conditions (Kudra, 2012).

In Nigeria, okra (*Hisbiscus esculentus* or *Abelmoschus esculentus* L.) is regarded as an important vegetable crop for its economical and nutritive values. In the Eastern part of Nigeria, many good local varieties such as Perkin's long pod, new lady's finger, *nwaidu* etc. exist (Anyanwu *et al.*, 1986). Okra is usually available in large quantities between April and December in the South eastern part of Nigeria. Two distinct seasons exist for its production in Nigeria: the peak and the lean seasons. During the lean season (October to March), the product is produced in small quantities and the product becomes very scarce and expensive. Large quantities are produced in the peak season (April to September) in excess of the consumption capacity of the local populace and thereby require some level of preservation. Considerable amounts of energy is required during its drying process to a desired safe moisture level (Nwakuba *et al.*, 2016) due to its high initial moisture content of about 88 – 90% wet basis (Doymaz, 2005; Kumar *et al.*, 2011; Tiwari, 2012). This makes it susceptible to deterioration which leads to chemical, physical and biological changes as well as appreciable economic loss in the annual income of the farmer. Therefore, with increasing pressures to reduce environmental degradation, both from the public and governments, it

is necessary to improve drying processes by optimizing its process parameters to reduce its high energy consumption and greenhouse gas (GHG) emissions, while still providing a high quality dried okra with minimal increase in economic input. This, in all would reduce the cost of drying operation; enhance the crop shelf-life, product diversity, substantial volume reduction, availability and acceptance of dried food products in the market at a reasonable price (Maskan, 2001; El-Mesery and Mwithiga, 2012). The objectives of this study were to dry sliced okra samples in a convective hybrid solar dryer and to optimize the drying conditions for high dried product quality as well as analyze the overall energy efficiency in terms of the specific energy consumption, drying efficiency and thermal utilization efficiency of the process.

## **2. Materials and Methods**

### **2.1 Sample preparation**

Fresh okra samples were purchased from one of the municipal markets (Relief market) in Owerri, Imo State of Nigeria. The okra samples were selected based on similar colour, size and shape; and sliced to three thickness sizes of 10, 15 and 20 mm using a sharp stainless-steel knife and a vernier caliper with the direction of cutting perpendicular to the vertical axis of the samples. The initial mass of the sliced samples was determined using a digital weighing balance (0.01 g, Camry instruments, China). The sliced samples were placed side-by-side on the drying racks in thin layers in such a way that the drying air flows axially into the sample matrix for uniform drying and increased drying rate. The sample initial moisture content was determined gravimetrically (Koyuncu *et al.*, 2007; Darvishi *et al.*, 2013).

### **2.2 Experimental procedure**

The drying equipment was positioned in the open and the solar collector faced towards the North-South axis for maximum solar flux collection. Steady-state condition was allowed to be maintained in the drying chamber. The dryer was operated at three different air temperatures (50, 60 and 70°C), air velocities (1.0, 1.5 and 2.0 ms<sup>-1</sup>) and slice thicknesses (10, 15 and 20 mm). Fresh sliced okra samples with initial moisture content of 87.8% (wet basis) were dried using the hybrid heat unit. The quantity of moisture loss at 30 min intervals were recorded with a high definition (up to 0.01g) weighing balance (Figure 1, S/N 18). The amount of energy consumed at the three slice thicknesses, three air temperatures and three air velocities were measured and recorded by the control unit. The experiment was repeated for varying air velocities, air temperatures and sample thicknesses for a batch of 900 g. Drying was terminated when the samples attained a weight corresponding to a safe moisture level of 0.5 % w.b.

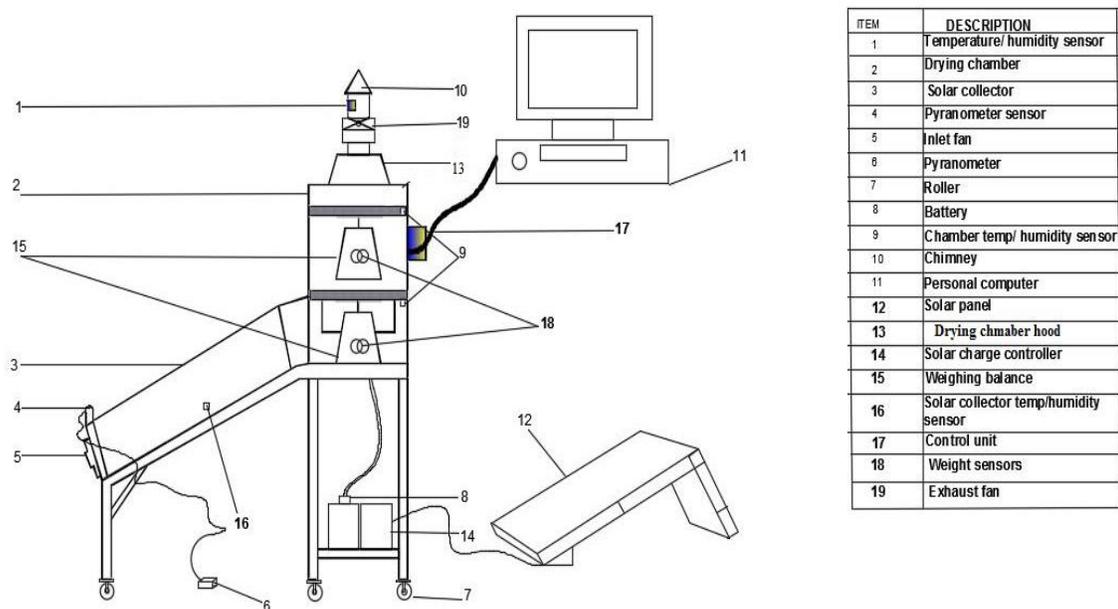


Figure 1: A schematic view of the dryer.

### 2.3 Experimental design

The drying experiments were designed using the Box-Behnken method of Design Expert statistical package (version 7.0) and randomized in order to reduce the unexplainable effects in the observed experimental responses. Three independent process variables: air temperature (50, 60 and 70°C), air velocity (1.0, 1.5 and 2.0ms<sup>-1</sup>) and slice thickness (10, 15 and 20mm) replicated three times to generate five dependent or response variables. Response surface methodology (RSM) was adopted in determining the relative contributions of each of the experimental variables (air temperature, air velocity and slice thickness) to the response variables (drying duration, specific energy consumption, colour change, firmness, and rehydration capacity). Table 1 presents the Box-Behnken design RSM layout adopted for the drying experiments, which was a three-factor, three-level (3<sup>3</sup>) arrangement applied to evaluate the linear (main), interaction and quadratic (curvature) effects of the process variables in order to optimize the convective hot air drying conditions for quality dried okra slices in a hybrid solar-electric dryer.

**Table 1:** Levels of independent process variables of the randomized factorial design layout used in the RSM optimization of okra drying conditions.

Process variables	Symbols		Levels	
	Actual	Coded	Actual	Coded
Air temperature (°C)	T	A	50°C	-1
			60°C	0
			70°C	1
Air velocity (ms <sup>-1</sup> )	A	B	1.0 ms <sup>-1</sup>	-1
			1.5 ms <sup>-1</sup>	0
			2.0 ms <sup>-1</sup>	1
Slice thickness (mm)	S	C	10 mm	-1
			15 mm	0
			20 mm	1

The experimental data analyses involved the use of multiple regression method using the least squares method. A second order polynomial function was used to express the response variable ( $V_r$ ) as given in Equation (1):

$$V_r = \beta_0 + \beta_1A + \beta_2B + \beta_3C + \beta_4AB + \beta_5AC + \beta_6BC + \beta_7A^2 + \beta_8B^2 + \beta_9C^2 \quad (1)$$

Where:  $V_r$  is the response variable (drying duration in mins and specific energy consumption in kWh/kg);  $\beta_0$  represents the model intercept; A, B, and C represent the independent variables: air temperature ( $^{\circ}\text{C}$ ), air velocity ( $\text{ms}^{-1}$ ), and sample slice thickness (mm) respectively;  $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9$  are coefficients of regression. Also  $\beta_1A, \beta_2B,$  and  $\beta_3C$  represent the linear effects;  $\beta_4AB, \beta_5AC,$  and  $\beta_6BC$  represent the interaction or cross-product, whereas  $\beta_7A^2, \beta_8B^2,$  and  $\beta_9C^2$  represent the quadratic or curvature effects.

## 2.4 Energy consumption

Artificial dryers are known for promoting high-quality dried food products in spite of their considerable energy consumption (Nwakuba *et al.*, 2016). The energy consumption of any drying equipment during drying operation is an important criterion in the economic evaluation of the process. Specific energy consumption is referred to as the ratio of the total energy consumed in evaporating a kilogram of water from a drying product during the drying process to the initial mass of the dried sliced product sample. The total energy consumption for drying a 900 g batch of the sliced okra samples in the hybrid solar dryer at the given air velocities, slice thicknesses, and air temperatures is expressed in Equation (2) (Afolabi *et al.*, 2014; Koyuncu *et al.*, 2007; Minaei *et al.*, 2014; Nwakuba *et al.*, 2016) as:

$$E_T = Av\rho_a C_{pa} \Delta T D d \quad (2)$$

Where:  $E_T$  is total energy consumption per batch (kWh); A is area of rack ( $\text{m}^2$ ), v is air velocity ( $\text{ms}^{-1}$ ),  $\rho_a$  is air density ( $\text{kgm}^{-3}$ ), d is total drying duration per batch (h),  $\Delta T$  is temperature difference between ambient and hot air ( $^{\circ}\text{C}$ ), and  $C_{pa}$  is specific heat of air ( $\text{kJkg}^{-1}\text{^{\circ}\text{C}}$ ).

The total energy consumption ( $E_T$ ) for drying a batch of sliced okra samples at varying process conditions was obtained by adding the electrical energy (as measured by the arduino micro-processor) and the solar energy absorbed by the solar collector (measured by the pyranometer). Comparison was made between the measured and calculated  $E_T$  values which was less by an average of 5.2% of the calculated  $E_T$  values. This marginal difference was as a result of the constant air density and air velocity used in the calculated  $E_T$  values; whereas in the measured  $E_c$  values, varying air velocities were considered by the arduino-micro-processor where air densities varied with air temperature, thus a negligible value difference. The calculated  $E_T$  values were used to calibrate the system as well as validating the measured  $E_T$  values.

The specific energy consumption is expressed by Equation (3) (Koyuncu *et al.*, 2007; Motevali *et al.*, 2014; Afolabi *et al.*, 2014; Minaei *et al.*, 2014) as:

$$E_S = \frac{E_T}{M_0} \quad (3)$$

Where:  $E_s$  is specific energy consumption ( $\text{kWhkg}^{-1}$ );  $M_o$  is mass of moisture expelled (kg).

## 2.5 Thermal utilization efficiency

Thermal utilization efficiency (TUE) is an indicator of the degree of accomplishment of air-to-material transfer process or energy conversion in a device that consumes thermal energy. It is defined as the ratio of latent heat of vaporization of sample moisture to the energy requirement for moisture evaporation from free water. TUE was determined using Equation (4) (Beigi, 2016; Minaei *et al.*, 2014; Hebbbar *et al.*, 2004) as:

$$\eta_{th} = \frac{P \cdot A_s \cdot h_{fg} \cdot M_w}{Q \cdot t} \quad (4)$$

Where:  $\eta_{th}$  = thermal utilization efficiency, %;  $M_w = \frac{(M_i - M_f)}{(100 - M_f)}$  = mass of water removed, g;  $P$  = load/weight density of sample ( $\text{gm}^{-2}$ );  $A_s$  = total sample area ( $\text{m}^2$ );  $h_{fg}$  = latent heat of vaporization ( $\text{kJkg}^{-1}$ );  $M_i$  and  $M_f$  = initial and final moisture contents respectively (%w.b);  $Q$  = power of the heat source (kW);  $t$  = operation time of the heat source (mins.).

The latent heat of vaporization was calculated using Equation (5) (Aghbashlo *et al.*, 2013) as:

$$h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3 (T_{abs} - 273.16) \quad (5)$$

Where:  $T_{abs}$  is the absolute temperature of drying air, °K.

## 2.6 Energy efficiency

This is the ratio of heat energy utilized for sample moisture evaporation to the heat supplied to the dryer. Energy efficiency is expressed as in Equation (6):

$$\eta_e = \frac{Q_s}{E_T} \quad (6)$$

Where:  $E_T$  is the total energy consumption per batch (kWh);  $Q_s$  is the heat supplied to dryer (kJ) expressed as Equation (7) (Motevali *et al.*, 2014).

$$Q_s = h_{fg} \cdot M_w \quad (7)$$

## 2.7 Drying efficiency

This is the ratio of the energy used for heating the sample evaporation moisture to the total energy supplied/consumed. This was determined using Equation (8):

$$\eta_D = \frac{Q_s + Q_m}{E_T} \quad (8)$$

Where:  $Q_m$  is energy used for heating the product (kJ) and was determined using Equation (9) (Beigi, 2016).

$$Q_m = W_{ds} C_p (T_{mo} - T_{mi}) \quad (9)$$

Where:  $W_{dm}$  is the weight of the dry sample (g),  $T_{mi}$  and  $T_{mo}$  are the inlet and outlet sample temperature (°K), respectively;  $C_p$  is the sample specific heat capacity ( $3.97 \text{kJkg}^{-1} \text{°K}$ ).

## 2.8 Optimization technique and statistical analysis

Multivariate response method of numerical optimization of the drying conditions was performed (Equation 10), which is referred to as overall desirability function/index,  $D_x$  (Abano *et al.*, 2014; Giri and Prasad, 2007; Myers and Montgomery, 2002):

$$D_x = (V_1 \times V_2)^{\frac{1}{n}} \quad (10)$$

Where:  $V_1$  and  $V_2$  are response variables;  $n$  is the total number of responses = 2.

DI ranges between 0 and 1, with 0 and 1 representing the least and most desirable coded levels respectively. DI illustrates how well matched or desirable the experimental responses are at any given level of input/independent variable. The goal in RSM optimization studies is the maximization of DI. This numerical RSM optimization process involves goals and priorities for the process/independent and response variables (Abano *et al.*, 2014). This study however, has the goal for the process variables at any level within the range of the design values; whereas the response variables had a goal of minimization of specific energy consumption and drying duration.

A second order polynomial function (Equation 1) was used in fitting the average values of the experimental data with Design Expert version 7.0 statistical package (Stat-Ease Inc., Minneapolis, USA) in order to analyze data, carry out response surface plots to obtain three dimensional graphs for the response variables. Analysis of variance (ANOVA) was used to determine the significant variables in the model for the response variables at 5% level of probability. The model adequacies were checked by calculating  $R^2$ , adjusted- $R^2$ , adequate precision, PRESS and CV. The model accuracy was checked against the normal probability residual plots, predicted versus actual plots and  $R^2$ - values. For the two responses, one process variable was kept constant and 3-D response surface plots for other two variables were generated.

### 3. Results and Discussion

The experimental results of Box-Behnken design (BBD) are presented in Table 2, with the input factors expressed in actual and coded forms. The estimated effects for the process variables (air temperature, air velocity, and slice thickness) and their interactions (Equation 1) as well as the values of the corresponding coefficient of determination ( $R^2$ ) and coefficient of variation (CV) were determined as shown in Table 3. Coefficients A, B, C, AB, AC, BC,  $A^2$ ,  $B^2$ , and  $C^2$  are as earlier defined. The  $R^2$ -value indicates the degree of fit of the polynomial model for each response variable and is referred to as the ratio of explainable variation to the total variable (Kumar *et al.*, 2011, Giri and Prasad, 2007). The analysis of variance in Table 3 indicates that the models for all the response variables are highly significant ( $p > 0.05$ ) as well as the  $R^2$ -values ( $> 0.95$ ). The CV values according to Kumar *et al.* (2011) should be  $< 10\%$  and what was observed was  $< 8.5\%$  for the models. This is an indication of model adequacy.

**Table 2.** Process and response factors of Box-Behnken design.

Run No	Actual values (coded values)				
	A	B	C	Dd (mins.)	Es (kWh/kg)
1	60.00 (0)	2.00 (1)	20.00 (1)	150	23.44
2	50.00 (-1)	1.50 (0)	10.00 (-1)	180	14.95
3	60.00 (0)	1.50 (0)	15.00 (0)	180	21.91
4	50.00 (-1)	1.00 (-1)	15.00 (0)	240	42.05
5	60.00 (0)	1.50 (0)	15.00 (0)	180	21.91
6	70.00 (1)	1.00 (-1)	15.00 (0)	120	13.83

7	60.00 (0)	1.00 (-1)	10.00 (-1)	150	15.15
8	50.00 (-1)	2.00 (1)	15.00 (0)	180	22.84
9	60.00 (0)	2.00 (1)	10.00 (-1)	90	4.36
10	50.00 (-1)	1.00 (0)	20.00 (1)	240	56.47
11	60.00 (0)	1.50 (0)	15.00 (0)	180	21.91
12	70.00 (1)	2.00 (1)	10.00 (-1)	120	3.21
13	70.00 (1)	2.00 (1)	15.00 (0)	60	4.32
14	60.00 (0)	1.50 (0)	15.00 (0)	180	21.91
15	60.00 (0)	1.50 (0)	15.00 (0)	180	21.91
16	70.00 (1)	1.50 (0)	20.00 (1)	150	21.89
17	60.00 (0)	1.00 (-1)	20.00 (1)	210	42.86

*Specific energy consumption (E<sub>s</sub>), Drying duration (DD)*

**Table 3.** Regression coefficients of the response surface quadratic model for the process variables.

Process variables/model terms (coded units)	Estimated coefficients	
	Dd (mins.)	E <sub>s</sub> (kWh)
Intercept (β <sub>0</sub> )	180	22.05
A	-48.75	-11.63
B	-30	-7.37
C	26.25	13.37
AB	8.7	2.43
AC	-7.5	-5.71
BC	21.4	-2.16
A <sup>2</sup>	-3.75	-5.62
B <sup>2</sup>	-26.25	-3.18
C <sup>2</sup>	-3.75	8.21
R <sup>2</sup>	0.9689	0.9796
CV (%)	7.72	8.36

### 3.1 Effect of process factors on response variables

#### 3.1.1 Drying duration

The effect of the process factors on drying duration of okra slices is presented in Table 4. In this case, the effect of the linear terms, B, and C), the interaction effect of air temperature and slice thickness (AC), quadratic/curvature effects of air temperature (A<sup>2</sup>) and slice thickness (C<sup>2</sup>) on drying duration were significant. The result of the second order quadratic model fitted to the drying duration in coded terms is given by Equation (11) as:

$$V_{Dd} = 180 - 48.75A - 30B + 26.25C - 7.5AC - 3.75A^2 - 3.75C^2 \quad [R^2 = 0.9689] \quad (11)$$

Where: V<sub>Dd</sub>, A, B, and C are as earlier defined.

**Table 4.** Analysis of variance for drying duration by response surface quadratic function.

Source	Coefficient estimate	Sum of squares	Df	F-value	P-value Prob. > F
Intercept ( $\beta_0$ )	180				
Model		35086.76	9	24.26	<0.0002*
$\beta_1A$	-48.75	19012.50	1	118.30	< 0.0001*
$\beta_2B$	-30	7200.00	1	34.30	0.0006*
$\beta_3C$	26.25	5512.50	1	74.80	0.0003*
$\beta_4AB$	8.7	138.31	1	0.000	1.0000 <sup>ns</sup>
$\beta_5AC$	-7.5	225.00	1	1.40	0.0353*
$\beta_6BC$	21.4	78.42	1	0.000	1.0000 <sup>ns</sup>
$\beta_7A^2$	-3.75	59.21	1	0.37	0.0230*
$\beta_8B^2$	-26.25	2901.32	1	18.05	0.5736 <sup>ns</sup>
$\beta_9C^2$	-3.75	59.21	1	0.37	0.0213*

\*Significant; \*\* Not significant; lack of fit is insignificant at  $P > 0.05$ .

The quadratic effect of air velocity ( $B^2$ ), interaction effects of air velocity-slice thickness (BC), air temperature-air velocity (AB) were statistically insignificant ( $P > 0.05$ ) on the drying duration, and as such were not added in Equation (11). The high  $R^2$  (0.9689) showed that a greater percentage of the experimental variability was described by the response surface quadratic model. Figures 2a and b show the suitability of the model verified with the normal probability plot of the drying duration residuals and the plot of predicted versus experimental drying duration, respectively.

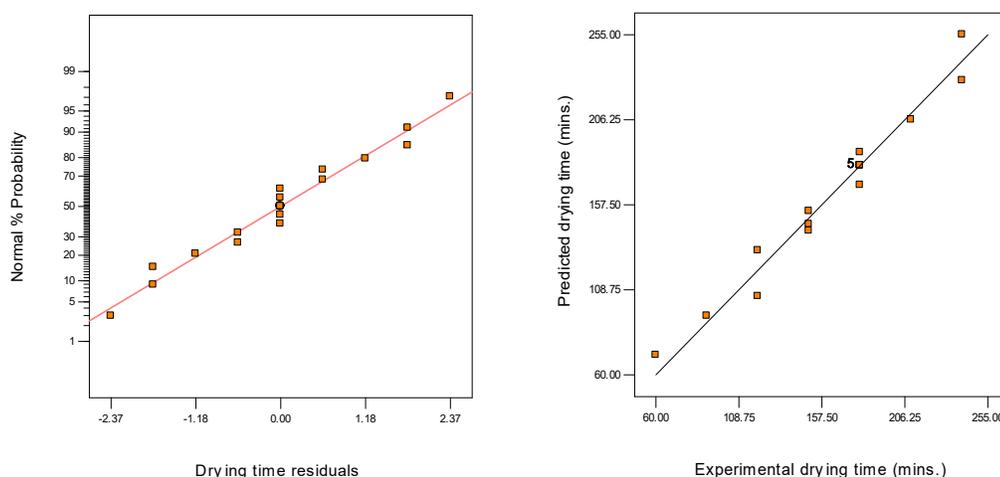


Figure 2. (a) Normal % probability plot of drying duration residuals; (b) Predicted versus

The model was validated by the closeness of the plotted data to the straight line (at 45°) which indicated agreement between the predicted and experimental drying duration of dried okra slices as well as good agreement with the normality and severity of outliers in the experimental data of the drying duration. The 3-D response surface plots for the drying duration quadratic model are presented in Figure 3. Increasing the drying air temperature and air velocity decreased the drying duration significantly (Abano *et al.*, 2014; Kumar *et al.*, 2011; Montgomery and Runger, 2002). This was as a result of increased kinetic energy of

internal water molecules to diffuse and evaporate at a higher rate from the interior and surface of the okra sample to the ambient air respectively; increased drying air temperature gradient between the drying air and the sliced okra samples which increased the moisture diffusion and surface water evaporation rates from the sample matrix to the convective air. This thus, increased the drying rate and reduced the drying duration. Whereas increasing the slice thickness of the okra samples significantly increased the drying duration. This is as a result of increased capillary distance of the sample matrix through which internal moisture diffused to the surface for evaporation into the ambient air.

Different relative importance however, can be deduced from the variations in the estimated coefficients of the independent variables. Air temperature was observed to have the highest effect on the drying duration, followed by the slice thickness and lastly the air velocity. The least drying duration was observed at the highest air temperature and air velocity. The independent variables: air temperature, (A) air velocity (B) and slice thickness (C) had significant effects on the drying duration. Increasing A and decreasing C at constant B increased the drying duration, whereas increasing C at constant A and C increased the drying duration as shown in Figure 3. The effects of air temperature on the drying duration of okra slices corroborated with the reports of Abano *et al.* (2014) for tomato slices; Afolabi *et al.* (2014) for ginger slices; Doymaz (2004a and b) for carrot and okra slices respectively.

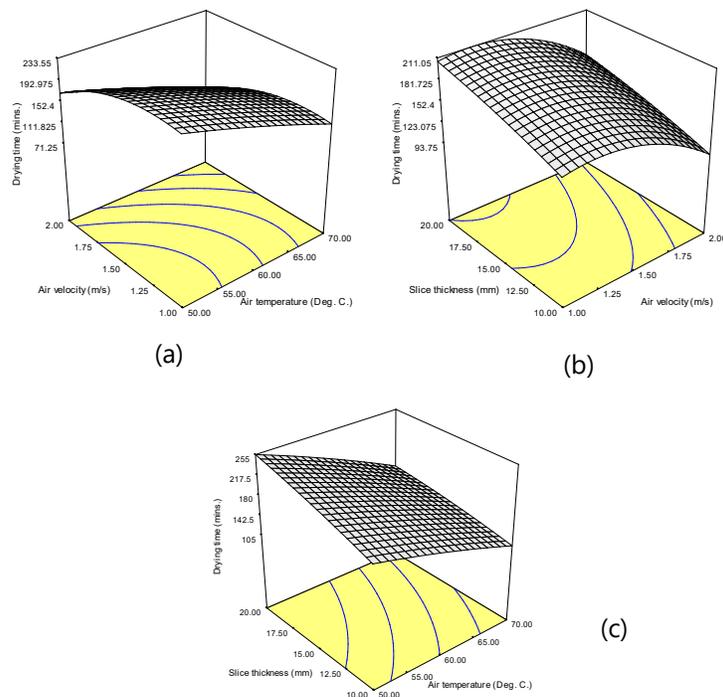


Figure 3. Response surface plots showing the effects of different drying conditions on drying duration: (a) Air velocity and drying air temperature at constant slice thickness; (b) slice thickness and air velocity at constant temperature; (c) slice thickness and air temperature at constant air velocity.

### 3.1.2 Specific energy consumption

The experimental result of the model fitted to the specific energy consumption under varying drying conditions as presented in Table 2 is expressed as Equation (12):

$$E_s = 22.05 - 11.63A - 7.37B + 13.37C - 5.71AC + 16.94A^2 + 3.17C^2 \quad [R^2 = 0.9796] \quad (12)$$

As a result of the statistical non-significant effects of the means of AB, BC and B<sup>2</sup> on specific energy consumption, they were not included in Equation (12). It is evident that drying air temperature (A), air velocity (B) and sample slice thickness (C) had remarkable effects on the specific energy consumption for drying of okra slices in the hybrid solar dryer (Figure 4). Drying a thicker sample layer at a low air temperature and air velocity increased the specific energy consumption (Figure 4a). This was as a result of more time taken for the larger sample layer to diffuse product moisture to the surface for eventual evaporation by a slow-moving convective hot air, thus increased drying duration and specific energy consumption. The maximum and minimum specific energy consumption (56.47 kWh kg<sup>-1</sup> and 3.21 kWh kg<sup>-1</sup> respectively) were obtained at 50°C, 1.0 ms<sup>-1</sup> 20 mm, and 70°C, 2.0 ms<sup>-1</sup> 10 mm, respectively. This generally implied that less specific energy was consumed at increased air temperature and air velocity for drying any slice thickness.

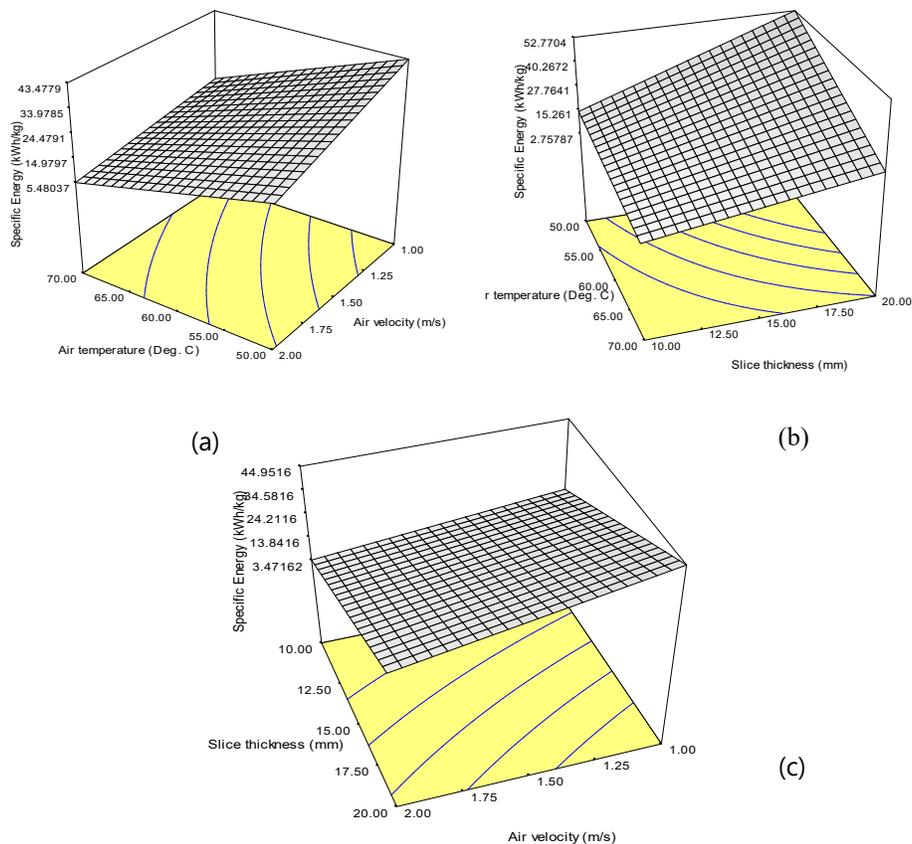


Figure 4. Response surface plots showing the effects of different drying conditions on the specific energy consumption: (a) air temperature and air velocity at constant slice thickness; (b) air temperature and slice thickness at constant air velocity; (c) slice thickness and air velocity at constant air temperature.

This result agrees with the findings of Sharma and Prasad (2006) for garlic cloves; Jindarat *et al.* (2011) for non-hygroscopic materials; Afolabi *et al.* (2014) for ginger slices; El-Mesery and Mwithiga (2012) for onions slices with a decreasing trend in specific energy consumption with increase in the drying air temperature and air velocity. With increased drying air temperature and decreased sample thickness, less specific energy was consumed (Figure 4b), since more moisture diffused at increased air temperature and drying duration decreased, thus reduction in the specific energy consumption. The specific energy consumption increased with increasing sample thickness at reducing air velocity (Figure 4c) as a result of gross reduction in mass transfer rate and increased capillary distance for moisture diffusion. Table 5 shows that the quadratic function was highly significant at  $P < 0.05$ , with a high  $R^2$  value (0.9796). This shows that the RSM model described a greater percentage of the experimental variability (Abano *et al.*, 2014). The P-values for the linear (main) terms had significant effect on the specific energy consumption for drying ( $p < 0.05$ ). Variables A (air temperature) and B (air velocity) had negative coefficients, whereas S was positive. This is an indication that increased air temperature and air velocity may have a significant reduction effect on the specific energy consumption, and also increase in the sample slice thickness may increase the specific energy consumption.

**Table 5.** ANOVA result for the specific energy consumption by response surface quadratic model.

Source	Coefficient estimate	Sum of squares	Df	F-value	P-value Prob. > F
Intercept ( $\beta_0$ )	22.05				
Model		3120.03	9	107.74	< 0.0001*
$\beta_1A$	-11.63	1082.52	1	224.28	0.0042*
$\beta_2B$	-7.37	434.09	1	89.94	< 0.0021*
$\beta_3C$	13.37	1430.86	1	296.45	< 0.0013*
$\beta_4AB$	2.43	23.52	1	4.87	0.0518 <sup>ns</sup>
$\beta_5AC$	-5.71	130.42	1	27.02	0.0004*
$\beta_6BC$	-2.16	18.62	1	3.86	0.0779 <sup>ns</sup>
$\beta_7A^2$	16.94	1876.24	1	11.21	<0.0001*
$\beta_8B^2$	-20.41	1459.73	1	8.35	0.3822 <sup>ns</sup>
$\beta_9C^2$	3.17	128.87	1	9.41	0.0003*
CV	7.36%				

\*Significant; <sup>ns</sup> Not significant; lack of fit is insignificant at  $P > 0.05$ .

The quadratic effect of air velocity, interaction effects of air temperature-air velocity and air velocity-slice thickness had no significant effect on the specific energy consumption of okra slices. A coefficient of variability (CV = 7.36%) less than 10% was observed (Giri and Prasad, 2007; Kumar *et al.*, 2011), and it indicates that the quadratic function adequately represented the experimental data and closely predicted the specific energy consumption for drying of okra slices as observed by Kumar *et al.* (2011). The suitability of the model was further validated with the normal probability plot of the specific energy consumption residuals and the predicted versus experimental specific energy consumption plot (Figures 5 a and b respectively). The closeness of the data to the straight line indicated equality between the predicted and experimental specific energy consumption values as well as showing that no problem existed between the normality and severity of outliers in the

experimental data of energy consumption (Abano *et al.*, 2014). The positive coefficients of the model terms were indication of positive quadratic effect on the specific energy consumption for drying of okra slice in the hybrid solar dryer. The interaction effect of the process factors on the specific energy consumption is presented in the response surface plots (Figures 4a – c). All model terms had significant effect on the specific energy consumption ( $P < 0.05$ ) except the interaction effects of velocity ( $P \geq 0.05$ ) between drying air temperature and air velocity, air velocity and slice thickness, and the quadratic effect of air velocity.

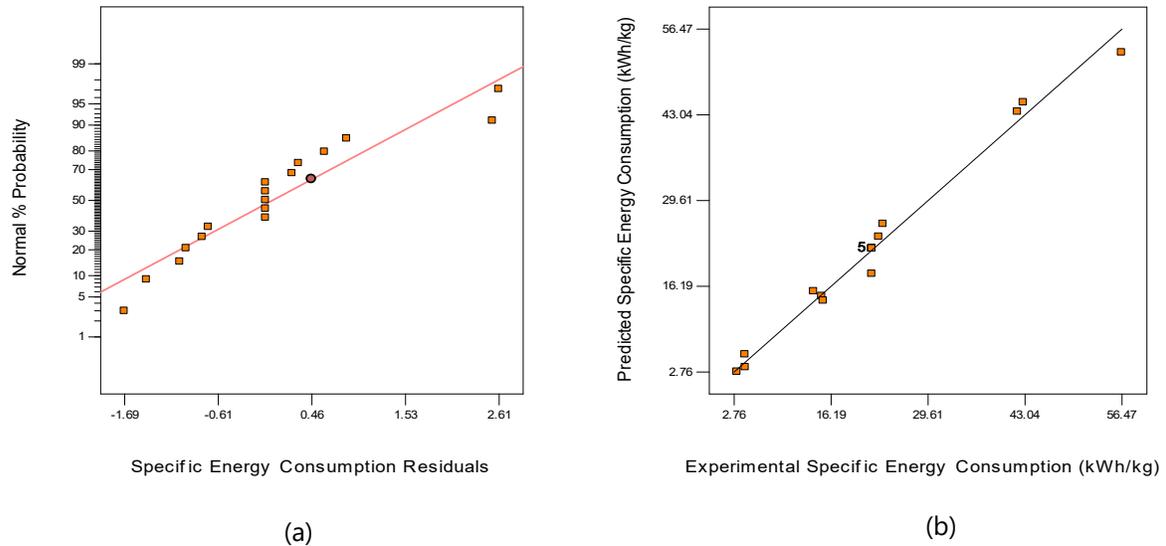


Figure 5. (a) Normal % probability plot of drying duration residuals; (b) Predicted versus experimental specific energy consumption for drying of sliced okra samples.

### 3.2 Optimization of the drying conditions

The optimal drying conditions were obtained for maximum desirability index of 0.808 (Equation 10). The optimal simulated values of the process variables at 95% confidence level were: 59.81°C air temperature, 2ms<sup>-1</sup> air velocity and 10mm slice thickness. The corresponding simulated values for response factors (drying duration and specific energy consumption) were 94.54 mins and 3.54kWhkg<sup>-1</sup> respectively. These predicted values are closer to their corresponding experimental values. The surface plot of the desirability for the optimum conditions is shown in Figure 6. The optimum values of the independent variables were close to that of Kumar *et al.* (2011) for microwave drying of okra slices, with 2.41Wg<sup>-1</sup> of specific energy use. Abano *et al.* (2014) obtained an optimum drying duration of 752.603mins. of similar batch size in a convective type dryer at lower temperature thresholds.

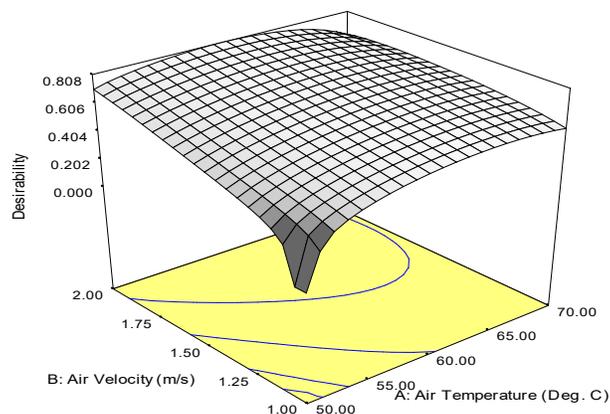


Figure 6. Response surface plot of the desirability index for the optimum drying conditions.

### 3.3 Energy analysis

#### 3.3.1 Total energy consumption

The total energy consumption for drying a batch of okra slices increased with increase in slice thickness and decreased with air temperature at constant air velocity as shown in Figure 7. With increasing slice thickness, sample capillary distance increased, more time was taken to diffuse and evaporate product internal and surface moisture, which increased the mean energy consumption but decreased as air velocity increased. At increased air velocity, more convective air passes across the product surface increasing surface moisture evaporation as well as reducing the drying duration, thus decreasing the energy consumption. Increasing the air velocity at increasing air temperature reduced the mean energy consumption because of more convective air entering the drying chamber to increase the rate of surface moisture evaporation as well as increasing the sample kinetic energy of internal moisture for rapid diffusion and reduced resistance to capillary transport. For each slice thickness and air velocity, mean energy decreased as air temperature increased because of faster drying rate due to increased thermal gradient between the drying air and the sample product. Less drying duration was obtained at higher air temperatures, thus less energy consumed by the sliced samples. The maximum and minimum energy consumed in drying of 900 g batch size of sliced okra were 33.94 and 1.02 kWh, respectively. The results obtained were similar to those obtained by Koyuncu *et al.*, 2007 (for Cornelian cherry fruits); Sarsavadia, 2011 (for sliced onions); El-Mesery and Mwithiga, 2012 (onion slices); Motevali *et al.*, 2012 (Jujube fruits); Afolabi *et al.*, 2014 (for ginger slices); Minaei *et al.*, 2014 (for St. John's Worth leaves); and Beigi, 2016 (for apple slices).

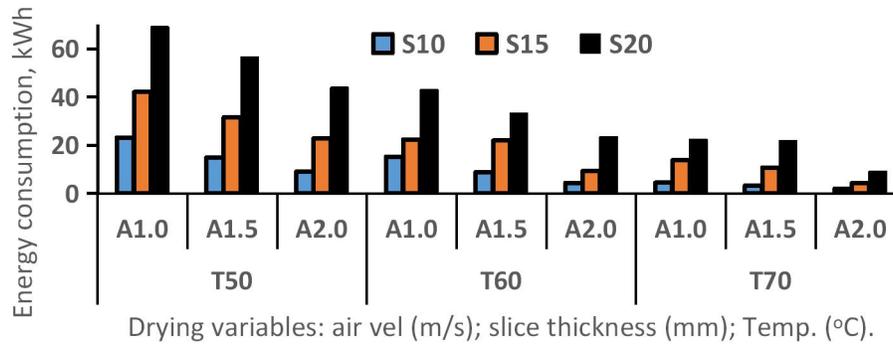


Figure 7. Energy consumption of 0.9kg batch of okra slices in a hybrid dryer

Equations (13) – (18) were obtained for the second order polynomial relationship between energy consumption and drying air velocity, as well as the energy consumption and drying air temperature at varying slice thicknesses:

$$E_{C10mm} = 0.0193T^2 = 3.3209T + 142.34 \quad [R^2 = 0.9703] \quad (13)$$

$$E_{C10mm} = 1.3387A^2 - 12.743A + 24.47 \quad [R^2 = 0.9731] \quad (14)$$

$$E_{C15mm} = 0.0475T^2 - 7.4031T + 297.4 \quad [R^2 = 0.9882] \quad (15)$$

$$E_{C15mm} = 3.6278A^2 - 24.492A + 46.557 \quad [R^2 = 0.9812] \quad (16)$$

$$E_{C20mm} = 0.0594T^2 - 9.7334T + 414.88 \quad [R^2 = 0.9946] \quad (17)$$

$$E_{C20mm} = 6.2603A^2 - 38.45A + 77.499 \quad [R^2 = 0.9938] \quad (18)$$

The high  $R^2$  values ranging between 0.9703 and 0.9946 indicate strong correlation between the energy consumption parameters and drying variables at different slice thicknesses. The coefficient of determination increased with increase in slice thickness for air temperature and air velocity treatment combinations.

### 3.3.2 Thermodynamic parameters

The thermal utilization efficiency (TUE) for drying of okra slices varied from 10% to 38.8% as presented in Table 6. TUE increased with increase in drying air temperature, decrease with air velocity and reduced sample thickness. The highest TUE (38.8%) was observed at 70°C air temperature, 0.1ms<sup>-1</sup> air velocity and 10mm slice thickness, whereas the lowest TUE (11.1%) was observed at 50°C air temperature, 2.0ms<sup>-1</sup> air velocity and 19mm slice thickness. Similar trends were observed by Jindal and Reyes (1987; El-Mesery and Mwithiga (2012); Minaei *et al.* (2014). Since TUE is a ratio of latent heat for moisture evaporation to energy required for moisture evaporation, increasing the sample thickness increased the quantity of moisture in the sample structure per fixed energy input. Much of the heat required for sample surface moisture evaporation were absorbed by the sample matrix to initiate capillary diffusion, leaving a marginal heat quantity for the actual surface moisture evaporation, thereby slowing down the moisture evaporation rate to a point that the input energy could not effectively overcome the sample energy barrier for internal water diffusion, thus low TUE. Increasing the air temperature had noticeable effect on the thermal utilization

due to higher mass and moisture reduction associated with increased air temperature which usually increase TUE. This is consistent with the result of Aviara *et al.* (2014) in a tray dryer for cassava starch and Azadbakht *et al.* (2017) on fluidized bed dryer for sliced eggplant. Additionally, low air velocity had more resident contact time with the drying samples and evaporated their surface moisture more efficiently than at higher velocity - creating turbulence in the drying chamber plenum and exhausted with less contact effect on the samples. These observations are in agreement with the results of Beigi (2016), Minaei *et al.* (2012), Motevali *et al.* (2014), and Koyuncu (2007) for apple slices, St John’s worth leaves, jujube fruits, and cornelian cherry fruits, respectively.

**Table 6.** Thermal utilization efficiency of okra under varying drying conditions

Slice thickness (mm)	10			15			20		
Air vel. (ms <sup>-1</sup> )	1	1.5	2	1	1.5	2	1	1.5	2
Air temp. (°C)	Thermal utilization efficiency (%)								
50	33.2	29.4	26.2	23.4	20.4	18.2	14.9	12.3	10.0
60	35.5	31.3	28.3	25.2	22.3	20.1	17.7	15.2	13.2
70	38.8	34.9	30.2	27.5	24.9	20.6	19.2	17.5	15.4

Figure 8 shows the energy efficiency ( $\eta_e$ ) for drying of okra samples at different drying variables calculated using Equation (6). The energy efficiency values varied between 11.2 – 45.6%. Energy efficiency increased with increase in sample thickness and drying air temperature and decrease in air velocity. This is because, at larger sample thickness, more heat is consumed to remove moisture from the inner sections of the samples at constant temperature, hence increased  $\eta_e$  (since it is a ratio of heat used to total heat supplied). Increasing the air temperature increased the energy consumed for moisture removal at constant air velocity and slice thickness. However, increase in air velocity increased the heat and mass transfer rate but affected the energy utilized for moisture evaporation negatively through turbulence at the dryer plenum, hence reduced energy efficiency. These observations are in conformity with the results of Beigi (2016) in drying of apple slices; Motevali *et al.* (2014) for flowers; Minae *et al.*(2014) for St. John’s wort leaves.

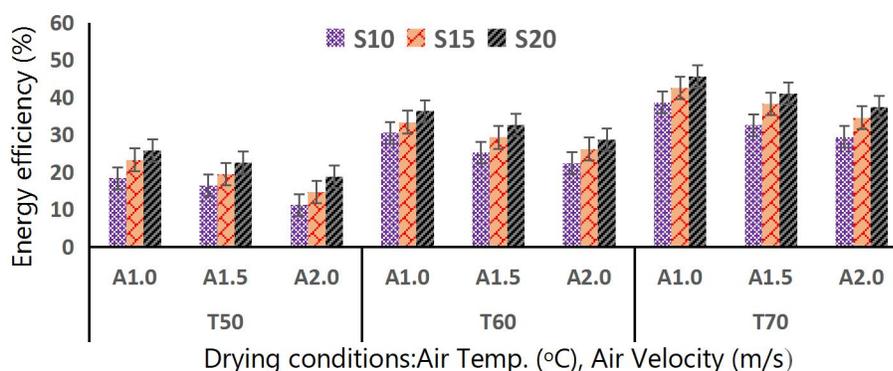


Figure 8. Energy efficiency of okra at varying drying conditions in a hybrid solar dryer

The drying efficiency of the okra samples at different drying air conditions and sample thicknesses is shown in Table 8. Increase in air temperature at decreasing air velocity and slice thickness increased drying efficiency; whereas any increase in air velocity and slice thickness at constant or varying air temperature decreased drying efficiency. This is because, at higher air temperatures, more energy was utilized which caused vapour pressure deficit and increased the kinetic energy for moisture diffusion and evaporation, hence increased drying rate. Drying efficiency varied from 22.7 – 49.6% as a result of less amount of heat used for moisture evaporation, as larger proportion of the heat supplied was used in raising the product temperature from ambient level to drying air temperature level. Much of the supplied heat was lost through air turbulence at higher air velocity and exited through the chimney without much impact on the product. thus, the need for incorporation of heat recovery units to improve the energy efficiency of the dryer (Kudra, 2012; Aghashlo *et al.*, 2013). The efficiency for drying reduced as the capillary distance increased. More energy was consumed to reduce the product energy barrier and initiate capillary diffusion. Heat and mass transfer rate was better at low air velocity due to more residence time of drying air within the products. These results agree with the reports of Azadbakht *et al.* (2017), Beigi (2016), Jindarat *et al.* (2011), Vieira *et al.* (2007). It can be observed from Figure 8 and Tables 6 and 7 that drying efficiency is higher than thermal utilization and energy efficiencies since greater proportion of the energy consumed was used in heating up the drying air and increasing the product temperature, assuming negligible thermal loss.

**Table 7.** Drying efficiency values at varying drying air conditions and sample thicknesses

Slice thickness (mm)	10			15			20		
Air vel. (ms <sup>-1</sup> )	1	1.5	2	1	1.5	2	1	1.5	2
Air temp. (°C)	Drying efficiency (%)								
50	40.1	36.3	33.1	37.1	34.2	30.6	33.4	30.7	28.1
60	44.3	39.7	36.4	39.3	36.3	28.1	35.4	27.0	25.6
70	49.6	44.5	40.1	44.9	39.1	32.4	37.0	24.6	22.7

#### 4. Conclusion

This study revealed that mean energy consumption for drying of okra slices increased with decrease in air temperature and air velocity and increased with increase in slice thickness. The maximum mean energy consumption (69.02kWh) occurred at 50°C air temperature, 0.1ms<sup>-1</sup> air velocity and 20mm slice thickness, whereas the minimum mean energy consumption (2.02kWh) was obtained at 70°C air temperature, 2ms<sup>-1</sup> air velocity and 10mm slice thickness. Second order polynomial models of the energy consumption at varying slice thicknesses were developed. The R<sup>2</sup>-values were found to increase with increase in slice thickness at varying drying parameters. Thermal utilization efficiency increased with increase in air temperature, decrease in air velocity and sample thickness. The highest thermal utilization efficiency (38.8%) was observed at 70°C air temperature, 0.1ms<sup>-1</sup> air velocity and 10mm slice thickness. Energy efficiency increased with increase in sample thickness and air temperature and decrease in air velocity. Maximum energy efficiency (45.6%) was obtained with 70°C air temperature, 1ms<sup>-1</sup> air velocity and 20mm slice thickness. Drying efficiency increased with increase in air temperature at decreasing air velocity and slice thickness. The maximum efficiency obtained was 49.6% at 70°C air temperature, 1ms<sup>-1</sup> air velocity and 10mm slice thickness.

The effects of three independent drying variables (air temperature, air velocity, and slice thickness) on two response variables (drying duration and specific energy consumption) of dried okra slices were also studied. The drying variables were optimized based on the specific energy and dried okra quality. Second order polynomial functions and response surface plots were developed. The drying factors had significant effects on the response variables. Increasing the drying air temperature and air velocity decreased the drying duration significantly, whereas increase in slice thickness increased the drying duration. Increasing the sample thickness at low air temperature and air velocity increased the specific energy consumption. The optimal predicted drying conditions obtained for maximum desirability index of 0.808 were 59.81°C, 2ms<sup>-1</sup> and 10mm for air temperature, air velocity and slice thickness, respectively. At this optimum condition, the respective values of drying duration and specific energy consumption obtained were 94.54 mins and 3.54kWhkg<sup>-1</sup>, respectively.

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