THIN-LAYER DRYING CHARACTERISTICS OF SLICED TOMATO UNDER FORCED CONVECTION SOLAR ENERGY DRYING

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ABSTRACT

Thin layer drying characteristics of sliced tomato under forced convection solar drying was investigated. Using airflow rate and sliced thickness as variables, five model equations were evaluated. Each of the equations was linearised and then least square technique was used to obtain the models' parameters. The results revealed that at 15 and 20 mm sliced thicknesses, Page's and Modified Page's model equations adequately describe the thin layer drying characteristic while at 25 mm sliced thickness only Modified Page's model equation gave the best prediction. The best results were obtained at 15mm slice thickness and 4.50m^3/s air flow rate. The results, also, showed that the resistance to moisture diffusion increases with increase in slice thickness. The Modified Page's model adequately describes the drying characteristics of sliced tomato under forced convection solar drying.

Keywords: Sliced tomato, drying characteristics, solar energy, forced convection, drying, model equation.

1.0 INTRODUCTION

The process of thin layer drying of agricultural products has been described mathematically with several model equations (Henderson and Pabis, 1961; Misra and Brooker, 1980; Chinnan, 1984; Lee et al., 2004). The available model equations, according to Parti (1993) and Abdalla and Amri (1999), can be divided into three groups, namely; theoretical, empirical and semi-empirical equations. Theoretical models are said to be based on analytical solution of the differential equation of diffusion (Lee et al., 2004). Even though analytical solution has been used to describe the drying process of many agricultural crops, the method is found to give inexact results in the first and last stages of drying because they tend to ignore the temperature change and moisture content dependence of the diffusion coefficient. The empirical models are based on experimental data from thin layer drying tests and yield a direct relationship between moisture content and drying rate (Lee et al., 2004). However, empirical equations are not usually used because they neglect the internal resistance to mass transfer(Parti, 1993; Abdalla and Amri, 1999). Semi-empirical equations are the exponential model equations, and they are analogous to Newton's law of cooling (Lee et al., 2004). These equations have been successfully applied by many researchers to describe drying rates of various agricultural products.

Generally, thin-layer drying model equations have contributed to the understanding of heat and mass transfer phenomena for designing and improving of drying equipment. The general form of these equations according to Chen and Jayas (1998) is:

$$MR = \frac{M_t - M_e}{M_o - M_e} = F(t) \quad (1)$$

where,

MR = moisture ratio
M_t = moisture content at time, t (% db)
M_o = initial moisture content (% db)
M_e = equilibrium moisture content (% db)
F(t) = a function of drying time

Several forms of Equation 1 have been used by researchers to describe thin-layer drying of grains and other agricultural products. Some of the equations are as discussed below:

The Lewis drying equation (or logarithmic model) as presented by Henderson *et al*., (1997) takes the form:

$$MR = e^{-Kt} \quad (2)$$

where,

K = drying rate constant (h^{-1})
t = drying time (h)

Combining Equations 1 and 2 and rearranging one obtains,

$$M_t = (M_O - M_e)\, e^{-(Kt)} + M_e \quad (3)$$

Equation 3 is analogous to Newton's law of cooling and is referred to as the Newton model (Sun and Woods, 1994). The equation assumes that all the resistance to moisture transfer is at the water surface of the product and it has been shown to adequately predict changes in moisture content of thin layers of grain during drying (Bruce, 1985; Jayas and Sokhansanj, 1988).
A modified version of Lewis (1921) model as proposed by Hansen *et al*. (1993) take the general form:

$$MR = \sum_{i=1}^{j} A_i e^{-Kit} \qquad (4)$$

where,

A_i = characteristics constants
K_i = drying rate constant (h^{-1})

This is an empirical as well as theoretical model based on heat and mass transfer for rate of moisture loss. For the case of j = 1, K is known as the drying constant and is evaluated from thin-layer drying curves by plotting on semi log paper (Hall, 1980). Most K values are reported as a function of temperature only (Syarief*et al*., 1984).

The Page (1949) equation or modified logarithmic model is a modified version of the Lewis (1921) drying equation. The modification includes additional parameter to the Lewis equation, resulting in better agreement with experimental data (Kulasiri*et al*., 1989; Otten*et al*., 1989; Tang *et al*., 1989). This equation is expressed as:

$$MR = \exp(-kt^n) \qquad (5)$$

where,

n = dimensionless coefficient

The above equation is said to be more flexible in fitting the drying data, and it is ASAE recommended thin – layer drying equation for grains and other agricultural crops (ASAE, 2000a).

The equation reported by Overhults*et al*. (1973), White *et al*. (1981), Jain and Pathare (2004) is in the classical form for thin layer drying equations and it is similar to Page equation. That is,

$$MR = \exp(-(kt)^n) \qquad (6)$$

Equation 6 is commonly referred to as Modified Page Model for thin layer drying.

Adu*et al*. (1994) reported that a drying characteristic curve obtained from drying data might be mathematically described using diffusion-based semi-theoretical or empirical drying equations. Diffusion based equation can be represented as:

$$MR = \frac{6}{\pi^2}\sum_{i=1}^{\infty}\frac{-1}{n^2}\exp[-n^2\pi^2\left(\frac{D}{R^2}\right)t] \qquad (7)$$

where,

D = diffusion coefficient of moisture within the grain (m^2/s)
R = equivalent radius of grain kernel (m)

Sharaf-Eldeen*et al*. (1979) as cited by Adu*et al*. (1994) also reported that semi-theoretical thin-layer model can be statistically fitted into a finite number of terms of a modified form of the infinite series solution of Fick's diffusion equation to the drying data. This semi-theoretical equation have been given as:

$$MR = A_o\exp(-K_o t) + A_1\exp(-K_1 t) + - - - + A_n\exp(-K_n t) \qquad (8)$$

where,

A_o, A_1, A_n = characteristics constants
K_o, K_1, K_n = drying rate constants (h^{-1})

This form of equation removes the restrictions presented by the material's geometric shape, and represents the effect of the material shape and the drying conditions in the form of drying constants.

Jain and Pathare (2004) adopted one-term of equation 8 to describe the thin layer drying characteristics of onion slices. The equation is in form of:

$$MR = A\exp(-Kt) \qquad (9)$$

where,

A = characteristics constant

Equation 9 is popularly referred to as Henderson and Pabis model (Westerman*et al*., 1973; Chhinman, 1984).

Another thin layer drying equation that has being used by researchers as reported by Chandra and Singh (1995) is Geometric Model and it is in form of:

$$MR = At^{-n} \qquad (10)$$

This equation was used by Jain and Pathare (2004) to describe the thin layer drying characteristics of onion slices.

Various research works (Hulasare*et al*., 1999; Okpala, 2003; Satimehin, 2003; Lee *et al*., 2004; Satimehin and Alabi, 2005; Musa-Makama, 2006; Sobukola*et al*., 2006; Rasouli*et al*., 2011;) have been done on thin layer drying characteristics. Musa-Makama (2006) using artificially heated air studied kinetics of convective drying of sliced tomato. Using two temperature levels of 50°C and 65°C, as the drying factor, drying data were generated and fitted to only Fick's diffusion equation. It was concluded that the drying process of tomato is diffusion controlled and that the entire drying rate took place in the falling rate period. Movagharnejad and Nikzad (2007) carried out experimental works on tomato drying using power of heater and air flow velocity. The collected data were modelled using artificial neural network and empirical mathematical equations. The results showed that artificial neural network model fit the experimental data more accurately than the empirical mathematical equations. In all these research works none has reported the behaviour of tomato crop when subjected to forced convection solar energy drying process. This information is needed as an input for effective design of functional drying equipment, especially vegetable crops with high moisture content. It is, therefore, the objective of this study to generate experimental data and determine thin layer drying characteristics of sliced tomato under forced convection solar energy dryer.

2.0 MATERIALS AND METHODS

2.1 Design of Experiment

In evaluating the model equations, two factors namely; air flow rate and tomato slice thickness were considered. Air flow rate was selected because it is an important factor that affects drying operation especially during harvesting periods of tomato. The periods are characterized by cold/low temperature and low humidity. So, variation in air flow rate plays an important role in drying rate. In the case of slice thickness, it determines the capacity of the dryer, the quality of the dried product and the drying rate. The air flow rate was at three levels (3.28, 4.50 and 5.25m^3/s) and tomato slice thickness along transverse direction at three levels (15, 20 and 25mm) using Aliu(2000) recommendation of 15cm slice thickness for natural convection solar energy dryer as a bench mark. The two factors were arranged randomly in 3^3 factorial experimental design. The experiment was replicated three times.

2.2 Sample Preparation

Roma 539 tomato variety popularly grown among tomato farmers in some of the production areas in Kaduna, Kano and Katsina states of northern Nigeria was used as test crop. The tomato was obtained from Experimental farm of the Institute for Agricultural Research, Ahmadu Bello University, Zaria - Nigeria. The tomato fruits were sorted to uniform sizes. This was followed by removal of bad and unripe fruits. The sorted fruits were washed and allowed to drain. Then, the fruits were sliced transversely into thicknesses of 15, 20 and 25 mm.

2.3 Experimental Set-up

The experiment consists of 27 samples as outlined in experimental design. Three dryers with nine sample trays in each were used. Each of the empty trays were coded, weighed and recorded. The sliced samples were evenly spread on the trays to form a single layer and the loaded samples were re-weighed. This was followed by arrangement according to the layout of the experimental design inside the drying chambers. Thereafter, the fan units were switched on for the drying process to commence. The ambient temperatures (wet and dry), the inlet temperatures (to collector and drying chamber) and the outlet temperatures from the drying chambers were also measured and recorded. The relative humidity was equally measured and recorded for each of the above locations. During the drying process, the air outlets' velocities, solar irradiance and samples' moisture contents were also measured. The first readings of the samples weights were taken and recorded one hour into drying time. Subsequent readings of the samples weights were taken at two hours intervals until constant weight (within the limit $\pm$0.01g between three successive readings) was reached for each of the samples. The initial and final moisture contents of the samples were determined according to the procedure detailed by ASAE (1996). Each of the five equations was linearised and then least square technique was used to obtain the models' parameters with their coefficient of determinations (R^2) and standard errors (SE).

3.0 RESULTS AND DISCUSSION

3.1 Results

The results for the models' parameters with their coefficient of determinations (R^2) and standard errors (SE) are as presented in Tables 1 – 3. From the tables, it can be observed that Page's and Modified Page's models gave the highest and the lowest values for coefficient of determination and standard error, respectively when compared with the other three models. The values of the coefficient of determination and standard error were in the range of 0.957 to 0.992 and 0.096 to 0.215, respectively for the two models, indicating good fit of the two models to the data. The high coefficient of determinations and low standard errors for these equations indicate a strong trend between moisture content and drying time. This implies, that the two equations adequately describe the thin layer drying characteristic of sliced tomato because of their strong correlation. However, the best result was obtained at 15mm slice thickness and 4.50m^3/s air flow rate. On the other hand, the geometric model gave the least and the highest values of coefficient of determination and standard error when compared with the other four models. Based on the highest value of the coefficient of determination and the lowest value of standard error, it can be stated that the Page's and the Modified Page's models adequately described the thin layer drying of sliced tomato under the range of experimental conditions considered for this study.

The values obtained for the drying constant, K decreased with increase in slice thickness. This shows that the resistance to moisture diffusion increases with increase in slice thickness. There is no definite pattern in variation of the coefficient, n with slice thickness or air flow rate. This implies that the mean experimental value can be utilized for model prediction.

Table 1: Model parameters for 15mm slice thickness

Slice thickness(mm)	Equation	Air flow rate (m^3/s)	k (hr^{-1})	N	a	R^2	SE (%, w.b.)
15	5	3.28	0.262	0.846	-	0.988	0.1138
		4.50	0.315	0.860	-	0.992	0.0958
		5.25	0.303	0.800	-	0.967	0.1783
	6	3.28	0.205	0.846	-	0.988	0.1138
		4.50	0.261	0.860	-	0.992	0.0958
		5.25	0.224	0.800	-	0.967	0.1783
	3	3.28	-0.151	-	-	0.953	0.4373
		4.50	-0.188	-	-	0.983	0.3209
		5.25	-0.137	-	-	0.939	0.4590
	9	3.28	-0.151	-	0.802	0.953	0.4373
		4.50	-0.188	-	0.749	0.983	0.3209
		5.25	-0.137	-	0.633	0.939	0.4590
	10	3.28	-1.510	-	2.259	0.835	0.8238
		4.50	-1.895	-	2.808	0.873	0.8886
		5.25	-1.410	-	1.785	0.870	0.6688

Table 2: Model parameters for 20mm slice thickness

Slice thickness(mm)	Equation	Air flow rate (m^3/s)	k (hr^{-1})	N	a	R^2	SE (%, w.b.)
20	5	3.28	0.200	0.818	-	0.957	0.2147
		4.50	0.223	0.793	-	0.972	0.1687
		5.25	0.204	0.850	-	0.985	0.1357
	6	3.28	0.140	0.818	-	0.957	0.2147
		4.50	0.151	0.793	-	0.972	0.1687
		5.25	0.154	0.850	-	0.985	0.1357
	3	3.28	-0.121	-	-	0.925	0.4522
		4.50	-0.117	-	-	0.944	0.3739
		5.25	-0.127	-	-	0.951	0.3803
	9	3.28	-0.121	-	1.022	0.925	0.4522
		4.50	-0.117	-	0.925	0.944	0.3739
		5.25	-0.127	-	0.945	0.951	0.3803
	10	3.28	-0.165	-	2.092	0.749	0.8275
		4.50	-1.138	-	1.913	0.783	0.7345
		5.25	-1.250	-	2.123	0.798	0.7717

Table 3: Model parameters for 25mm slice thickness

Slice thickness(mm)	Equation	Air flow rate (m^3/s)	k (hr^{-1})	N	a	R^2	SE (%, w.b.)
25	5	3.28	0.108	0.833	-	0.978	0.1580
		4.50	0.163	0.754	-	0.987	0.1209
		5.25	0.169	0.776	-	0.982	0.1308
	6	3.28	0.069	0.833	-	0.978	0.1580
		4.50	0.090	0.754	-	0.987	0.1209
		5.25	0.101	0.776	-	0.982	0.1308
	3	3.28	0.063	-	-	0.942	0.2878
		4.50	0.064	-	-	0.939	0.1757
		5.25	0.075	-	-	0.968	0.2521
	9	3.28	0.063	-	1.017	0.942	0.2878
		4.50	0.064	-	0.839	0.939	0.1757
		5.25	0.075	-	0.885	0.968	0.2521
	10	3.28	-0.807	-	1.989	0.704	0.6529
		4.50	-0.853	-	1.825	0.796	0.5379
		5.25	-0.983	-	2.113	0.766	0.6764

Equation 5: Page's Model
Equation 6: Modified Page's Model
Equation 3: Newton Model
Equation 9: One term exponential Model
Equation 10: Geometric Model

3.2 Discussion

Considering the appropriateness of Page's and Modified Page's models, the two models were further examined using Jain and Pathane (2004), and Sobukola et al. (2006) methods of model comparison by comparing the experimental moisture ratio with the predicted moisture ratio for the two models. The results are as presented in Figures 1 – 3.

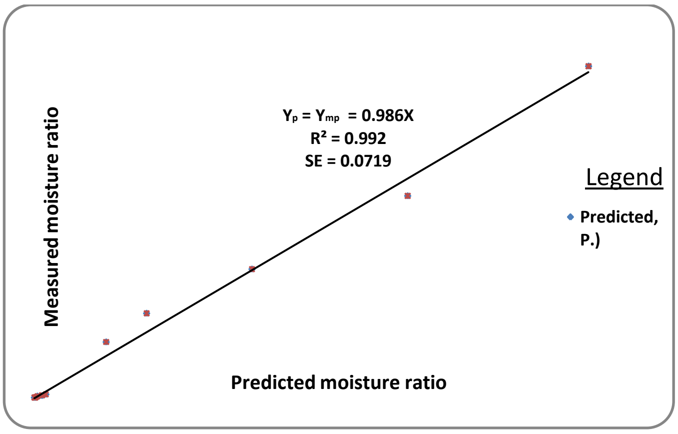

Fig. 1: Comparison of measured and predicted moisture ratio for Page's and Modified Page's Models at 15mm slice thickness

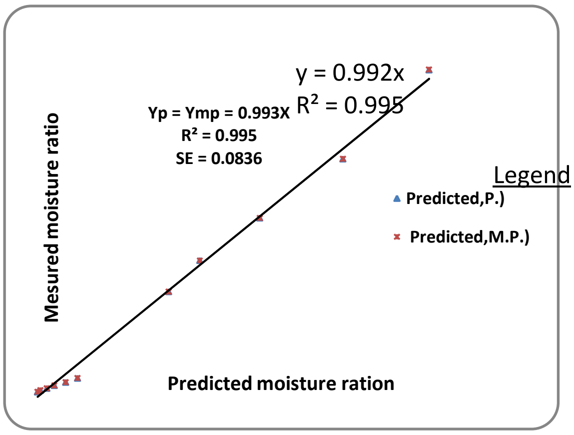

Fig. 2: **Comparison of measured and predicted moisture ratio for Page's and Modified Page's Models at 20mm slice thickness**

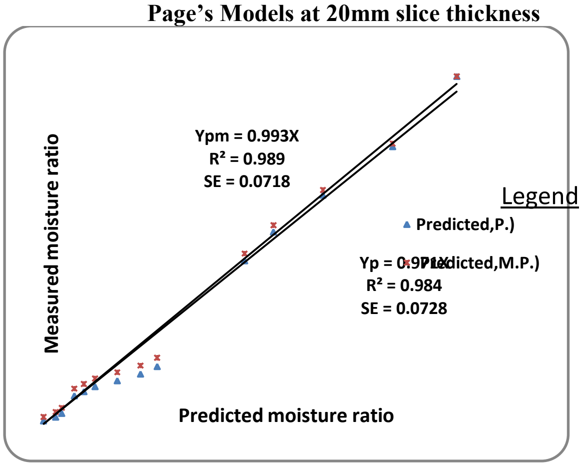

Fig. 3: Comparison of measured and predicted moisture ratio for Page's and Modified Page's Models at 25mm slice thickness

From Figure 1, the two models have the same relationship, at slice thickness of 15mm, with coefficient of determination (r^2) and standard error of 0.993 and 0.072, respectively. In Figure 2, the same pattern was established for 20mm slice thickness with the two models having coefficient of determination (r^2) and standard error of 0.996 and 0.084, respectively. However, at slice thickness of 25mm, there is difference in the predicted values for the two models as can be seen in Figure 3. In these later results, higher value of coefficient of determination (r^2) and low value of standard error were obtained for Modified Page's model when compared with Page's model. The results show that the two models predicted the experimental data accurately at 15mm and 20mm slice thicknesses while the Modified Page's model best fitted the experimental data than the Page's model at 25mm slice thickness.

The established relationships in Figures 1 – 3 are in the form of Y = βX. Ideally, Y = X if the predicted moisture ratio is equivalent to the measured moisture ratio. However, the variability of the predicted and the measured moisture ratio for all the thicknesses are not statistically significant at 95% probability level, as shown in Table 4. From Fig. 3, the superiority of Modified Page's model was further confirmed. It is clear from Fig. 3 that Y = βX for the Modified Page's model gave the best prediction when compared with the Page's model. Therefore, it can be concluded that the Modified Page's model adequately describe the drying characteristics of sliced tomato under forced convection solar drying.

Table 4: Calculated and tabular t – values for models comparison

Slice thickness	Calculated, t		Tabular, t	
	Pade's	Modified Page's	5%	1%
15mm	0.4836 ns	0.4838 ns	2.262	3.250
20mm	0.3218 ns	0.3202 ns	2.262	3.250
25mm	0.6537 ns	0.2041 ns	2.179	3.055

ns = Not significant

4.0 CONCLUSION

Thin layer drying characteristics of sliced tomato under forced convection solar drying was investigated using two variables (airflow rate and sliced thickness) and five model equations. The following can be concluded from the study:

i. The resistance to moisture diffusion and the requirement for air flow rate increase with increase in slice thickness but at 25 mm thickness there is no definite pattern for air flow rate. The best results were obtained at 15mm slice thickness and 4.50m^3/s air flow rate.

ii. At 15 and 20 mm sliced thicknesses, Page's and Modified Page's model equations adequately describe the thin layer drying characteristic while at 25 mm sliced thickness only Modified Page's model equation gave the best prediction.

iii. The prediction of Modified Page's model fit the experimental data more accurately in comparison with the other four models evaluated

iv. TheModified Page's modelcan be used to describe the drying characteristics of sliced tomato under forced convection solar energy drying.

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