J.Natn.Sci.Foundation Sri Lanka 2011 ***39*** *(1): 61- 67*

RESEARCH ARTICLE

Thin layer drying characteristics of fresh tea leaves**

W.S. Botheju[1*], K.S.P. Amarathunge[2] and I.S.B. Abeysinghe[1]
[1] *Tea Research Institute, St. Coomb's Estate, Talawakelle.*
[2] *Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya.*

Revised: 25 October 2010 ; Accepted: 17 December 2010

Abstract: Thin layer drying characteristics of fresh tea leaves were investigated to quantify the rate of moisture transfer of fresh tea leaves during the withering process within the temperature range of 20 – 35 °C, and a relative humidity range of 40 – 90 % at 1.2 ± 0.3 m/s airflow rate. Five different mathematical models available in the literature were used with the drying data for fresh tea leaves using a constant climatic chamber. Results indicated that the Two-term model gives better predictions for moisture transfer than others. The desorption process of tea leaves occurred in falling rate period. The effective diffusivity of water in tea leaves varied from $3.3409 - 5.4669 \times 10^{-10}$ m^2/s over the temperature range investigated with an activation energy of 1477.75 kJ/kg. The temperature dependence of diffusivity coefficient was described satisfactorily by a simple Arrhenius type relationship.

Keywords: Constant climatic chamber, desorption process, effective diffusivity, fresh tea leaves, tea withering, thin layer drying.

INTRODUCTION

Tea withering is an important unit operation in black tea processing. Fresh tea leaves received at the factory may contain 70 – 83 % (w.b.) moisture depending on the climatic condition and the type of tea cultivar (Samaraweera, 1986). The moisture is reduced to about 55 – 60 % (w.b.) during withering operation by careful handling of air temperature. A thick layer of leaf is loaded to a trough and an axial flow fan delivers 0.6 – 0.65 m^3/min/kg green leaves (GL) volume of air through the bed of leaves against the pressure of the 12 – 15 mm water gauge (Samaraweera, 1986). During the initial stage of withering, temperature of air is maintained around 32 °C if surface water is present in the leaves. At the later stage of withering, air temperature should be maintained well below 32 °C to preserve the quality of the leaves (Ranatunga *et al*., 1986).

Moisture transfer during withering influences the temperature changes of air due to the magnitude of latent heat of vaporization. To study the deep bed simulation of withering process, data on moisture transfer properties of fresh tea leaves at ambient conditions are needed. This study investigates moisture transfer characteristics of a thin layer of fresh tea leaves. Very little work has been done on thin layer drying characteristics of fresh tea leaves. Jayarathnam and Abdul Gaffer (1979) studied the desorption process of fresh tea leaves and reported that the constant rate period was observed for six different tea cultivars. However, the original source of data was not available.

Many studies have been conducted on thin layer drying characteristics of different food materials (Madamba *et al*., 1996; Panchariya *et al*., 2002) and different mathematical models have been used to describe thin layer drying data for different temperature ranges. These mathematical models can be categorized as theoretical, empirical and semi-empirical. Computational procedures of these models varied from simple to complex.

The objective of this study was to quantify the rate of moisture transfer of fresh tea leaves in the temperature range of withering operation carried out based on thin layer drying data. The experimental data were fitted into five different mathematical models which were available in the literature. Using the best-fit mathematical model, a relationship was developed between the drying coefficient of fresh tea leaves, air

---

[*] Corresponding author (wsbotheju@yahoo.com)

[**] Part of this paper was presented at the 2nd Plantation Crop Research Symposium held from 16-17 October, 2008 at the Bandaranaika Memorial International Conference Hall (BMICH), Colombo.

temperature and relative humidity (RH). The moisture diffusivity and activation energy of fresh tea leaves were also determined.

METHODS AND MATERIALS

Moisture desorption of leaves of tea cultivar TRI 2025 free from surface water was measured by a dynamic ventilator method. Air temperatures of 20, 25, 30 and 35 °C and relative humidities of 40, 50, 60 and 90 % were achieved using a constant climatic chamber (model TMC 185/CRP-15, Teacraft, UK). These temperature and RH ranges covered the withering conditions in a tea factory. In practical situations, during dry periods in up country area, the RH drops well below 50% (dry and wet bulb difference is about 12 – 14 °F with dry bulb around 90 °F). On wet days it increases up to about 90%. Therefore the two maximum possible extremes were considered in this study. The instrument is set at predetermined dry and wet bulb temperatures with an accuracy of ± 0.1 °C to obtain required RH (Table 1). The instrument was allowed to run empty for about 3 h to become stable, after setting dry and wet bulb temperatures.

As shown in Figure 1, 50 g leaf sample thinly spread on the tray was hung at the bottom of the electronic balance (Denver S-203) with an accuracy of ± 0.001 g. A balance was connected to the computer *via* RS-232 serial cable to log the weights of leaf sample at constant time intervals. Readings were taken until the weight of sample reached a constant value. The dry weight of the resulting sample was determined by drying in an air oven at 103 °C for 6 h. The constant airflow rate of 1.2 ± 0.3 m/s was maintained in the chamber throughout the sorption period. The experiment was carried out in duplicate for the temperature and RH ranges studied.

Determination of drying coefficient in the desorption process: Moisture ratio (MR) versus drying time was fitted to five mathematical equations (Table 2). MR represents $(M - M_e)/(M_o - M_e)$; where M_o and M are denoted as moisture contents at the beginning and at a given time during withering, respectively. A non-linear regression programme (NLREG, Phillip H. Sherrod 6430 Annandale Cove, Brentwood, USA) was employed to fit experimental data into the five mathematical models.

The equilibrium moisture content (M_e) of fresh tea leaves at a given temperature and RH were calculated using the modified Oswin equation (Botheju *et al.*, 2008).

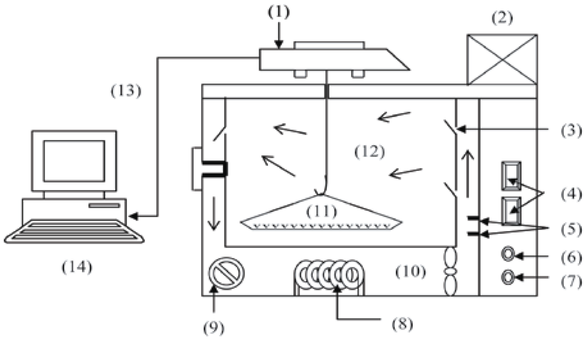
Table 1: Relative humidity of air corresponding to different dry and wet bulb temperatures

Temperature (°C)		Relative
Dry bulb	Wet bulb	humidity (%)
20	18.9	90
25	16.3	40
25	17.9	50
25	19.6	60
25	23.8	90
30	22.6	50
30	23.9	60
30	28.6	90
35	23.9	40
35	28.3	60
35	33.5	90

Table 2: Mathematical models given by various authors for thin layer drying of materials

Model no.	Model name	Equation
(1)	Lewis	$MR = \exp(-kt)$
(2)	Henderson & Pabis	$MR = a.\exp(-kt)$
(3)	Logarithmic	$MR = a.\exp(-kt) + c$
(4)	Page	$MR = \exp(-kt^n)$
(5)	Two term model	$MR = a.\exp(-k_o t) + b.\exp(-k_1 t)$

Where k, k_o and k_1 are drying coefficients; a, b, c and n are constants and t is time



(1) Electronic balance
(2) Compressor
(3) Conditioned air inlet
(4) Dry and wet bulb temperature display
(5) Dry and wet bulb temperature probes
(6) Timer
(7) Thermostat
(8) Heating element
(9) Freezer unit
(10) Fan
(11) Thin layer of leaves
(12) Chamber area
(13) RS-232 serial cable
(14) Computer

Figure 1: Schematic diagram of the constant climatic chamber used for dynamic desorption of tea leaves

$$M_e = \left(55.4994 - 0.1272T\right)\left[\frac{a_w}{1-a_w}\right]^{0.2275} \qquad ...(1)$$

where T is temperature (K) and a_w is water activity (decimal).

Analysis of data: Four statistical parameters *viz*. standard error of estimate (SEE) in equation (3), mean relative deviation percentage (P) in equation (2), coefficient of determination (R^2) and the residual plots were used in the selection of the best-fit equation.

$$P = \frac{100}{N}\sum\frac{|Y - Y'|}{Y} \qquad ...(2)$$

$$SEE = \sqrt{\frac{\sum(Y - Y')^2}{df}} \qquad ...(3)$$

where Y is the experimental data; Y' is the value predicted by the model; N is the number of data points; if residual plot indicates a clear pattern, the model is not accepted (Weisberg, 1986).

An Arrhenius type relationship was developed between drying coefficient (k) of tea leaves and temperature and RH of air studied.

Calculation of effective diffusivity and activation energy: The drying characteristics of biological products in falling rate period can be described by using Fick's diffusion equation. The solution to this equation developed by Crank (1975) can be used for various regularly shaped bodies. The equation (4) given below can be applicable for food materials with slab geometry by assuming uniform initial moisture distribution.

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff} t}{4L_0^2}\right) \qquad ...(4)$$

where D_{eff} is the effective diffusivity (m^2/s) and L_0 is the half thickness of slab (m). For long drying period, equation (4) can be further simplified to only the first term of series (Tutuncu & Labuza, 1996) and the logarithmic form can be given as follows (equation 5), which has similar form proposed by Henderson & Pabis (1961).

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}\, t}{4L_0^2} \qquad ...(5)$$

Diffusivities are determined by plotting experimental drying data in terms of ln *MR* versus drying time (*t*) in equation (5). The slope of the straight line gives;

$$Slope = -\frac{\pi^2 D_{eff}}{4L_0^2} \qquad ...(6)$$

The temperature dependency of effective diffusivity is described by an Arrhenius type relationship (Madamba, *et al*., 1996; Akgun & Doymaz, 2005) as follows;

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \qquad ...(7)$$

where D_0 is a constant equivalent to indefinitely high temperature and E_a is the activation energy.

RESULTS AND DISCUSSION

TRI 2025, a common cultivar in tea estates in Sri Lanka, was selected to study thin layer drying properties of fresh tea leaves. Eleven combinations of temperature and relative humidity (Table 1) were studied using a constant climatic chamber. Initial moisture content of leaf samples varied between 75 – 80 % (w.b.). Equilibrium moisture contents (M_e) at selected temperature and RH were calculated using equation (1).

Moisture ratios (MR) verses drying time for tea leaves for eight combinations of temperature and RH are shown in Figure 2. It indicates that increasing air temperature or decreasing RH speeds up the drying/withering process and thus shortens the withering time. Similar results were obtained for dehydration of apple (Vergara *et al*., 1997), drying of kiwifruit and apple pomace (Fenton & Kennedy, 1998) etc.

The plots of drying rate verses drying time and the drying rate verses moisture content are shown in Figures 3 and 4 (six combinations were considered to avoid congestion) respectively. Figure 3 indicates that no constant rate period is observed in the withering process of tea leaves. Withering process takes place in a falling rate period and the rate of moisture removal is faster at the beginning than that at the end (Figure 4). This observation is in agreement with results on withering experiments carried out by Ghodake *et al*. (2006). Two falling rate periods could be observed in the tea withering process (Figure 4). The first falling rate period occurred when the moisture content of tea leaves was above 72 % (w.b.) or 260 % (d.b.), while the other was observed below 260 %.(d.b.).

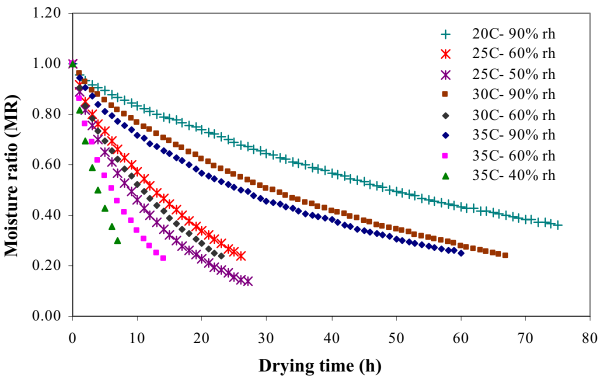


Figure 2: Thin layer drying curves of tea leaves at different temperatures and relative humidity levels

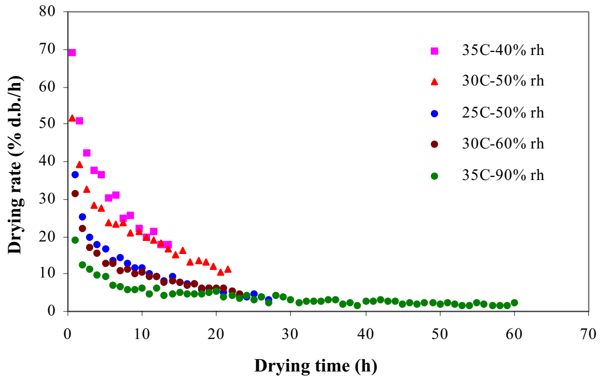


Figure 3: Drying rate versus drying time of tea leaves at different temperatures and relative humidity levels

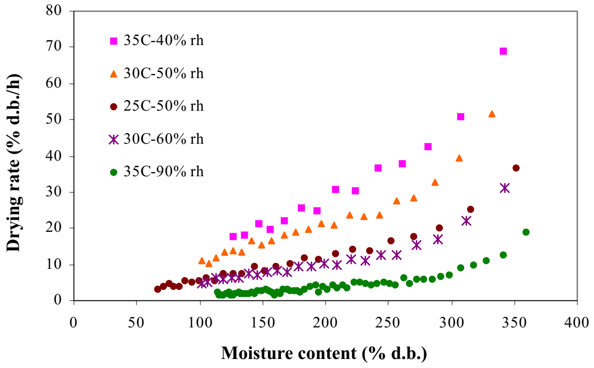


Figure 4: Drying rate versus moisture content of tea leaves at different temperatures and relative humidity levels

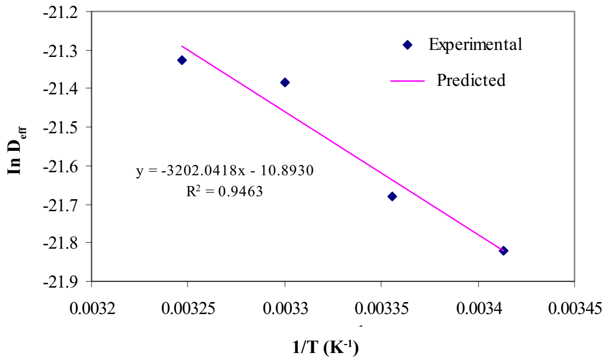


Figure 5: The relationship between ln D_{eff} and 1/T of drying

The colloidal and hyperbolic nature of food materials causes the water molecules to be tightly bound to the material (Mazza & Le Maguer, 1980). Hence, the drying of almost all biological products takes place in the falling rate period. A constant rate period was observed before the falling rate in the study done by Jayaratnam and Abdul Gaffar (1979) for drying tea leaves of six different cultivars. Until the free surface water was removed from tea leaves, a constant rate period was observed in their drying curve.

Temple *et al*. (2000) reported that a single falling rate period was enough to describe the whole process of tea. However, using some industrial equipment a constant rate period could be observed due to limited evaporative capacity of the air. In such cases, constant rate period was a property of air supply rather than a drying property of the material.

Modelling thin layer drying of tea leaves

The curve of MR versus drying time (Figure 2) at different temperature and RH values was fitted to five mathematical models. Non-linear regression programme (NLREG) was performed to analyze the data. R^2, SEE, P and residual plots were employed to evaluate the best-fit model and the calculated coefficients of each model are presented in Table 3.

R^2 obtained for all five models were greater than 0.99. However, Page and Two-term models gave consistently higher R^2 than the other three models. SEE and P calculated for Two-term model gave comparatively very low values than others. Moreover, when the residual plots for all model equations were compared, the Two-term model characterized a random distribution for all treatments except the graph drawn for 35 °C and 60 % RH.

Table 3: Drying curve parameters for five models and the curve fitting criteria for each model for withering of tea leaves

Model	T°C	RH%	Constants				R^2	SEE	P	R/Plot
Lewis	20	90	k = 0.0002				0.9987	0.0179	2.0593	Pattern
	25	40	k = 0.0014				0.9981	0.0181	2.8486	Pattern
	25	50	k = 0.0013				0.9984	0.0186	4.0216	Pattern
	25	60	k = 0.0009				0.9974	0.0195	2.4583	Pattern
	5	90	k = 0.0003				0.9979	0.0151	2.0526	Pattern
	30	60	k = 0.0011				0.9970	0.0207	3.1426	Pattern
	30	90	k = 0.0004				0.9987	0.0196	3.3193	Pattern
	35	40	k = 0.0029				0.9988	0.0120	1.5264	Pattern
	35	60	k = 0.0019				0.9982	0.0196	3.5677	Pattern
	35	90	k = 0.0004				0.9955	0.0345	6.2345	Pattern
Hen & Pabis	20	90	k = 0.0002		a = 0.9576		0.9986	0.0057	0.3842	Random
	25	40	k = 0.0013		a = 0.9608		0.9976	0.0103	1.2525	Pattern
	25	50	k = 0.0012		a = 0.9555		0.9980	0.0106	1.4896	Pattern
	25	60	k = 0.0009		a = 0.9582		0.9974	0.0112	1.1769	Pattern
	25	90	k = 0.0003		a = 0.9683		0.9978	0.0086	1.2254	Random
	30	60	k = 0.0010		a = 0.9530		0.9965	0.0120	1.0755	Random
	30	90	k = 0.0003		a = 0.9544		0.9982	0.0086	1.1713	Random
	35	40	k = 0.0028		a = 0.9791		0.9987	0.0081	0.8630	Random
	35	60	k = 0.0018		a = 0.9581		0.9975	0.0114	1.6978	Pattern
	35	90	k = 0.0004		a = 0.9195		0.9932	0.0166	2.5324	Pattern
Logarit	20	90	k = 0.0002		a = 0.9281	c = 0.0321	0.9987	0.0056	0.3929	Random
	25	40	k = 0.0015		a = 0.8779	c = 0.0959	0.9986	0.0076	0.9813	Random
	25	50	k = 0.0013		a = 0.9300	c = 0.0350	0.9984	0.0096	1.6188	Pattern
	25	60	k = 0.0009		a = 0.9397	c = 0.0214	0.9984	0.0114	1.3594	Pattern
	25	90	k = 0.0003		a = 0.9134	c = 0.0609	0.9980	0.0082	1.0813	Random
	30	60	k = 0.0012		a = 0.8945	c = 0.0694	0.9972	0.0112	1.5851	Random
	30	90	k = 0.0004		a = 0.8948	c = 0.0719	0.9989	0.0068	0.9857	Random
	35	40	k = 0.0031		a = 0.9350	c = 0.0491	0.9989	0.0077	1.0286	Pattern
	35	60	k = 0.0021		a = 0.8885	c = 0.0857	0.9988	0.0078	1.2036	Pattern
	35	90	k = 0.0005		a = 0.8058	c = 0.1422	0.9973	0.0104	1.3871	Pattern
Page	20	90	k = 0.0006		n = 0.8782		0.9975	0.0086	1.0656	Pattern
	25	40	k = 0.0029		n = 0.8783		0.9994	0.0043	0.7164	Random
	25	50	k = 0.0026		n = 0.8940		0.9991	0.0069	1.7905	Pattern
	25	60	k = 0.0020		n = 0.8895		0.9976	0.0111	1.9684	Pattern
	25	90	k = 0.0006		n = 0.9045		0.9979	0.0084	1.1221	Random
	30	60	k = 0.0026		n = 0.8657		0.9985	0.0086	1.7201	Random
	30	90	k = 0.0009		n = 0.8794		0.9994	0.0057	0.9340	Random
	35	40	k = 0.0044		n = 0.9259		0.9994	0.0057	0.9420	Random
	35	60	k = 0.0039		n = 0.8782		0.9998	0.0035	0.7031	Random
	35	90	k = 0.0021		n = 0.7887		0.9994	0.0051	0.8962	Random
Two term	20	90	k_o = 0.0002	k_1 = 0.0002	a = 0.9788	b = 0.0788	0.9986	0.0058	0.3842	Random
	25	40	k_o = 0.0012	k_1 = 0.0168	a = 0.9327	b = 0.0673	0.9998	0.0023	0.3574	Random
	25	50	k_o = 0.0012	k_1 = 0.0195	a = 0.9279	b = 0.0726	0.9999	0.0017	0.4175	Random
	25	60	k_o = 0.0008	k_1 = 0.0248	a = 0.9403	b = 0.0601	0.9994	0.0057	1.0517	Random
	25	90	k_o = 0.0003	k_1 = 0.0073	a = 0.9587	b = 0.0418	0.9986	0.0068	0.9960	Random
	30	60	k_o = 0.0010	k_1 = 0.0184	a = 0.9245	b = 0.0759	0.9997	0.0037	0.7124	Random
	30	90	k_o = 0.0003	k_1 = 0.0045	a = 0.9300	b = 0.0662	0.9998	0.0027	0.5085	Random
	35	40	k_o = 0.0027	k_1 = 0.0594	a = 0.9630	b = 0.0371	0.9998	0.0032	0.5189	Random
	35	60	k_o = 0.0018	k_1 = 0.0018	a = 0.9791	b = 0.0791	0.9975	0.0119	1.6978	Pattern
	35	90	k_o = 0.0003	k_1 = 0.0041	a = 0.8652	b = 0.1274	0.9997	0.0037	0.6169	Random

When comparing all statistical parameters Two-term model fitted well with the experimental data than the other four models. Therefore, Two-term model was selected as the best-fit mathematical equation to explain the experimental desorption data of fresh tea leaves.

Regression analysis was used to find the relationship between withering temperature, RH as against drying coefficients k_o and k_1 (min^{-1}) of Two-term model. Thus the drying coefficients k_o, k_1 against temperature and RH can be expressed as an Arrhenius type relationship. A similar type of relationship has been developed for deep bed rice drying (Murata *et al*., 1996).

$$k_o = \exp\left(\frac{l_1h^3 + l_2h^2 + l_3h + l_4}{T} + l_5\right) \qquad ...(8)$$

l_1 = 17348.8243 $R^2 = 0.981$ SEE = 0.1422×10^{-3}
l_2 = -34192.6303
l_3 = 20236.1163
l_4 = -10548.7579
l_5 = 16.2159

$$k_1 = \exp\left(\frac{m_1h^3 + m_2h^2 + m_3h + m_4}{T} + m_5\right) \qquad ...(9)$$

m_1 = 3088.9199 $R^2 = 0.990$ SEE = 0.2234×10^{-2}
m_2 = -7028.6863
m_3 = 3744.3320
m_4 = -8633.3896
m_5 = 23.3388

Table 4: Effective diffusivities of fresh tea leaves at different temperatures

Temperature (°C)	Average effective diffusivities (× 10^{-10} m^2/s)
20	3.3409
25	3.8471
30	5.1632
35	5.4669

where *h* and *T* are relative humidity (decimal) and temperature (Kelvin) respectively.

The constants 'a' and 'b' did not show any significant variation for the range of temperature and RH (Table 3) studied. Therefore, the average values of 'a' and 'b' were considered. The final Two-term model can be expressed as follows.

$$MR = 0.9462\exp(-k_ot) + 0.0691\exp(-k_1t) \qquad ...(10)$$

Determination of effective diffusivities and activation energy

The results have shown that internal mass transfer resistance controls the drying time due to presence of the falling rate period. The values of effective diffusivity (D_{eff}) at different temperatures could be obtained by using equations (5) and (6). The average values of effective diffusivities of tea leaves in the desorption process at 20 – 35 °C varied in the range of 3.3409 – 5.4669 × 10^{-10} m^2/s (Table 4). The effective diffusivity increases exponentially with the increase of air temperature. These results are in agreement with the previous investigations within the general range of 10^{-9} to 10^{-11} m^2/s for food materials (Botheju *et al*., 2008).

A linear relationship was derived from the equation (7) and natural logarithmic of D_{eff} was plotted as against 1/T (Figure 5). The energy of activation (E_a) for water diffusion of tea leaves calculated from the slope of the straight line was found to be 1477.75 kJ / kg, which was in the range of drying onion 1200 kJ/kg (Mazza & Le Maguer, 1980), rice 1183 kJ/kg (Pinaga *et al*., 1984) and paprika 2036 kJ/kg (Carbonell *et al*., 1986). The activation energy barrier must be overcome to activate moisture diffusion. To increase drying rates by increasing moisture diffusion, use of high temperatures would be beneficial but it is advisable to use optimum temperatures (Ranatunga *et al*., 1986; Keegal, 1965) to maintain the quality of tea leaves during withering.

References

1. Akgun N.A. & Doymaz I. (2005). Modeling of olive cake thin layer drying process. *Journal of Food Engineering* **68**(4): 455 – 461.
2. Botheju W.S., Amaratunge K.S.P. & Abeysinghe I.S.B. (2008). Modeling desorption isotherms of fresh tea leaves. *Proceedings of the National Symposium,* 23-24 October, Faculty of Agriculture, University of Ruhuna, pp. 136.
3. Carbonell J.V., Pinaga F., Yusa V. & Pena J.L. (1986). Dehydration of paprika and kinetics of colour degradation. *Journal of Food Technology* **5**(3): 179 – 193.
4. Crank J. (1975). *The Mathematics of Diffusion*. Oxford University Press, London, UK.
5. Fenton G.A. & Kennedy M.J. (1998). Rapid dry weight determination of kiwifruit pomace and apple pomace using an infrared drying technique. *New Zealand Journal of Crop and Horticulture Science* **26**(1): 35-38.
6. Ghodake H.M., Goswami T.K. & Chakraverty A. (2006). Mathematical modeling of withering characteristics of tea leaves. *Drying Technology* **24**(2): 159-164.
7. Jayaratnam S. & Abdul Gaffar N.M. (1979). Equilibrium moisture content and withering. *Tea Quarterly* **48**(1 & 2): 21-25.

8. Keegal E.L. (1965). Withering. *Tea Manufacture in Ceylon. Monographs on Tea Production in Ceylon* (eds. E.L Keegal), 2nd edition, pp. 28-41. Tea Research Institute of Sri Lanka, St. Coombs Estate, Talawakelle.
9. Madamba P.S., Driscoll R.H. & Buckle K.A. (1996). The thin-layer drying characteristics of garlic slices. *Journal of Food Engineering* **29**(1): 75-87.
10. Mazza G. & Le Maguer M. (1980). Dehydration of onions: some theoretical and practical considerations. *Journal of Food Technology* **15**(1): 191-194.
11. Murata S., Amaratunga K.S.P., Tanaka F., Shibuya K. & Koide S. (1996). Simulation of moisture adsorption by polished rice in deep-bed. *Food Science & Technology International Tokyo* **2**(2): 86-91.
12. Pinaga F., Carbonell J.V., Pena J.L. & Miguel J.J. (1984). Experimental simulation of solar drying of garlic using an absorbent energy storage bed. *Journal of Food Technology* **3**(3): 187 - 203.
13. Panchariya P.C., Popovic D. & Sharma A.L. (2002). Modeling of black tea drying process. *Journal of Food Engineering* **52**(4): 349-357.
14. Ranatunga D.B.J., Boęrje K. & Senanayake G. (1986). Energy needs of tea manufacture. *Transactions* **1**(1): 30-51.
15. Samaraweera D.S.A. (1986). Technology of tea processing. *Handbook on Tea* (eds. P. Sivapalan, S. Kulasegaram & A. Kathiravetpillai), pp. 158-207. Tea Resesearch Institute of Sri Lanka, St. Coombs Estate, Talawakelle.
16. Temple S.J., Tambala S.T. & van Boxtel A.J.B. (2000). Monitoring and control of fluid-bed drying of tea. *Control Engineering Practice* **8**(1): 165-173.
17. Tutuncu M.A. & Labuza T.P. (1996). Effect of geometry on the effective moisture transfer diffusion coefficient. *Journal of Food Engineering* **30**(4): 433-447.
18. Vergara F., Amezaga E., Barcenas M.E. & Welti J. (1997). Analysis of the drying processes of osmotically dehydrated apple using the characteristic curve model. *Drying Technology* **15**(3&4): 949-963.
19. Weisberg S. (1986). *Applied Linear Regression*, 2nd edition, pp. 132. John Willey & Sons, New York, USA.