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Modeling Moisture Ratio of High Moisture Potato Slices in Forced Convection Multi Tray Solar Dryer

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Abstract— In the work being presented, the performance of an indirect forced convection multi tray solar dryer for drying potato slices has been investigated. Active indirect, thin layer drying experiments were conducted on potato slices kept in multi tray cabinet dryer with PCM (Lauric acid) as energy storage system on 14/3/2014 and 24/3/2014 under Indian climatic conditions. The experimental setup consists of a flat plate solar collector with a blower and a drying cabinet with PCM kept in a chamber. The study was performed in the drying temperature ranging from300.2Kto332K and at 0.4 m/Sec air velocity. Seven common thin layer drying models were fitted to the experimental data and several statistical tools (R^2, RMSE and SSE) were used to evaluate the performance of thin layer drying models. The two term model was the best fit model for describing forced convection drying behavior. Potato slices drying was found to take place during complete "falling drying rate period". These findings are being presented in this paper.

Keywords- solar drying, mathematical modeling, drying kinetics, moisture ratio

I. INTRODUCTION

Drying of food material involves simultaneous heat and mass transfer. The water content of food material is transferred by diffusion from inside of the food material to the air-food interface and from interface to the air stream by convection [1]. The required energy resource for drying purpose may be conventional or non conventional. Among the renewable energy resources solar energy is a free gift of god on the green planet due to its unrestricted accessibility, abundant supply, purity and non polluting in nature [2]. It can be tapped at relatively low cost and has no associated environmental effects [3,4]. Applying solar energy systems due to its relative advantages such as energy saving, generation of new jobs and diminishing the environmental pollutions are remarkable in the many countries of the world. [2] According to [5] the food products are usually dried under the open sun which is a common practice. A number of disadvantages are associated with the natural sun drying process such as degradation due to windblown, rain, insect infestation, rodent's birds, over/under drying etc. This is observed that open Sun dried food products are most often of low quality as a result of unpredictable sun shine, slow drying rate and contamination from air borne dust [6 ,7]. Looking into the problem from so many angles, a controlled drying system may be recommended as an alternate to traditional open Sun drying method. Controlled drying system may be further broadly divided into forced and natural convection type drying.

The natural convection (passive) solar drying system has been reported to have a good potential in many countries. This system is found suitable for a limited capacity because of low drying rate; low buoyancy induced air flow in the drying chamber and reduced quality of dried products [8, 9]. Natural convection dryer rely on the movement of hot air through buoyancy while the forced convection dryers require electricity to drive inbuilt fan. A good number of research studies have been performed on forced convection active solar dryers for fruits and vegetables [10, 11, 12, and 13]. The survey of above literature reveals that forced convection drying not only significantly reduces the drying time but also results in many improvements in the quality of dried products [9, 12]. In forced convection (active) dryer, the food product is exposed to hot air delivered through collector where as at the same time food product may also be exposed to incident solar radiation along with hot air available from collector. This drying process is known as mixed mode solar drying.

According to Koli.S.A et al.,[14] the drying rate is influenced by the nature of the food material, initial moisture content, mass of the food material per unit exposed area, drying air temperature, humidity of the drying chamber and drying air velocity. Moisture removal processes and their dependence on above parameters may be expressed in terms of drying kinetics; hence the determination of the drying rate is essential for the development of reliable process model. There have been many researches on the mathematical modeling and experimental studies of solar drying process of various vegetables, fruits and medicinal plants, such as sesame hulls [15], grapes [16], Egg [6], Chili [12] and red pepper [14].

Although considerable amount of literature is available on drying kinetics of a number of food products using thin layer drying models but limited information on the drying characteristics of potato slices in multi tray drying system is available. Hence the objectives of the proposed study are;

i) To study the drying kinetics of potato slices in forced convection (active) multi tray solar dryer.

ii) To plot moisture ratio v/s drying time and moisture ratio v/s drying temperature curve for each tray.

iii) To fit the moisture ratio curves with seven mathematical models and select the best fit model for the proposed drying based on the statistical parameters.

II. MATERIALS & METHODS:

Potato were purchased from a local market of Varanasi nearby I.I.T (BHU) Varanasi. Initial moisture content of the potato was determined by moisture measuring equipment after the potato were cleaned and washed. Thereafter manually cut into slices in spherical slab of approximately 2.5 mm thickness using very sharp knife.

2.1Experimental setup:

The experimental setup as shown in (Fig.1) consists of four number of flat plate solar collectors , area of each collector being 1.93m^2 and a drying chamber made of Aluminium sheet of size (1m x 0.15 m x 0.5m) which can accommodate six no of Aluminum trays of size (0.76 m x 0.555m) . Drying cabinet is divided into two parts i.e. air chamber and drying chamber. In air chamber 5.15 Kg of PCM material (Lauric acid) is kept in a PCM chamber of size (0.15m x 1mx 0.15m). A blower of 0.37 Kw capacity at 2785 rpm was used to force the air through the solar collector. The solar energy collected by solar collector is taken away by atmospheric air which is forced through collector and finally which enters into drying chamber via air chamber which ultimately causes the dehydration of food stuffs. During day time thermal charging of PCM takes place due to which it stores energy in the form of either sensible or latent heat and the stored energy is released whenever the solar radiation is not available or during bad weather conditions.

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2.2 Experimentation:

Drying experiment was conducted on the roof of Renewable energy Lab, Dept. of Mechanical Engg. IIT (BHU) Varanasi, India for several days during the month of June 2013 and March 2014. The latitude, longitude & altitude of Varanasi are 25.2^0N& 83.0^0 E and 80.71 m above the sea level. Initially the dryer was allowed to run for 1 hr so that steady state condition was achieved before recording observations.. The thee identical trays of size 0.76m x 0.555m were loaded with clean, washed potato slices in thin layer and were kept in the drying cabinet. Hourly data of climatic conditions like ambient air temperature, atmospheric air humidity, solar radiation incident on solar collector and wind speed were collected.. The analog type solar meter instrument (type SM 201) has been used to measure the solar radiation of intensity in the range of 50-1200w/m^2 with a resolution of 1 w/m^2. The drying air temperature at collector inlet and outlet , at drying chamber outlet and crop temperatures at each three trays were measured by copper- constantan thermocouples which were connected to a digital temperature indicator. The indicator can be used to measure the temperature in the range of 0-200^0C with an accuracy of . Wind velocity has been measured by two channel hot wire anemometer with an accuracy of $\pm(2\% + 0.1m/sec)$.Atmospheric air and drying chamber moist air humidity was measured by a humidity meter of accuracy of Temp;$\pm 0.1°C$ and humidity; $\pm 5\ \%\ RH$. . After each one hour, samples from all the three trays were taken and moisture content in potato slices were determined experimentally using moisture measuring instrument. Moisture evaporation rate was recorded by the concept of loss of weight. Based on consistency of observations, the data recorded on 24/3/14 has been taken for modeling and analysis purpose.

Fig. 1 Flat Plate Solar Collector [17]

Fig. 2 Measuring Instruments [17]

2.3 Moisture Ratio:

2.3.1 Determination of Moisture Ratio

The moisture ratio M.R (kg of water/ kg of dry matter) was determined using the following equation:

$$M.R =(M – M_e)/ (M_i – M_e) \quad 2.1$$

Where M.R = moisture ratio , M = moisture content at any specified time (% dry basis)
M_i = Initial moisture content(% dry basis) ,M_e = Equilibrium moisture content (% dry basis)

Literature reveals that Guggenheim-Anderson-de Boer (GAB) equation is considered as the most versatile model capable of application to situation over a wide range of water activity ($0.1 < aw < 0.9$) and to various materials. The GAB equation is probably the most suitable for process analysis and design of drying because of its reliability, it's simple mathematical form and its wider use. Parameter values of the GAB equation for potato crop may be given as-

$$\text{Equilibrium moisture content } X= (b_0b_1b_2a_w) / [(1- b_1a_w) . (1-b_1a_w + b_1b_2a_w)] \quad 2.2$$

where for potato crop, $b_0 = 8.7$, $b_1 = b_{10} \exp(b_{11} / RT)$
$b_2 = b_{20} \exp(b_{21} / RT)$, $b_{10} = 1.86 \exp (-5)$, $b_{11} = 34.$ $b_{20} = 5.68$, $b_{21} = 6.75$

$$\text{water activity } a_w = p/ p_w = R_{Heq} / 100 \quad 2.3$$

During drying of potato slices , values of equilibrium moisture content as per GAB EQUATION were relatively small as compared to M and M_i. Therefore the equation No. 2.1 may be further modified as per (Doymaz . 2004) and may be given below-

$$M.R. = M / M_i \qquad 2.4$$

Moisture ratio data obtained from equation No. 2.4 for each trays were fitted to seven thin layer drying equations to assess their suitability as models for thin layer drying kinetics of potato slices of 2.5 mm thickness. MATLAB 7.9 was used to fit the experimental data to seven thin layer models. Coefficient of determination (R^2) was used to determine the appropriateness of the model while the accuracy of fits was assessed using root mean square of error and sum square of error. For quality fit, R^2 value has been chosen very close to unity while SSE and RMSE values have been taken very close to zero. The seven models chosen are represented in Table. No. 1

The fit parameters (such as a, b, c, k.etc) and fit statistics (R^2, SSE, RMSE) associated with all the seven drying models for each trays has been computed and the result of comparative analysis of each trays has been incorporated in drying models..

Table No. 1. Some thin layer drying models

S. No	Name of Model	Equation
1	Newton	$MR = \exp(-kt)$
2	Logarithmic	$MR = a*\exp(-kt) + c$
3	Henderson and Pabis	$MR = a*\exp(-kt)$
4	Page	$MR = \exp(-kt^n)$
5	Two term exponential	$MR = a*\exp(-kt) + (1-a) *\exp(-kat)$
6	Two – term	$MR = a*\exp(-kt) + c*\exp(-k_1t)$
7	Wang and Singh	$MR = 1 + at + bt^2$

EXPERIMENTAL RESULTS

3.1 Experimental Observations: The experiments were performed on the setup and data were recorded, which is being given below-

Table No.2 Observation Data Recorded Hourly on 24/03/14 for moisture content (m_c) and Crop Weight (w) of Potato Slices Kept in Tray1, Tray2 and Tray3 respectively

Time	Tray1 (m_{c1})	Tray2 (m_{c2})	Tray3 (m_{c3})	Crop weight in trayI,W_1 (kg)	Crop weight in tray2,W_2 (Kg)	Crop weight in tray3,W_3 (Kg)	Relative Humidity γ (%)
9:00 AM	85.4	85.4	85.4	0.875	1.212	1.67	12.8
10:00	60	63	65	0.624	0.896	1.267	11.8
11:00	45	48	50	0.468	0.683	0.974	11.7
12:00	37	40	42	0.384	0.569	0.818	10.5

1:00 PM	29	33	36	0.301	0.469	0.701	10.4
2:00 PM	24	28	32	0.249	0.398	0.623	10.6
3:00 PM	20	24	26	0.208	0.341	0.506	10.4
4:00 PM	15	18	20	0.156	0.256	0.389	10
5:00 PM	10	12	16	0.13	0.178	0.3	10

3.2 Experimental Results and Analysis

The data of **Table No. 2** have been used for analyzing different parameters in drying process of potato slices.

3.3 Moisture ratio analysis and Models

3.3.1Drying Time Based Analysis:

Experimental moisture ratio (MR) data for thin potato slices kept in tray1.tray2 and tray 3 have been computed using equation No. 2.4 and being represented in Fig.3 In order to predict the drying behavior of potato slices of each trays, moisture ratio curves have v/s Drying time been plotted and represented in Fig. 4 to 6. Seven mathematical models were fitted to the moisture data of each trays and best fit curves have been drawn and represented in Fig.4, Fig. 5 and Fig.6 respectively. The most suitable thin layer drying model which predicts the most appropriate drying behavior of each trays were determined by comparing the best fit results of each seven thin layer models for each trays. The result of most suitable thin layer drying model, tray wise may be given as-

Tray1: Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.1

a=0.3173, b=0.2941, c=7.262, d=2.253

SSE = 1.82E(-0.5) , R^2 = 1, Adjusted R^2 = 1, RMSE = 0.00213

Tray2: : Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.2

a=5.475, b=1.975, c=0.3106, d=0.2575

SSE = 1.6E(-0.5) , R^2 = 1, Adjusted R^2 = 1, RMSE = 0.00202

Tray3: : Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.3

a=4.598, b=1.804, c=0.3060, d=0.2335

SSE = 4.8E(-0.5) , R^2 = 0.9999, Adjusted R^2 = 0.9999, RMSE = 0.00347

On comparison of statistical fit parameters R^2, Adjusted R^2 and RMSE, it was found that the **TWO TERM** model presents the suitable performance in prediction of high moisture potato slices' drying behavior.

3.3.2 Drying Temperature Based Analysis :

Another analysis of moisture ratio has been carried out by plotting moisture ratio v/s drying temperature curves for potato slices kept in all three trays and seven mathematical models have been fitted to the moisture ratio data. Based on statistical fit parameters and as a result of comparative analysis of best fit curves as shown in Fig. 7 to 9, the most appropriate moisture ratio model has been selected. The result is given below-

Tray1: Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.4

a=53.25, b=0.07781, c= -53.29, d= 0.07779

SSE = 5.18E(-1) , R^2 = 0.3072, Adjusted R^2 = 1, RMSE = 0.3598

Tray2: : Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.5

a= 15090, b= -0.7767, c= -15110, d=0.07772

SSE = 6.3E(- 1) , R^2 = 0.1389, Adjusted R^2 = 1, RMSE = 0.3967

Tray3: : Two Term Model; MR = a.exp(b. x) + c. exp(d. x) 3.6

a= -245.8, b= 0.06031, c= 245.7, d=0.06032

SSE = 5.94E(-1) , R^2 = 0.174, Adjusted R^2 = 0.9999, RMSE = 0.3854

On further comparison of statistical fit parameters R^2, R.M.S.E. S.S.E and Adjusted R^2, this has been again found that **TWO TERM** model is the most suitable model which predicts the drying behavior of potato slices most appropriately.

Referring to moisture ratio analysis 3.3.1 based on **drying time** and 3.3.2 based on **drying temperature,** this may be inferred that drying time of potato crop has evenly affected moisture ratio variation and may be well predicted. A gradual trend in parameters governing moisture ratio is observed. The effect of drying temperature on moisture ratio variation has been observed as erratic. On 24/03/14 the solar intensity after 1. P.M falls sharply from 965 w/m^2 to 27 w/ m^2 and consequently the drying air temperature varies from 333K to 317 K in erratic manner. This is the reason why statistical fit parameters has been observed more significant in case of drying time based analysis as compared to drying temperature based analysis.

On combining the outcomes of both analysis , this finding may be established that **TWO TERM** model is the most appropriate model which may be inferred for the prediction of drying behavior of potato crop in Indian climatic condition

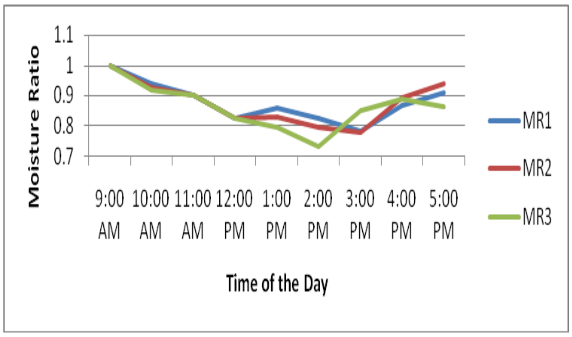

Fig. 3 Moisture Ratio v/s Time (in Hours)

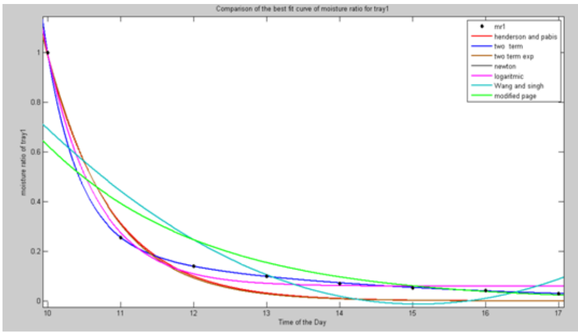

Fig. 4 Curve Fitting of moisture Ratio of Tray1 based on Drying Time

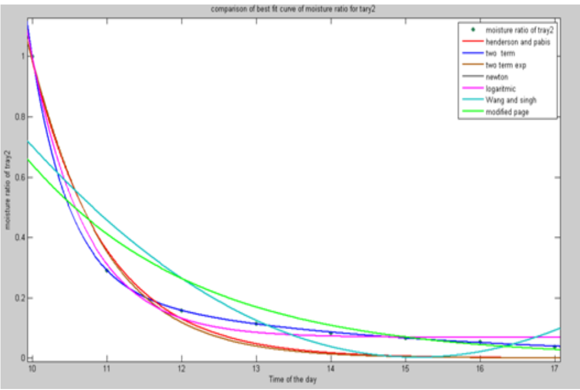

Fig.5 Curve Fitting of moisture Ratio of Tray2 based on Drying Time

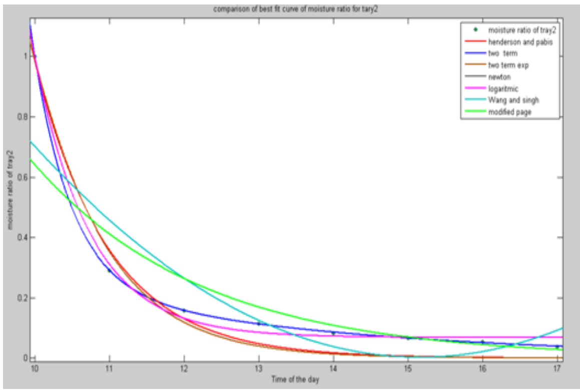

Fig.6 Curve Fitting of moisture Ratio of Tray3 based on Drying Time

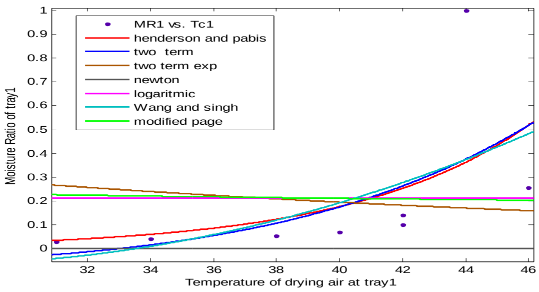

Fig.7 Curve Fitting of Tray1 based on Drying Temperature

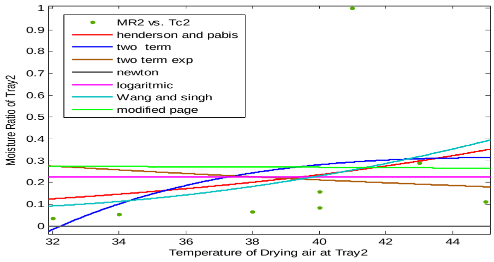

Fig.8 Curve Fitting of Tray2 based on Drying Temperature

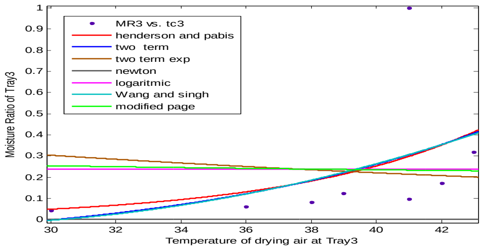

Fig.9 Curve Fitting of Tray3 based on Drying Temperature

CONCLUSIONS

Based on the above studies and experimental results obtained, it can be concluded that there is a potential of integrating (PCM) phase change material with solar drying system for drying of fruits and vegetable, throughout the day and night, during crop harvesting seasons in rural, semi urban and urban areas. From above study, it is inferred that -

The moisture ratio variation for each tray follows almost the same trend. Drying process of potato slices become saturated in between 12:30 PM to 1: PM in each tray as in that duration drying air temperature inside drying chamber and crop temperatures in corresponding trays also attain peak values. Relative humidity inside drying chamber has been observed fairly constant. After 3: PM an increase in moisture ratio of each tray has been observed because of back up energy provided by PCM material during its discharge. **Two Term** thin layer drying model was the most fitting model for the estimation of moisture ratio for high moisture potato slices drying kinetics

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