Drying characteristics of Orthodox broken type tea

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Abstract- Drying characteristic of Orthodox broken type tea was examined using a laboratory-scale fluid bed tea dryer. Drying experiments were carried out at loading of 29 kg/m^2 and moisture content of tea was reduced from 106% to 7% on dry basis. Hot air temperature was varied in the range of 108 - 127 °C as applicable for industrial type tea dryers. Semi-theoretical thin-layer drying models of Lewis, Henderson and Pabis, Logarithmic, Page, Modified Page and Two-term exponential model were tested. Page model gave better predictions than other models, and satisfactorily described drying characteristics of Orthodox broken type tea. Results suggested that internal mass transfer resistance has fully controlled the drying process after 4 minutes of drying. The effective diffusivity of water in tea during latter stage of drying was found to be 3.796 x 10^{-11} (m/s) and 5.062 x 10^{-11} (m/s) at hot air temperatures in the range of 108–121 °C and 124–127°C respectively. An empirical model was proposed to describe the variation of moisture content with tea-bed temperature and the predicted values were in close agreement with the measured data. The bulk density of the tea bed was found to increase with time and that might have reduced the channeling effect during latter stages of drying.

Index Terms- effective diffusivity, fluidized tea-bed, drying models, drying rate.

1. INTRODUCTION

Orthodox broken type tea is a special type of tea produced in 180 tea factories in Sri Lanka and exported mainly to Europe and Japan. Drying is important in tea manufacturing for partly to obtain the tea character and also to retain the tea character already achieved through early stages of the manufacturing process. Continuous type fluid bed tea dryers (FBD) are found to contribute effectively in this context.

Notable changes to tea manufacturing process was taken place in late nineties with the increased demand for Broken Orange Pekoe Fannings (BOPF) grade and as a result presently tea is manufactured with high percentage (more than 95%) of smaller size tea particles of less than 1 mm in size (Raveendran, et al, 2012). Consequently the effectiveness of the available fluid bed tea dryers became questionable. At present, many factories are experiencing difficulties in obtaining fluidization of tea with co-existence of continuous phase and bubble phase. Consequently, time to discharge from the dryer is affected and tea often get under-fired or over-fired and fine tea particles are carried over by the fluid stream leading to increased losses. Therefore, it is an essential requirement to study drying characteristics of Orthodox broken type tea with a view to improve fluidized bed drying.

In the past many theoretical, semi-theoretical and empirical models were developed for thin-layer drying of various foods and agro-based products. Theoretical models based on Fick's second law (Eq. [1]) takes into account only the internal resistance to moisture transfer. Therefore, this model is only useful in predicting the drying behaviour of regularly shaped food products such as hazelnuts (Demirtas et al, 1998) and rapeseed (Crisp & Woods, 1994).

$$\frac{\partial M}{\partial t} = D\nabla^2 M. \qquad [1]$$

Semi-theoretical models are generally derived by simplifying general series solutions of Fick's second law or modification of simplified models. Lewis model (Eq. [2]), Henderson and Pabis model (Eq. [3]), Logarithmic model (Eq. [4]), Page model (Eq. [5]), modified Page model (Eq. [6]) and Two-term exponential model (Eq. [7]) are the widely used semi-theoretical thin-layer drying models (Botheju et al, 2011, Panchariya et al, 2002).

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t) \qquad [2]$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) \qquad [3]$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) + C \qquad [4]$$

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t^n) \qquad [5]$$

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t)^n \qquad [6]$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) + A_1 \exp(-k_1 t) \qquad [7]$$

Where MR is the moisture ratio; M is the average moisture content in percentage (w/w, dry basis) at drying time t; M_o is the initial moisture content in percentage (w/w, dry basis); M_e is the equilibrium moisture content in percentage (w/w, dry basis); A_o, k_o, A_1, k_1 and n are the empirical coefficients.

Botheju et al. (2011) performed a regression analysis for various semi-theoretical models on their single layer drying data and suggested the Two-term model (Eq. [7]) as the most appropriate for drying fresh tea leaves. In several other studies the semi-theoretical thin-layer drying models were successfully used to describe the drying phenomenon of many products such as apple pomace (Zhengfu Wang et al, 2007), rough rice with high moisture content (Chiachung Chen & Po-Ching Wu.,2001), pistachio nuts (Kashaninejad et al, 2007), chicory root slices (Lee et al, 2004), garlic slices (Ponciano et al, 1996), pre-dried young coconut (Ponciano, 2003) and quercus (Tahmasebi et al, 2011). In tea manufacturing, due to severe maceration on leaf, a large number of cells are ruptured, cell sap has been mixed and there is a good accessibility for gas exchange within the particles of leaf (Temple & Van Boxtel, 1999a). Therefore, evaporation of water enhances due to increased surface area resulting in reducing the role of diffusion within the particle relative to the surface and air boundary layer resistance. Temple & Van Boxtel (1999b) studied drying rate kinetics of “Cutting, Tearing and Curling” tea (CTC tea) considering Lewis model with an assumption that the resistance for water vapour transport is all over the surface of the particle. They varied the drying temperature between 50 and 150°C. Panchariya et al, (2002) studied thin-layer drying characteristics of CTC tea produced in India at drying air temperatures in the range of 80–120°C. They found that drying is dominated in the falling rate period and Lewis model gave better predictions for CTC tea compared to other widely used semi-theoretical thin-layer drying models. The objective of the present study is to establish the drying characteristics of Orthodox broken type tea and to identify suitable drying model for describing its drying behaviour.

2. MATERIALS AND METHODS

2.1 EXPERIMENTAL APPARATUS

2.1.1 LABORATORY-SCALE FLUID BED TEA DRYER

Tea samples were dried using a laboratory-scale fluid bed tea dryer unit (Teacraft, UK). The unit was fixed with a cylindrical loading vessel (diameter 10cm and height 48cm) fabricated with transparent material (Figure 1). The loading vessel was covered using a lid fitted with nylon net to avoid entrainment of tea particles. Temperature was controlled by a PID controller with an accuracy of ± 1 °C. Inlet hot air temperature could be varied between 100 and 150 °C. Fluidization of tea with co-existence of continuous phase and bubble phase was obtained in the unit by changing air flow rate.

2.1.2 ECM (ENVIRONMENTALLY CONTROLLED MANUFACTURE) UNIT

The ECM Unit (model TMC 185/CRP-15, Teacraft, UK) consists of a purpose built environmentally controlled chamber with extremely tight control over temperature and humidity (controlled to ± 0.1 °C and ± 0.1% RH). The chamber incorporates a sealed refrigeration unit, modulated electric heating and a water vaporizing system coupled with a programmable control unit that can maintain the required set conditions of 15 –25 °C and up to 98% RH. The ECM unit (Figure 2) was used to keep tea samples without losing its moisture content.

Figure 1 : Fluid bed tea dryer

Figure 2 : ECM unit

2.2 EXPERIMENTAL MATERIAL

Partly fermented tea samples with a moisture content of 106 % (w/w, dry basis) were obtained from a typical tea factory and used in this study.

2.3 EXPERIMENTAL PROCEDURE

Generally green tea leaves undergo four series of processes named, withering, rolling, roll-breaking and fermentation before it is dried. Eight kilograms of partly fermented tea were collected and packed in eight separate polythene bags to contain 1 kg each. The polythene bags were then placed in ECM unit after setting both dry and wet bulb temperatures at 20 °C to maintain the same moisture level in tea samples. Initial moisture content was determined by oven drying of 25 g sample at 103 ± 2 °C. Loading of 29 kg/m^2 was selected on the basis of maximum possible loading to obtain fluidization with co-existence of continuous phase and bubble phase for Orthodox broken type tea with modified bedplates in industrial type fluid bed tea dryers (Raveendran et al, 2012). In order to have this loading, the loading vessel of the laboratory-scale fluid bed tea dryer was loaded with 250g of tea sample. The dryer unit was set to deliver hot air at 127 °C and a k-type thermocouple probe was placed in the loading vessel at a height of 7 cm to measure tea-bed temperature. Another thermocouple was placed at a height of 30 cm to measure exhaust temperature. Both the temperature and the moisture content were measured at 1-minute intervals. Experiment was continued until the tea-bed temperature reached 102 - 104 °C at which moisture content in tea reached the final level of 5 - 7% (w/w, dry basis). Moisture content in dried tea was determined by oven drying of 25 g sample at 103 ± 2 °C. The experiment was then repeated for eight different hot air temperatures in the range of 108 – 127 °C. This temperature range includes hot air temperature of 124 – 127 °C that is being practiced in fluid bed tea dryers in tea factories at present.

2.4 DATA ANALYSIS

Drying data were fitted to different semi-theoretical thin-layer drying models (Eq. [2] to [7]). Non-linear regression analysis was used to estimate the empirical constants of all the models starting with a set of initial values estimated from the corresponding linearized form. Several criteria for adequacy of fit such as correlation coefficient (R^2), root mean square error (RMSE, Eq. [8]) and reduced chi-square (x^2, Eq. [9]) were used to select appropriate model for Orthodox broken type tea. The model with the least root mean square and reduced chi-square and the highest coefficient of correlation was selected as the best fit.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{Pr}\,e,i}\right)^2\right]^{\frac{1}{2}} \qquad [8]$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N - m} \qquad [9]$$

3. RESULTS AND DISCUSSION

Variation of moisture content with drying time and the drying rate versus drying time for fermented tea dried at different hot air temperatures are shown in Figures 3 and 4 respectively. Drying rate was calculated as the amount of moisture evaporated per kg of dry tea within a unit time of 1 minute. Even though the drying experiments were performed for eight different hot air temperatures, the results of only four hot air temperatures, (108, 116, 124 & 127 ^{0}C) are shown in Figures for clarity.

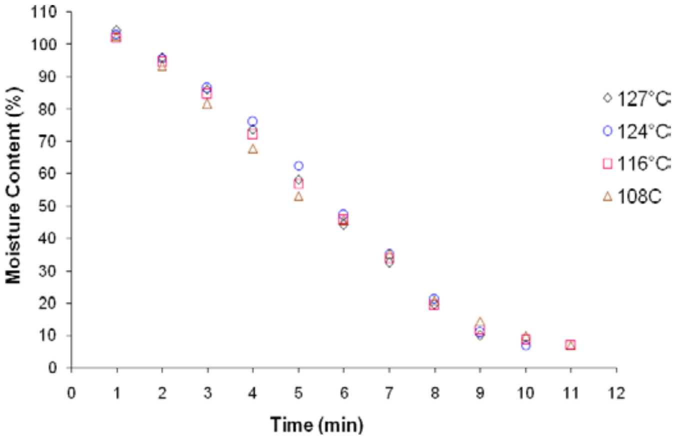

Figure 3 : Variation of moisture content with drying time

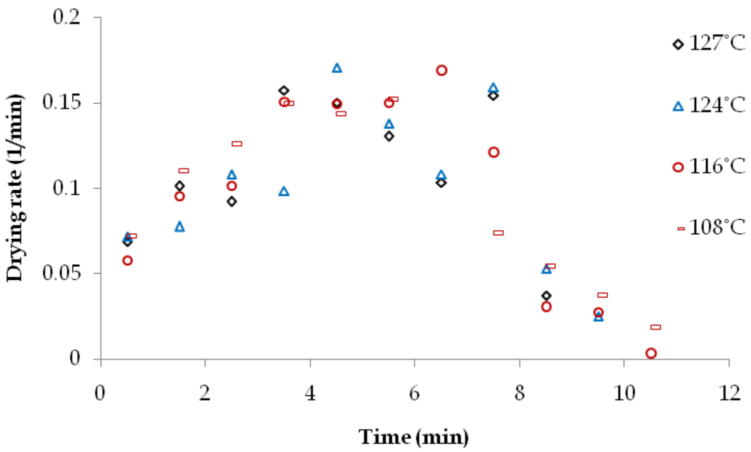

Figure 4 : Drying rate versus drying time

Variation of drying rate with time was very similar in nature for all different hot air temperatures examined in the present study. The initial drying rate was low due to the presence of sticky tea particles with high moisture content that prevented intensive mixing with hot air. The notable increase in drying rate at the beginning (as depicted in Figure 4) may be attributed to removal of surface moisture with time. The presence of surface moisture is also confirmed with the observation of marginal increase in tea-bed temperature (as shown in Figure 5) during first 4 minutes of drying. Figure 6 shows constant rate and falling rate periods after the period of increasing drying rate. Therefore it further confirms that surface moisture was available in tea when the moisture content was above 60% (w/w dry basis). A final moisture level in tea of 5 - 7% (w/w dry basis) was achieved within a short period of 10 - 11 minutes

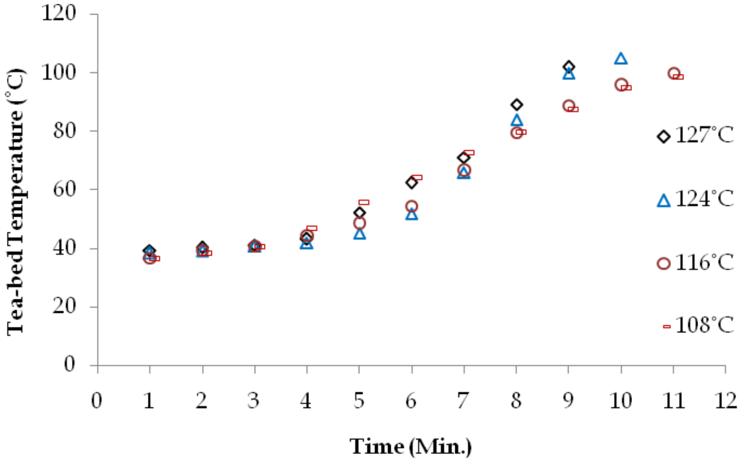

Figure 5: Tea-bed temperature versus drying time

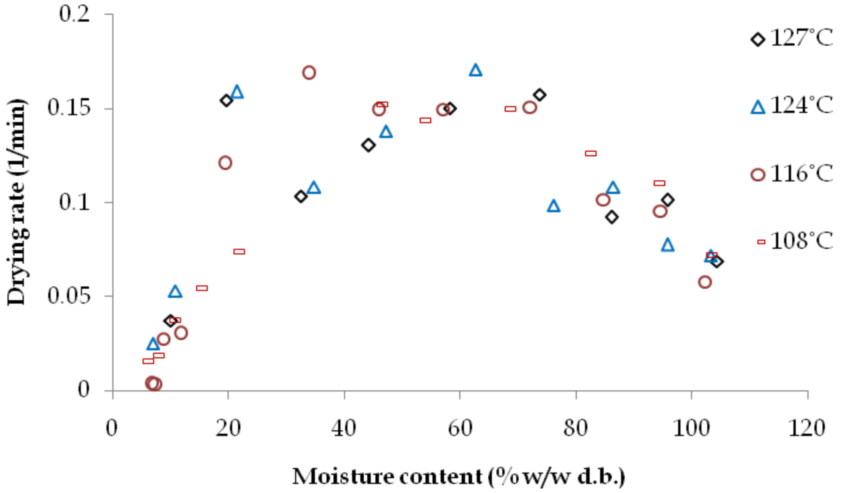

Figure 6 : Drying rate versus moisture content of tea

A typical characteristic drying curve (moisture ratio vs. time) for orthodox broken type tea is shown in Figure 7. Equilibrium moisture content was taken as zero in the calculation of moisture ratios for hot air temperatures over 100 °C as explained by Temple & van Boxtel (1999). Drying data were fitted to six different semi-theoretical thin-layer drying models (Eq. [2] to [7]). The results of the analysis in evaluating the models based on correlation coefficient (R^2), root mean square error (RMSE) and reduced chi-square (x^2) are presented in Table 1. Results indicate that semi-theoretical thin-layer drying models under investigation were in good correlation with the experimental data and Page model gave the best fit with a correlation coefficient above 0.99 for all the hot air temperatures. The RMSE and x^2 values were less than 0.0319 and 1.02×10^{-3} respectively. Since the semi-theoretical thin-layer models under investigation were derived using Fick's Law as the basis, internal resistance to moisture transfer was considered to be dominant.

Table 1 : Results of analysis in evaluating different thin-layer drying models

Model	T (°C)	Constants				R^2	RMSE	χ^2
Lewis	127	$k_o = 0.16628$				0.9652	0.1150	1.32x10^{-2}
	126	$k_o = 0.16477$				0.9713	0.1024	1.05x10^{-2}
	124	$k_o = 0.16389$				0.9582	0.1246	1.55x10^{-2}
	121	$k_o = 0.14346$				0.9661	0.1192	1.42x10^{-2}
	118	$k_o = 0.14729$				0.9605	0.1195	1.43x10^{-2}
	116	$k_o = 0.17045$				0.9734	0.1122	1.26x10^{-2}
	112	$k_o = 0.18171$				0.9881	0.0819	6.70x10^{-3}
	108	$k_o = 0.17481$				0.9796	0.0936	8.76x10^{-3}
Henderson and Pabis	127	$k_o = 0.21933$	$A_o = 1.27694$			0.9431	0.0835	6.97x10^{-3}
	126	$k_o = 0.20995$	$A_o = 1.24768$			0.9523	0.0751	5.63x10^{-3}
	124	$k_o = 0.21557$	$A_o = 1.29172$			0.9336	0.0941	8.85x10^{-3}
	121	$k_o = 0.18922$	$A_o = 1.28546$			0.9435	0.0848	7.19x10^{-3}
	118	$k_o = 0.19193$	$A_o = 1.27551$			0.9377	0.0891	7.94x10^{-3}
	116	$k_o = 0.22299$	$A_o = 1.30227$			0.9555	0.0765	5.86x10^{-3}
	112	$k_o = 0.22558$	$A_o = 1.23572$			0.9760	0.0527	2.78x10^{-3}
	108	$k_o = 0.22094$	$A_o = 1.25545$			0.9658	0.0637	4.06x10^{-3}
Logarithmic	127	$k_o = 0.02034$	$A_o = 6.25854$	$C = -5.17215$		0.9932	0.0302	9.12X10^{-4}
	126	$k_o = 0.04303$	$A_o = 3.00384$	$C = -1.92960$		0.9947	0.0257	6.60X10^{-4}
	124	$k_o = 0.03875$	$A_o = 3.87471$	$C = -2.77432$		0.9867	0.0432	1.86X10^{-3}
	121	$k_o = 0.03314$	$A_o = 3.58197$	$C = -2.47156$		0.9907	0.0351	1.23X10^{-3}
	118	$k_o = 0.03339$	$A_o = 3.55569$	$C = -2.45584$		0.9871	0.0413	1.71X10^{-3}
	116	$k_o = 0.10366$	$A_o = 1.69816$	$C = -5.39383$		0.9822	0.0492	2.42X10^{-3}
	112	$k_o = 0.12299$	$A_o = 1.47724$	$C = -3.62512$		0.9945	0.0255	6.48X10^{-4}
	108	$k_o = 0.11111$	$A_o = 1.26964$	$C = -4.44513$		0.9872	0.0397	1.58X10^{-3}
Page	127	$k_o = 0.03545$	$n = 1.91457$			0.9947	0.0262	6.86X10^{-4}
	126	$k_o = 0.04408$	$n = 1.75158$			0.9920	0.0307	9.44X10^{-4}
	124	$k_o = 0.02742$	$n = 2.01632$			0.9941	0.0294	8.67X10^{-4}
	121	$k_o = 0.02350$	$n = 1.97246$			0.9971	0.0197	3.88X10^{-4}
	118	$k_o = 0.02394$	$n = 1.98095$			0.9961	0.0239	5.71X10^{-4}
	116	$k_o = 0.03714$	$n = 1.86054$			0.9947	0.0259	6.74X10^{-4}
	112	$k_o = 0.06743$	$n = 1.56911$			0.9977	0.0160	2.57X10^{-4}
	108	$k_o = 0.05665$	$n = 1.63947$			0.9908	0.0319	1.02X10^{-3}
Modified Page	127	$k_o = 0.39644$	$n = 0.39644$			0.9621	0.1161	1.35X10^{-2}
	126	$k_o = 0.39791$	$n = 0.39792$			0.9687	0.1047	1.10X10^{-2}
	124	$k_o = 0.40484$	$n = 0.40485$			0.9582	0.1321	1.75X10^{-2}
	121	$k_o = 0.37874$	$n = 0.37877$			0.9661	0.1257	1.58X10^{-2}
	118	$k_o = 0.38382$	$n = 0.38374$			0.9605	0.1259	1.59X10^{-2}
	116	$k_o = 0.40843$	$n = 0.40842$			0.9710	0.1213	1.47X10^{-2}
	112	$k_o = 0.42203$	$n = 0.42204$			0.9871	0.0864	7.47X10^{-3}
	108	$k_o = 0.41821$	$n = 0.41821$			0.9866	0.0959	9.19X10^{-3}
Two-term exponential	127	$k_o = 0.22084$	$k_1 = 0.21971$	$A_o = 0.66164$	$A_1 = 0.61779$	0.9413	0.1009	1.02x10^{-2}
	126	$k_o = 0.03635$	$k_1 = 0.00865$	$A_o = 4.33212$	$A_1 = -3.25756$	0.9947	0.0277	7.66x10^{-4}
	124	$k_o = 0.00396$	$k_1 = -0.02132$	$A_o = 5.06993$	$A_1 = -4.00522$	0.9929	0.0337	1.14x10^{-3}
	121	$k_o = 0.18912$	$k_1 = 0.18928$	$A_o = 0.64258$	$A_1 = 0.64282$	0.9435	0.0962	9.25x10^{-3}
	118	$k_o = 0.00596$	$k_1 = 0.02918$	$A_o = -3.74482$	$A_1 = 4.84565$	0.9872	0.0441	1.94x10^{-3}
	116	$k_o = 0.22722$	$k_1 = 0.22227$	$A_o = 0.23613$	$A_1 = 1.06684$	0.9554	0.0868	7.53x10^{-3}
	112	$k_o = 0.22500$	$k_1 = 0.22617$	$A_o = 0.62833$	$A_1 = 0.60738$	0.9760	0.0598	3.57x10^{-3}
	108	$k_o = 0.22018$	$k_1 = 0.22132$	$A_o = 0.42365$	$A_1 = 0.83179$	0.9658	0.0722	5.21x10^{-3}

Panchariya et al. (2002) used general series solution of Fick's second law in spherical coordinates as given in Eq. [10] to describe drying of CTC black tea (average diameter of 500 μm). Constant diffusivity and spherical tea particles were the assumptions that he made in the equation where D_{eff} is the effective diffusivity (m^2/s) and R is the radius of the tea particles (m). Orthodox broken type tea produced at present also has particles in the range of 355 to 710 μm. Therefore, Eq. (10) was also examined for describing drying behaviour of Orthodox broken type tea as well.

$$\frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2 D_{eff}\pi^2}{R^2}t\right) \qquad \text{.... [10]}$$

The first term of Eq. [10] is also known as the Henderson and Pabis model. The slope, coefficient k, of this model is related to the effective diffusivity as given in Eq. [11].

$$k = \frac{D_{eff}\pi^2}{R^2} \qquad \text{.... [11]}$$

The effective diffusivity of water was calculated using the slope of Eq. [10] and deduced from the linear regression of ln(MR) versus time as shown in Figure 8. Initially up to 4 minutes, the effective diffusivity varied between 6.327 x 10^{-12} and 2.531 x 10^{-11} m^2/s for all the hot air temperatures. During the final stage of drying, it was 3.796 x 10^{-11} m^2/s at hot air temperatures of 108-121 °C and 5.062 x 10^{-11} m^2/s at hot air temperatures of 124-127 °C. This confirms that interaction between tea particles and hot air is difficult in tea-bed during early stages and then internal mass transfer resistance fully controlled the drying behaviour during the final stages of drying.

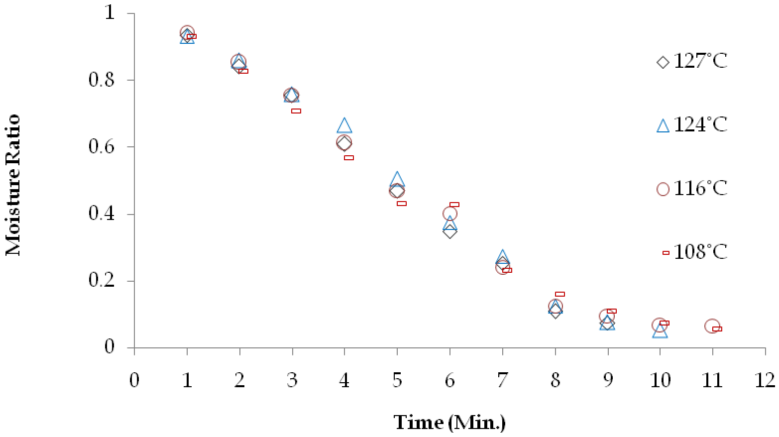

Figure 7 : Variation of moisture ratio with time

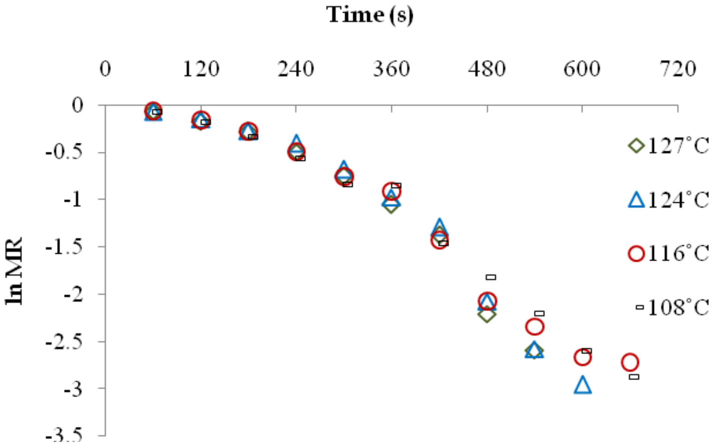

Figure 8 : Experimental logarithmic moisture ratio at different drying time

In industrial type fluid bed tea dryers, tea-bed temperature is monitored as one of the drying parameters to control the drying process. Variation of moisture content with tea-bed temperature was studied for the maximum and minimum hot air temperatures currently in operation with industrial dryers (124 & 116 °C). An empirical equation (Eq. [12]) has been proposed to describe the variation of moisture content with tea-bed temperature. MC is the moisture content and T is Tea-bed temperature. The values of empirical constants a and b are 1.619266 x 10^6 and - 2.322 respectively. The predicted and measured moisture contents are presented in Figures 9 and 10. The predicted values are found to be in close agreement with the measured values with correlation coefficients of 0.987 and 0.996 respectively.

$$MC = (aT^b)/Ln(T) \qquad \text{.... [12]}$$

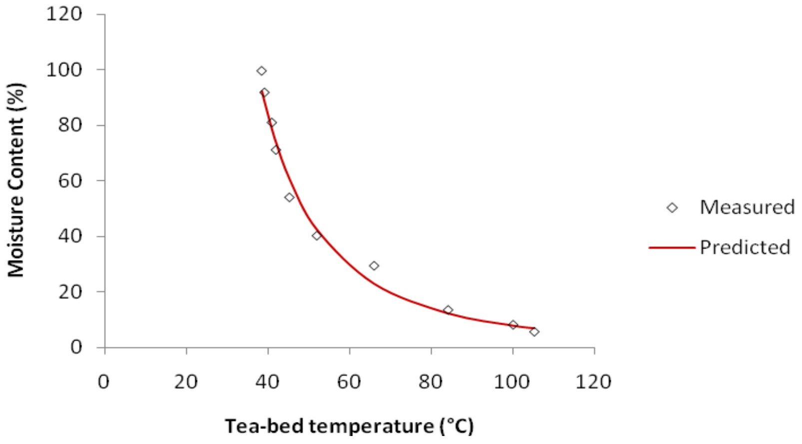

Figure 9 : Measured and predicted moisture content for the hot air temperature of 124 °C

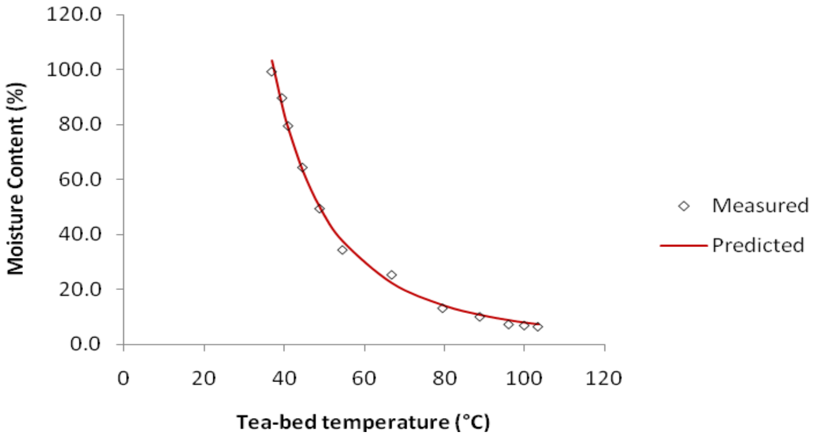

Figure 10 : Measured and predicted moisture content for the hot air temperature of 116 °C

Tea particle shrinks with time as it loses its moisture. As a result the bulk density varies with time. Variation of bulk density with time for tea dried at 124 °C was compared with tea dried at 116 °C as shown in Figure 11. Shrinking rate of tea particles would have been higher at 124 °C compared to that at 116 °C, especially after about 4 minutes of drying when most of the surface moisture is expected to be removed. This might have increased the bulk density during drying at 124 °C. The variation in the bulk density would have influenced fluidizing behaviour of tea and helped reducing channelling effect during final stage of drying.

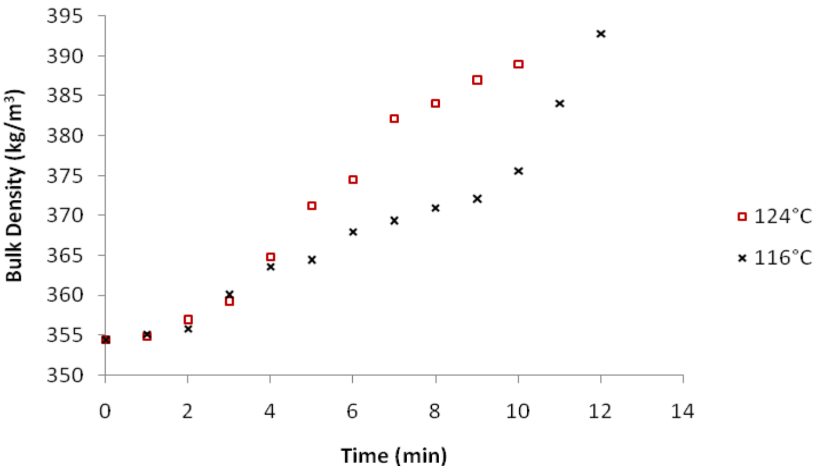

Figure 11 : Variation of bulk density of tea with time during drying

4. CONCLUSIONS

Drying curves for orthodox broken type tea were obtained by using a laboratory scale fluid bed tea dryer. The drying behavior was found to be very similar in the range of hot air temperatures from 108 – 127 °C. However, temperature and bulk density of the tea-bed were changing notably with the increase of hot air temperature after 4 minutes of drying time. Drying rate increased notably with time at initial stages and decreased sharply at final stages of drying to achieve the final moisture content of 5- 7% (w/w, dry basis). A short constant rate period was observed in between. Surface moisture was found to be present in tea with moisture contents above 60% (w/w dry basis). Drying characteristics of orthodox broken type tea was best described by Page thin-layer drying model. Effective diffusivity of water was found to be constant during final stage of drying with the values of 3.796×10^{-11} and 5.062×10^{-11} m^2/s within the range of hot air temperatures 108 – 121 °C and 124 – 127 °C respectively. The variation of moisture content with tea-bed temperature could be successfully predicted by the empirical equation $MC = (aT^b)/Ln(T)$. The bulk density of tea-bed was found to increase with drying time and this might have influenced the reduction of channeling effect in tea-bed during latter stages of drying.

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