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THIN-LAYER DRYING CHARACTERISTICS FOR GREEN CHILLI

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ABSTRACT

Thin-layer drying experiments under overflow–underflow and through flow conditions of green chilli were conducted with air temperature ranging from 40 to 65°C, relative humidity ranging from 10 to 60% and air velocity ranging from 0.10 to 1.0 m/s. The single exponential equation and the Page equation were used to determine the thin-layer drying characteristics for green chilli. Both the equations fitted well to the experimental data. The Page equation was found to describe the thin-layer drying of chilli better than the single exponential equation. The parameters of the Page equation and the single exponential equation were expressed as a function of drying air temperature, relative humidity and air velocity.

Key Words: Chilli; Empirical drying equations; Thin-layer drying

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INTRODUCTION

Chilli is generally harvested at very high moisture content ranging from 700 to 800% w/w (db) and dried to be very low moisture content of 8–10% w/w (db) for storage and 4–5% w/w (db) for grinding purposes (Pruthi, 1993; Miaruddin et al., 1995). It is essential to dry the chilli in a suitable environment to produce good quality (mainly colour and pungency) dried product.

Drying is a complex thermophysical and biochemical process comprising simultaneous heat and mass transfer between the surface of the material and the surrounding media, and a transfer of heat and moisture within the material. The transfer of moisture from the interior layer of the material to its surface depends on the structure and the properties of the material. In the initial stages, the moisture removal is rapid since the excess moisture on the surface of the products presents a wet surface to the drying air. Subsequently, drying depends upon the rate at which the moisture within the product moves to the surface by a diffusion process depending upon the material to be dried.

Simulation models provide an opportunity for the assessment of the energy conservation and saving alternatives. This process is advantageous because full scale experimentation of different products and configurations of drying system is very time consuming, costly and therefore not always possible in developing countries (Guarte, 1996; Bala, 1997). The efficiency of the drying system can be improved by the analysis of the drying process. Analysis of the drying system can be greatly expedited by using computer simulation. A generalized thin-layer chilli drying equation is therefore, needed for this purpose. The equation must be suitable for use at any temperature, relative humidity and air velocity of the drying air used in chilli drying.

Investigators developed theoretical, semi-theoretical and empirical equations to express and explain the thin-layer drying of agricultural products. The theoretical approach concerns with either the diffusion equations or simultaneous heat and mass transfer equations. The empirical equations give satisfactory fit to all experimental data and take less computing time in comparison to the theoretical equations. The semi-theoretical equations are analogous to Newton's law of cooling which assumes that the drying rate is proportional to the difference between actual and equilibrium moisture content.

Drying rate, $$\frac{dM}{dt} = -K(M - M_e) \tag{1}$$

If drying constant (K) in Eq. (1) is independent of M and M_e, the Eq. (1) may be integrated to:

$$\text{Average moisture ratio,}\quad \frac{M - M_e}{M_o - M_e} = \exp(-kt) \tag{2}$$

This equation is called single exponential equation. This equation was used by several researchers to determine the thin-layer drying characteristics for agricultural products: fully exposed pop-corn (White et al., 1981); malt (Bala and Woods, 1992); rough rice (Shei and Chen, 1998); marigold flower (Buser et al., 1999).

Page (1949) proposed the following empirical equation for shelled corn.

$$\frac{M - M_e}{M_o - M_e} = \exp(-kt^n) \tag{3}$$

Several investigators (Liu et al., 1989; Bala and Woods, 1992; Guarte, 1996; Bashir, 1998; Basunia and Abe, 1998; Afzal and Abe, 1999; Karathanos and Belessiotis, 1999; Wongwises and Thongprasert, 2000) have reported that Page equation adequately predicts the thin-layer drying of wide varieties of crops such as chilli, malt, copra, onion, rough rice, potato, fig, currant, sultana and plums. Hence, the single exponential equation and the Page equation are applicable for thin-layer drying of cereal grains, fruits, nuts and spices.

Many researchers have proposed numerous mathematical models for thin-layer drying of many agricultural products. Most of these studies have been carried out on thin-layer drying of cereal grains, fruits and vegetables, but very little information is available on thin-layer drying of chilli. This paper presents the basic information derived from the laboratory experiments and empirical drying equations for thin-layer drying of green chilli.

EXPERIMENTAL APPARATUS AND PROCEDURE

Thin-Layer Drying Apparatus

Thin-layer drying should be conducted under controlled conditions of drying air temperature, relative humidity and air velocity. An apparatus is therefore needed for the purpose of providing these required conditions. For the purpose of present work, a thin-layer drying apparatus was designed and constructed in the Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh, Bangladesh.

The schematic diagram of the apparatus is shown in Figure 1. To dry chilli under controlled conditions of air temperature, relative humidity and air velocity, atmospheric air was supplied by a centrifugal fan, through a GI pipe, fitted with an orifice plate, to the bottom of the metal tower, packed with plastic rings. The airflow was measured with a U-tube manometer, fitted to the inlet and outlet of the orifice plate. Water was pumped from a water tank by a water pump. Water in the water tank was heated by a water heater or cooled by water cooling unit to the required dew point temperature. The temperature of the water in the water tank was controlled by a temperature controller. At the top of the tower, water was sprayed by a nozzle, at the required dew point temperature of the air. The air passing through the packed tower was approximately saturated and was exhausted from the top of the water tower, through GI pipe to the heater box, and was heated to the required temperature by two electric heaters. The temperature of the air in the heater box was controlled by a temperature controller. The dew point temperature of the air was measured at the exit of water bath tank using copper-constantant thermocouple and a digital thermometer. The heated air was then passed through the GI pipe to the through flow

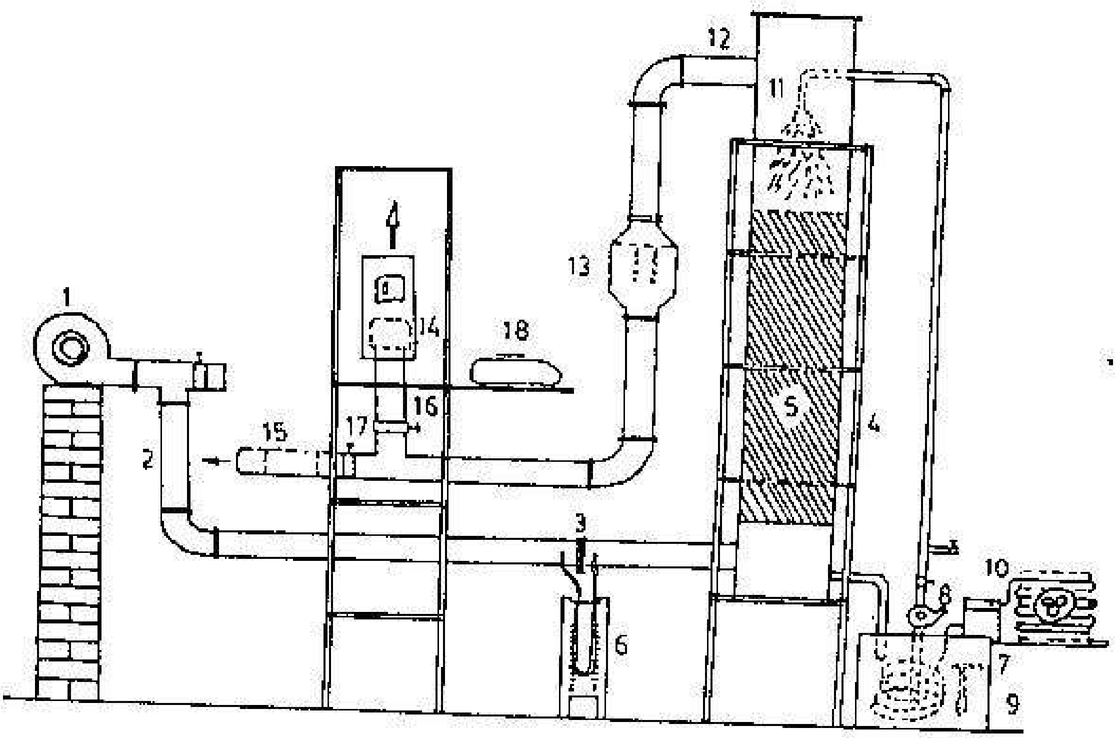

Figure 1. Schematic view of a thin-layer drying apparatus. 1. Blower, 2. Air flow pipe, 3. Orifice plate, 4. Water tower, 5. Plastic rings, 6. U-tube manometer, 7. Water tank, 8. Water pump, 9. Water heater, 10. Water cooling unit, 11. Water spray nozzle, 12. Humidified air outlet, 13. Heater box, 14. Through flow drying chamber, 15. Overflow underflow drying chamber, 16. Through flow gate valve, 17. Overflow underflow gate valve, 18. Balance.

drying chamber or overflow–underflow drying chamber. The through flow and overflow–underflow methods of drying were operated by two controlling valves. In the through flow drying chamber conditioned air passed through the tray containing chilli sample of one layer of thickness. In case of overflow–underflow drying chamber conditioned air passed over and under the tray containing chilli sample of one layer of thickness. The weight of tray containing chilli sample was weighed by an electronic balance, placed adjacent to the drying chamber.

Experimental Procedure

Freshly harvested green chilli of variety *Balujuri* (Mymensingh local) was procured from local market. It was cleaned and washed with fresh water and spread on a plastic filter tray to drain out excess water. The fresh chilli was then sealed in plastic bags and stored in a home refrigerator at a temperature of 5°C. Before starting any experiment, the required chilli sample was brought out from the refrigerator and kept until the sample attained the room temperature.

Thin-layer drying experiments under controlled conditions were conducted in two different types of airflow methods: (1) overflow–underflow method and (2) through flow method. Different combinations of air temperature, relative humidity and air velocity were considered and a total of 18 experimental runs were conducted for each of the different types of air flow methods. The values of temperature, relative humidity and air velocity used in the thin-layer drying of green chilli are given in Table 1.

Before starting any experimental run, the instrumentation system was checked carefully. The required temperature of water in the water tank and the temperature of drying air in the heater box were adjusted by the temperature controller. The gate valves were closed and opened according to the method of drying. The air velocity was adjusted by changing the speed of the electric motor using a variac. The velocity of air was

Table 1. The Values of Temperature, Relative Humidity and Air Velocity Used in Thin-Layer Drying of Green Chilli

Variables	Values of the Variables Used for the Experimental Runs					
Temperature (°C)	40	45	50	55	60	65
Relative humidity (%)	10	20	30	40	50	60
Air velocity (m/s)	0.10	0.20	0.30	0.50	0.75	1.00

measured by a U-tube manometer and checked by a vane type anemometer. The water pump, blower, water heater or cooler, electric heater in the heater box were started simultaneously. Time required stabilizing the whole system by drying air temperature, relative humidity and air velocity was about 2 h.

About 100 g of chilli sample was blanched in a hot water at 90°C for 3 min (FAO, 1995) and the sample was spread on a plastic filter tray to drain out excess water. After stabilizing the whole system, a sample of about 50 g of blanched chilli was placed evenly on the drying tray at single pod thickness and another 50 g sample was placed in three petridishes for moisture content determination. The initial weight of the tray with sample was recorded and the tray was placed on the seat of the drying chamber. The change of weight of the sample was recorded at 5 min interval. For moisture contents of the sample below 20% (db), the change in weight of the sample was recorded at 10 min interval. Time required for weight registration was about 10 s. When the weight of the sample became constant the experiment was stopped. At the completion of each experiment, the final moisture content of dried chilli sample was determined by drying the chilli sample in an air ventilated oven at 105°C temperature for 24 h (Misra, 1972).

Equation Fitting

The proposed equations were fitted to the experimental data by direct least square proposed by Davidon–Fletcher–Powell method (Bala, 1997). The fitting of the equation was evaluated on the basis of goodness of fit by the coefficient of determination (R^2) and root mean square error (RMSE).

$$R^2 = \frac{\left(\sum M_{\mathrm{exp}} M_{\mathrm{pred}}\right)^2}{\sum M_{\mathrm{exp}}^2 \sum M_{\mathrm{pred}}^2} \tag{4}$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \left(\frac{(M_{\mathrm{pred}} - M_{\mathrm{exp}})^2}{n} \right)} \tag{5}$$

A program was written in BASIC for estimation of the parameters, coefficient of determination and root mean square error of the single exponential equation and the Page equation.

RESULTS AND DISCUSSION

Fitting of Equations to Experimental Data

The single exponential equation and the Page equation were fitted to experimental data of 18 experimental runs of overflow–underflow method as well as 18 experimental runs of through flow method by direct least square procedure. The parameters, coefficients of determination and root mean square errors of the single exponential equation and the Page equation varied with the temperature, relative humidity and air velocity for different experimental runs of both overflow–underflow and through flow methods. The mean parameters, coefficients of determination and root mean square errors of the single exponential equation and the Page equation under overflow–underflow and through flow method of drying are shown in Table 2. It is observed from Table 2 that the mean values of coefficients of determination were higher than 0.99 for both the single exponential equation and the Page equation of all experimental runs of overflow-underflow and through methods of drying. So, the fits of the single exponential equation and the Page equation were good with the experimental data. It is also observed from the Table 2 that for overflow–underflow and through flow method of drying, the mean coefficients of determination of the single exponential equation and the Page equation were almost same. The mean root mean square error of the Page equation was found to be lower than the single exponential equation. Hence, the experimental data of through flow method

Table 2. Estimated Mean Values of Parameters, Coefficient of Determination (R^2) and Root Mean Square Error (RMSE) of the Single Exponential Equation and the Page Equation Under Different Methods of Drying

Equation	Method of Drying	k (min^{-1})	u	M_e (w/w, db)	$M_0 - M_e$ (w/w, db)	R^2	RMSE (Decimal)
Single exponential	Overflow–underflow	0.00263		−1.4125	7.9152	0.9992	0.0753
	Through flow	0.00477		−0.9600	7.5116	0.9991	0.0762
Page	Overflow–underflow	0.00145	1.13570	−0.9004	7.2249	0.9993	0.0591
	Through flow	0.00145	1.13514	−0.9119	7.3359	0.9995	0.0521

was found to be better fitted to the Page equation than the single exponential equation.

The dynamic equilibrium moisture content was estimated by the best fitting of the single exponential equation and the Page equation by direct least square method. The mean values of estimated dynamic equilibrium moisture content obtained from the best fitting of the experimental data to the single exponential equation and the Page equation are given in Table 2. It is observed from the table that the estimated dynamic equilibrium moisture content was found very low and negative. The dynamic equilibrium moisture content is a hypothetical concept. It is obtained by the best fitting of the thin-layer drying equation to the experimental data and hence it can be negative for the best fit of the experimental data to the proposed equation. The concept of dynamic equilibrium moisture content has been criticized by some researchers (Chu and Hustrulid, 1968) because of the physical non-existence of such moisture content. But the dynamic equilibrium moisture content gives better estimates of drying rate and better description of drying behaviour than those of static equilibrium moisture content. Again, in this case using static equilibrium moisture content, the equations did not fit well to the experimental data. This is due to the fact that using static equilibrium moisture content forces the thin-layer drying equation to pass through the static equilibrium moisture content determined experimentally and then fits the experimental data on thin-layer drying equation. The constraint of passing the thin-layer drying equation through static equilibrium moisture content reduces the flexibility and degree of freedom of the fitting of the thin-layer drying equation.

Fitting Equations for Overflow–Underflow Drying Method

The drying rate constant (K) of the single exponential equation was found to be a polynomial function of air temperature (Figure 2), a linear function of relative humidity (Figure 3) and a linear function of air velocity (Figure 4). The following equation was developed for drying rate constant of the single exponential equation.

$$K = 0.008366 - 0.00038T + 4.62 \times 10^{-6}T^2 - 0.00357\psi + 0.002966V \quad (R^2 = 0.93) \tag{6}$$

Similarly, both M_e and $M_0 - M_e$ of the single exponential equation were found to be the polynomial functions of air temperature, linear functions of relative humidity and polynomial functions of air velocity. The following

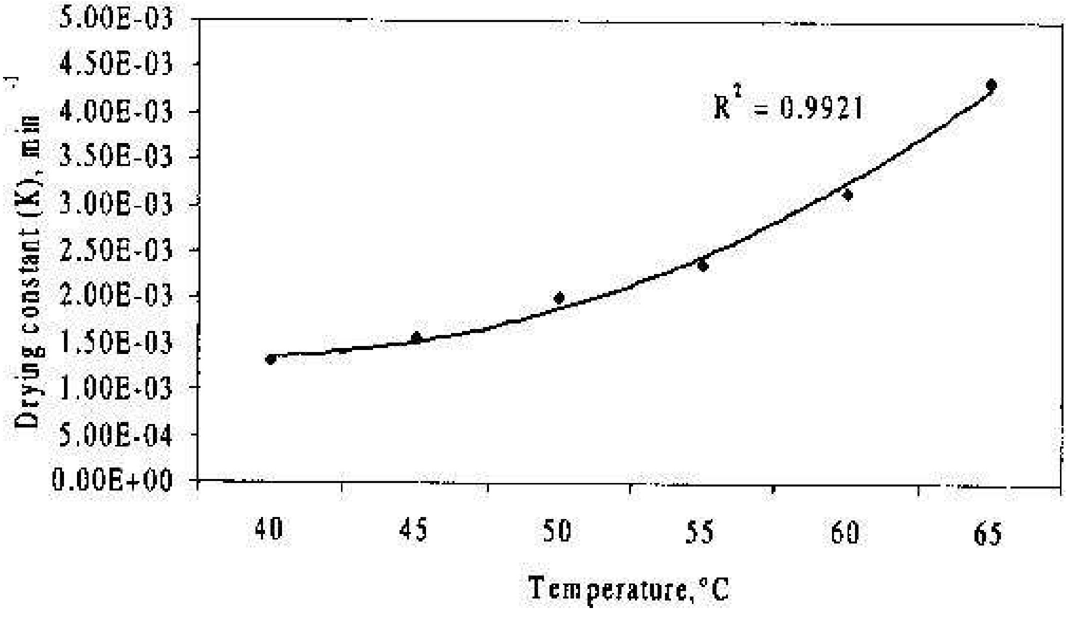

Figure 2. Drying constant as a function of temperature from the fit of the single exponential equation of overflow–underflow drying method.

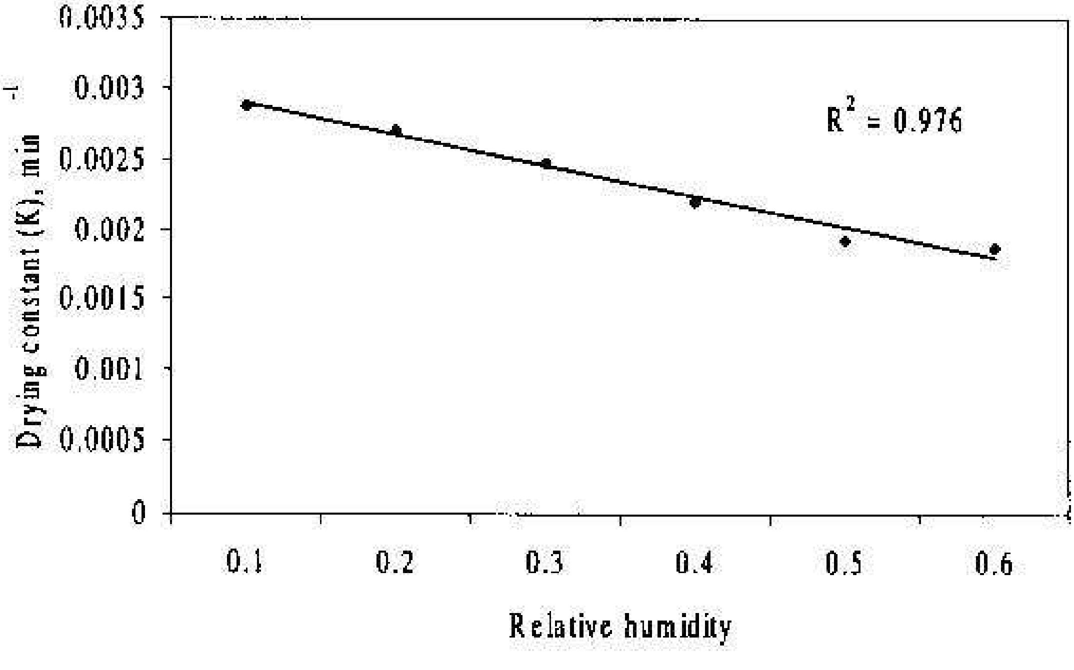

Figure 3. Drying constant is a function of relative humidity from the fit of the single exponential equation of overflow–underflow drying method.

equations were developed for M_e and $(M_o - M_e)$ of the single exponential equation.

$$M_e = 3.046685 - 0.22991T + 0.002445T^2 - 0.65388\psi + 1.67915V - 0.27376V^2 \quad (R^2 = 0.92) \qquad (7)$$

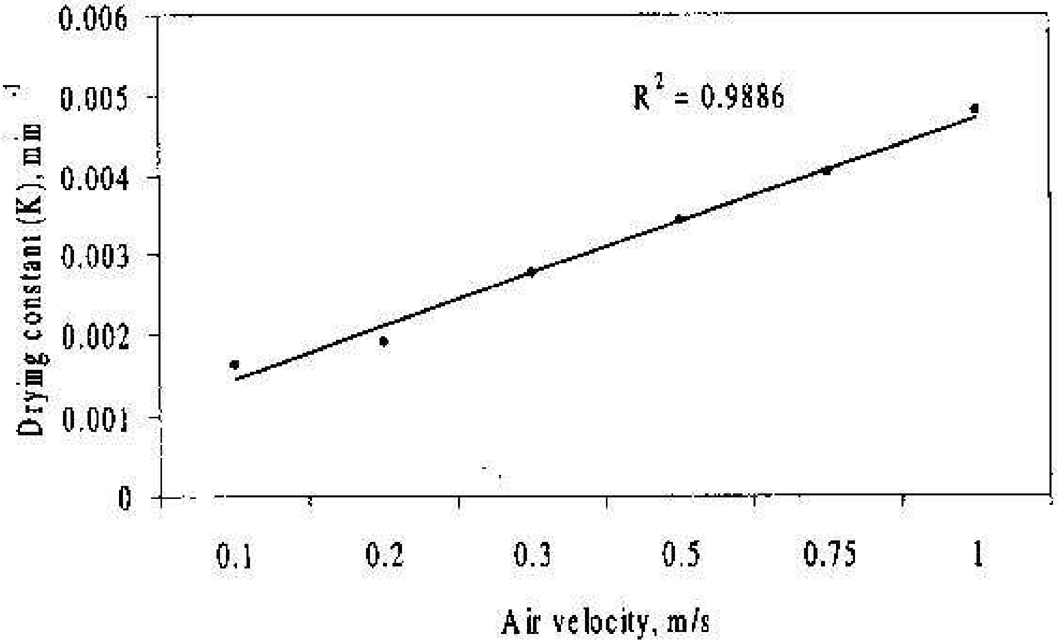

Figure 4. Drying constant is a function of air velocity from the fit of the single exponential equation of overflow–underflow drying method.

$$M_o - M_e = 3.057344 + 0.23956T - 0.00247T^2 + 0.077068\psi - 2.10205V + 0.620699V^2 \quad (R^2 = 0.91) \tag{8}$$

The drying constant of the Page equation was found to be a polynomial function of air temperature, a polynomial function relative humidity and a linear function of air velocity. The following equation was developed for drying constant of the Page equation.

$$K = 0.008759 - 0.00027T + 2.82 \times 10^{-6}T^2 - 0.01058\psi + 0.009057\psi^2 + 0.00166V \quad (R^2 = 0.85) \tag{9}$$

The exponent (u) of the Page equation was found to be a linear function of air temperature, a linear function of relative humidity and a linear function of air velocity. The following equation was developed for the exponent of the Page equation.

$$u = 0.563021 + 0.006435T + 0.63696\psi + 0.088298V \quad (R^2 = 0.93) \tag{10}$$

M_e of the Page equation was found to be a polynomial function of air temperature, a polynomial function of relative humidity and a linear function of air velocity. The following equation was developed for M_e of the Page equation.

$$M_e = -6.60875 + 0.088634T - 0.00046T^2 + 10.954\psi - 13.801\psi^2 + 0.939629V \quad (R^2 = 0.66) \tag{11}$$

$M_o - M_e$ of the Page equation was found to be a linear function of air temperature, a polynomial function of relative humidity and a linear function of air velocity. The following equation was developed for $M_o - M_e$ of the Page equation.

$$M_o - M_e = 12.53519 - 0.04732T - 13.4563\psi + 17.10614\psi^2 - 1.11099V \quad (R^2 = 0.76) \tag{12}$$

Fitting Equations for Through Flow Drying Method

The drying rate constant (K) of the single exponential equation was found to be a polynomial function of air temperature, a polynomial function of relative humidity, and a polynomial function of air velocity. The following equation was developed for drying rate constant of the single exponential equation.

$$K = -6.84593 + 0.148624T - 0.00102T^2 + 0.32091\psi - 2.7198\psi^2 + 3.30269V - 2.62254V^2 \quad (R^2 = 0.874) \tag{13}$$

Similarly, M_e and $M_o - M_e$ of the single exponential equation were found to be the polynomial functions of air temperature, relative humidity and air velocity. The following equations were developed for M_e and $M_o - M_e$ of the single exponential equation.

$$M_e = -6.84593 + 0.148624T - 0.00102T^2 + 0.32091\psi - 2.7198\psi^2 + 3.30269V - 2.62254V^2 \quad (R^2 = 0.93) \tag{14}$$

$$M_o - M_e = 14.8445 - 0.18331T + 0.001388T^2 - 8.13163\psi + 15.27832\psi^2 - 2.14959V + 1.7514V^2 \quad (R^2 = 0.92) \tag{15}$$

The drying rate constant (K) of the Page equation was found to be a polynomial function of air temperature, a polynomial function of relative humidity and a linear function of air velocity. The following equation was developed for drying rate constant of the Page equation.

$$K = -0.02184 + 0.000781T - 6.80 \times 10^{-6}T^2 + 0.004437\psi - 0.01335\psi^2 + 0.004522V \quad (R^2 = 0.86) \tag{16}$$

The exponent (u) of the Page equation was found to be a linear function of air temperature, a polynomial function of relative humidity and a polynomial function of air velocity. The following equation was developed for the exponent of the Page equation.

$$u = 0.580425 + 0.00465T - 1.2421\psi + 1.38450\psi^2 + 1.7177V - 1.2991V^2 \quad (R^2 = 0.83) \tag{17}$$

M_e and $M_o - M_e$ of the Page equation were found to be linear functions of air temperature, polynomial functions of relative humidity and polynomial functions of air velocity. The following equations were developed for M_e and $M_o - M_e$ of the Page equation.

$$M_e = -1.35338 + 0.020726T - 1.62963\psi + 1.8798\psi^2 + 1.204856V - 1.161V^2 \quad (R^2 = 0.91) \tag{18}$$

$$M_o - M_e = 8.97083 - 0.02159T + 1.50562\psi - 1.2773\psi^2 - 4.6066V + 3.539476V^2 \quad (R^2 = 0.85) \tag{19}$$

Validity of the Proposed Correlations

The coefficient of determination and the root mean square error for each of the runs are taken as the selecting criterion for the best fitting equation. The mean values of coefficient of determination, root mean square errors and mean relative deviation of the observed and predicted moisture content using the single exponential equation and the Page equation under overflow–underflow and through flow methods are given in Table 3. For overflow–underflow method, it is observed from the tabulated results that high coefficients of determination ($R^2 > 0.99$) obtained between the observed and the predicted moisture contents using the single exponential equation and the Page equation. So, the over all agreements between the observed and the predicted moisture contents using the single exponential equation and the Page equation are good.

The mean coefficient of determination of single exponential equation and the Page equation are also almost same. But root mean square error of the Page equation are found to be lower than the single exponential equation for both overflow–underflow drying method and through flow drying method. Hence, the over all fitting of the Page equation was better than the single exponential equation for both for overflow–underflow and through flow drying methods.

The fitted curves by the Page equation and the single exponential equation and the experimental points of overflow–underflow and through flow methods of drying for typical experimental runs are shown in Figures 5–8. The figures indicated that for overflow–underflow and through flow methods of drying, the predicted curves fitted to the experimental data were excellent by the Page equation and good by the single exponential equation.

Table 3. Mean Values of Coefficient of Determination (R^2) and Root Mean Square Error (RMSE) of the Observed and Predicted Moisture Content Using the Models Under Different Drying Methods

	Single Exponential Equation		Page Equation	
Drying Method	R^2	RMSE (Decimal)	R^2	RMSE (Decimal)
Overflow–underflow	0.9952	0.11029	0.9970	0.09314
Through flow	0.9913	0.15336	0.9967	0.10325

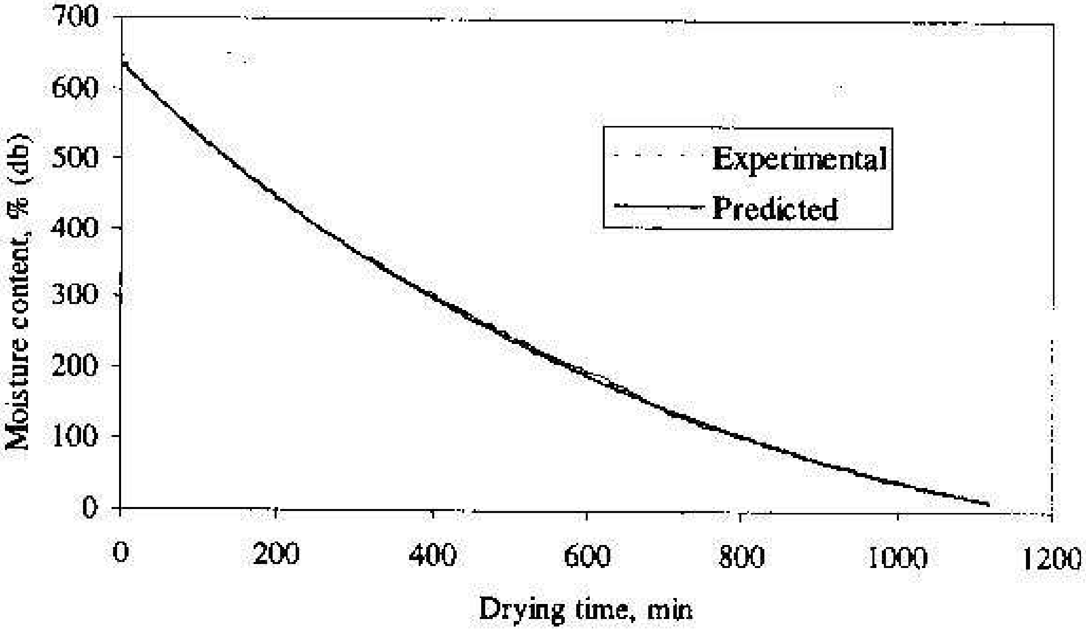

Figure 5. Observed and predicted moisture content of thin-layer drying of green chilli of run-1 ($T=40°C$, $\psi=20\%$, $V=0.50\,m/s$) using the Page equation under overflow–underflow drying method.

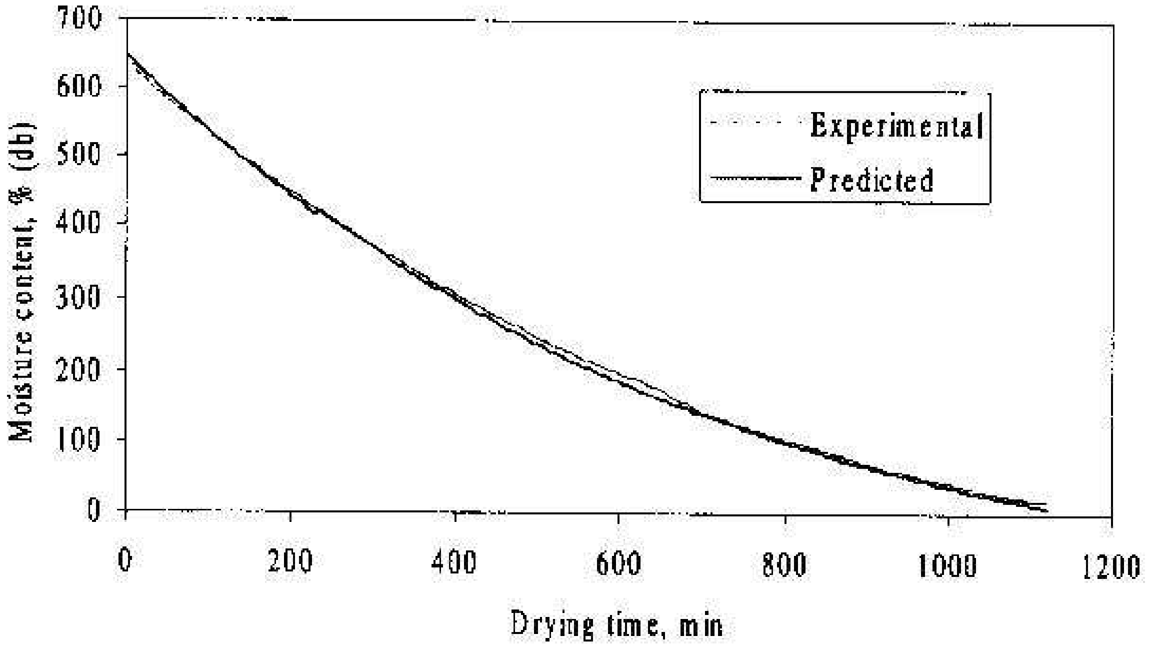

Figure 6. Observed and predicted moisture content of thin-layer drying of green chilli of run-1 ($T = 40°C$, $\psi = 20\%$, $V = 0.50\,m/s$) using the single exponential equation under overflow–underflow method of drying.

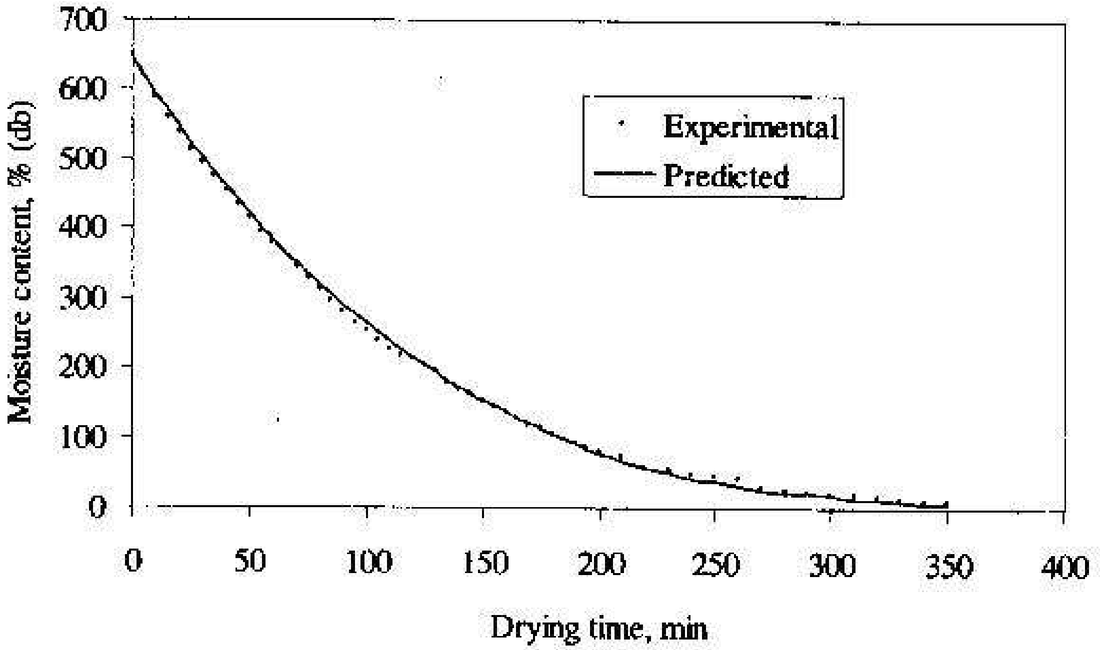

Figure 7. Observed and predicted moisture content of thin-layer drying of green chilli of run-18 ($T = 60°C$, $\psi = 20\%$, $V = 1.00\,m/s$) using the Page equation under through flow method of drying.

CONCLUDING REMARKS

Thin-layer drying experiments were conducted under controlled conditions of temperature, relative humidity and air velocity under

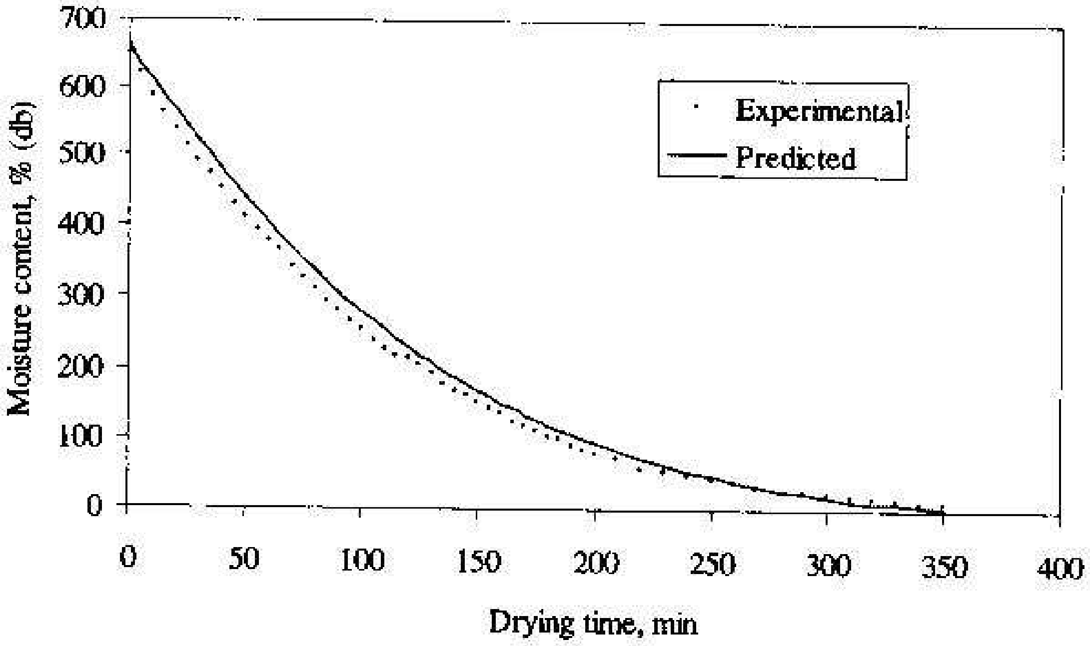

Figure 8. Observed and predicted moisture content of thin-layer drying of green chilli of run-18 ($T = 60°C$, $\psi = 20\%$, $V = 1.00\,m/s$) using the single exponential equation under through flow method of drying.

overflow- underflow and through flow drying methods. The single exponential equation and the Page equation were fitted to the experimental data by direct least square procedure. The parameters of the single exponential and the Page equation were found to be a function of temperature, relative humidity and air velocity. Both the equations fitted well to the experimental data of both overflow–underflow and through flow methods of drying. The Page equation was found to be better than the single exponential equation to describe the thin-layer drying of chilli.

NOMENCLATURE

K	Drying rate constant (min^{-1})
M	Moisture content (w/w (db))
M_e	Dynamic equilibrium moisture content (w/w (db))
M_{exp}	Experimental moisture content (w/w (db))
M_{pred}	Predicted moisture content (w/w (db))
M_o	Initial moisture content (w/w (db))
n	Number of data points
R^2	Coefficient of determination
RMSE	Root mean square error (decimal)
T	Air temperature (°C)

t	Drying time (min)
u	Exponent of the Page equation
V	Air velocity (m/s)
ψ	Relative humidity, ratio (%)

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