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Modeling and Evaluation of Thermal Diffusivity and Activation Energy of Potato slices in Forced Convection Multi Tray Solar Dryer

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Abstract In the work being presented, the modeling and analysis of thermal diffusivity and activation energy of high moisture potato slices in multi tray solar dryer has been investigated. 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 from 300.2K to 332K 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 adjudge the most appropriate model. Logarithmic model for effective moisture diffusivity and quadratic power model for activation energy were found as the most appropriate models for their computation. Effective diffusivity was found to vary from 1.17exp (-7) to 10.0889exp(-7)m^2/sec and activation energy was found to vary from 0.0525KJ/mole to 4.524742 KJ/mole. These findings are being presented in this paper.

Keywords: *moisture diffusivity. activation energy. moisture ratio, drying time*

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1. Introduction

Solar drying is in practice since the time long time for the preservation of food and agriculture crops. This was done particularly by open sun drying under open sky. This process has several disadvantages like spoilage of product due to adverse climatic condition like rain, wind, moist and dust, loss of material due to birds and animals deterioration of the material by decomposition, insects and fungus growth. Also the process is highly labor intensive, time consuming and requires large area. With cultural and industrial development artificial mechanical drying came into practice. This process is highly energy intensive and expensive which ultimately increases product cost. Thus solar drying is the best alternative as a solution of all the drawbacks of natural drying and artificial mechanical drying. Solar dryers are used in agriculture for food and crop drying on the other hand for industrial drying processes dryers can be proved to be most useful device from energy conservation point of view. It not only saves energy but also saves lot of time, occupies less area, improves quality of the product, makes the process more efficient and protects environment also. Solar dryers overcome some of the major disadvantages of classical drying. Solar drying can be used for the entire drying process or for supplementing artificial drying systems, thus reducing the total amount of fuel energy required.

As a result of extensive literature survey, this has been observed that drying characteristics and associated parameters were always the keen interest of researchers and scientists specially in the area of food Science and Technology. Crank, 1975 [1] has derived the general solution of moisture movement of standard geometries such as slab, cylinder and sphere using appropriate boundary condition.

Most of researchers have estimated effective moisture diffusivity by using only first term of general solution (Zoyzas et al.1996 b) assuming a constant thermal diffusivity for the whole drying process. But in actual process, it is rarely constant. Thermal diffusivity of the food stuff varies considerably with moisture content, temperature and special coordinate. Such finding has been reported by Puyate and Lawrence, 2006 [3], and Karthanos et al.(1990) [4].

Alp Akin, Necdet Ozbalta and Ali Gunger, 2009 [5] has represented a report on equilibrium moisture content and equations for fitting sorption isotherms of capsicum annum. Water activity and moisture contents of capsicum annum in different salt solutions have been determined. The sorption isotherms of capsicum annum were determined within the range of 10% to 98 % relative humidity at three different temperature say 30°C, 45°C and 60°C using static gravimetric method. A new model between equilibrium moisture content and relative humidity was developed. Thin layer drying models for sweet potato in tray dryer has been investigated and presented by Olawale, A.S. and S.O.Omole, 2012 [6]. The drying rate for blanched and unblanched sweet potato was modeled by fitting eight models and Page model has been reported as the best for all samples.

Sarsavadia [7] developed a solar assisted forced convection dryer for dehydration of onion slices for the controlled conditions of drying air temperatures and airflow rates similar to those employed in commercial onion dehydration. The dryer was also facilated with recirculation of exhaust air. The total energy required for drying of onion slices increased with increase in airflow rate and decreased with increase in drying air temperature.

The effect of air temperature and airflow rate on the drying kinetics of gelidium Sesquipedable was investigated by Mohmed et al. [8] in convective solar drying.The drying process was conducted by using an indirect forced convection solar dryer. It consisted of a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet. Drying was conducted at 40,50 and 60°C and thin layer convective solar drying of Gelidium Sesquipedable was investigated. From the obtained results it can be concluded that the main factor influencing drying kinetics was drying air temperature.

Ian C. Kemp et al. 2001 [9] has presented a review methods for processing experimental drying data obtained from drying kinetics rigs and pilot- plant trials. Different methods for fitting and smoothing drying curves are compared, aiming to generate curves that are usable in industrial design without losing vital information by over smoothing.

Abano E.E, Ma. H and W. Qu, 2011, [10] has investigated the influence of air temperature on the drying kinetics and quality of tomato slices. In particular, the effect of hot air temperature on the lycopene content, non-enzymatic browning, color and flavor changes during drying at various temperature in the range of 50-80°C was investigated. Drying time was considerably reduced from 1140 min to 540 min as the temperature increased from 50-80°C and lycopene levels of fresh tomato was observed fairly increasing.

Abdel basset Bessadok Jemai, 2013 [11] has investigated the drying kinetics of high water content materials such as agro food particles. Comparative study and analysis of agro food particles exhibiting non – Fickian mass transfer properties has been presented.

Therefore the aim of the work being presented may be given as-

i) To model moisture diffusivity and activation energy for high moisture potato crop.

ii) To find out best fit curve for moisture diffusivity and activation energy of potato crop.

iii)To calculate moisture diffusivity and activation energy for potato crop kept in three trays.

2. Materials and Methods

The potato purchased from a local market nearby I.I.T.B.H.U Varanasi, after cleaning were cut manually into slices of diameter 2.5cm and thickness 2.5mm. The samples were spread evenly in a single layer on three similar stainless steel wire mesh trays and were kept inside the drying chamber of forced convection solar dryer. Solar drying experiments were carried out on a clear sunny day.

2.1. Measurements

The tests on experimental setup of forced convection solar dryer were conducted for several days on the roof of Renewable Energy Laboratory, Mechanical Engineering Department, I.I.T BHU Varanasi during the month of March 2014 and observations recorded on 24/03/2014 have been taken for analysis purpose. During experiment, climatic parameters such as ambient air temperature, relative humidity of atmospheric air, wind speed and total solar radiation incident on collector surface were measured. Solar radiation was measured by the solarimeter. A solarimeter is a pyranometer type of measuring device which measures combined direct and diffused solar radiation.

Wind speed was measured using the anemometer with the range of 0.3–75 m/s. The accuracy of the anemometer is +2% + 0.2 m/s. The wind speed was always below 1 m/s and was recognized as small. Therefore the effect of wind speed and its direction was neglected.

The temperature of the air at the inlet and outlet of solar collector, at the exit of drying chamber and crop temperatures at each three respective trays were measured by calibrated copper–constantan thermocouples which have low-cost, acceptable accuracy and rapid response. The location of the thermocouples in the collector passage allowed the determination of temperature of entering and leaving air from collector. Thermocouple beads were put in the cylindrical passage 10 cm bellow. Atmospheric humidity and humidity inside the drying chamber were measured by humidity meter.

The sample weight loss was measured at regular intervals of time, using a precision Goldtech Brand electronic weighing machine maximum capacity 20kg and minimum 0.40gm. Moisture content (dry basis) was calculated from weight loss data and dry solid weight of the samples. Continuous drying was continued till the product was dried from initial moisture content of 85% to finally 12%. Moisture content of the samples based on wet basis have been measured by moisture measuring instrument. The dryer contributed to reduction in drying time in comparison with open sun drying.

The tests were conducted between 10:00 and 17:00 solar time. Hourly data recorded have been presented in Figure 1 to Figure 6.

3. Moisture Ratio

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

$$M.R = \left(M - M_e\right)\left(M_i - M_e\right) \quad (1)$$

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-

Equilibrium moisture content

$$X = (b_0 b_1 b_2 a_w) / \left[(1 - b_1 a_w).(1 - b_1 a_w + b_1 b_2 a_w)\right] \quad (2)$$

where for potato crop, $b_0 = 8.7$, $b_1 = b_{10} \exp(b_{11} / RT)$

$$b_2 = b_{20} \exp(b_{21} / RT), b_{10} = 1.86 \exp(-5),$$
$$b_{11} = 34, b_{20} = 5.68, b_{21} = 6.75$$

and Water activity

$$a_w = p / p_w = R_{Heq} / 100 \quad (3)$$

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.(1) may be further modified as per (Doymaz. 2004) and may be given below-

$$M.R. = M / M_i \quad (4)$$

3.1.1 Effective Moisture Diffusivity and Activation Energy

The term effective moisture diffusivity may be defined as the rate of moisture movement without any consideration of type of mechanism involved. A complete drying profile consists of the first stage of drying, a constant rate period, and a falling rate period. In most applications the dominating stage is third period. It is frequently agreed that the mechanism of moisture within a hygroscopic solid during the falling rate period could be represented by one dimensional diffusion equation as a good approximation for most practical systems. Effective moisture diffusivity for potato slices kept in all three trays were computed using Fick's Equation of diffusion expressed as below-

$$\frac{\partial X}{\partial t} = \nabla.(Deff.\nabla X) \quad (5)$$

where x = moisture content (kg of water/kg of dry matter).

Following assumptions were made for getting the solution of above partial differential equation –

(i) the shape of material remains uniform during the drying.

(ii) thermal equilibrium exists at the interfacing of material surface and drying air.

(iii) the initial moisture content is uniform throughout the bulk of food stuff.

(iv) external mass transfer resistance has been assumed as negligible.

The solution of above differential equation as proposed by Crank(1975) may be given as-

$$M.R = \frac{M - Me}{Mi - Me} = \frac{8}{\pi 2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)2} \exp\left\{-D_{eff}\,(2n-1)^2\, \pi^2 t / 4\,L^2\right\} \quad (6)$$

Drying time of potato slices being relatively very high, the first term of above equation as per Kingsly et al. (2007) may be given as-

$$\ln(MR) = \ln\left\{\frac{M - Me}{Mi - Me}\right\} = \ln(8/\pi^2) - \left\{-D_{eff}\,\pi^2 t / 4L^2\right\} \quad (7)$$

MR can be computed as given below-

$$MR = (8/2\pi)\exp\left\{-D_{eff}\,\pi^2 t / 4L^2\right\} \quad (8)$$

Effective moisture diffusivity may be computed from the expression given below-

$$\text{Slope of } \ln(MR) \text{ verses time curve} = \frac{\pi 2 Deff}{4L2} \quad (9)$$

According to (Babalis and Belessiotis.2004) as Arrhenius type of equation can be used for the computation of activation energy

$$D_{eff} = D_0 \exp(-E_a / RT) \quad (10)$$

$$\ln(D_{eff}) = \ln(D_0) - \left\{\frac{Ea}{RT}\right\}\left\{\frac{1}{T}\right\} \quad (11)$$

It is evident from equation No.11 that ln (D_{eff}) has been plotted against (1/ T) and slope of the curve i.e{ $\frac{Ea}{RT}$ } is the value of activation energy for the food stuff. Hence activation energy may be computed as-

$$\text{Slope of } \ln(D_{eff})\, v/s 1/T \text{ curve} = E_a / R \quad (12)$$

4. Experimental Observations

Experimental observations taken on 24/03/13 has been represented in graphical form from Figure 1 to Figure 6.

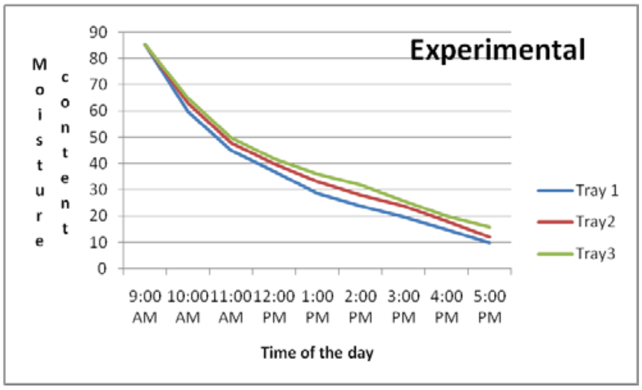

Figure 1. Moisture content of potato slices in tray1, tray2 and tray3 respectively

5. Results and Discussions

Moisture ratio on dry basis for each tray was computed by using experimental data presented in Figure 1 and formula (4). Equilibrium moisture content for potato slices of all three trays were computed by GAB Equation (2). The value of EMC being very small for each trays has been neglected in the formula (1) which was further modified and used as formula(4).

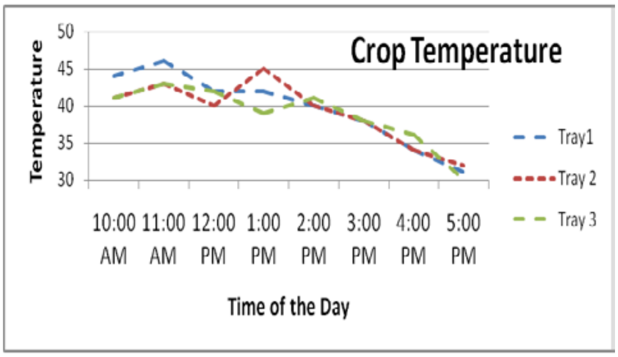

Figure 2 Crop Temperature of potato slices in tray1, tray2 and tray3 respectively

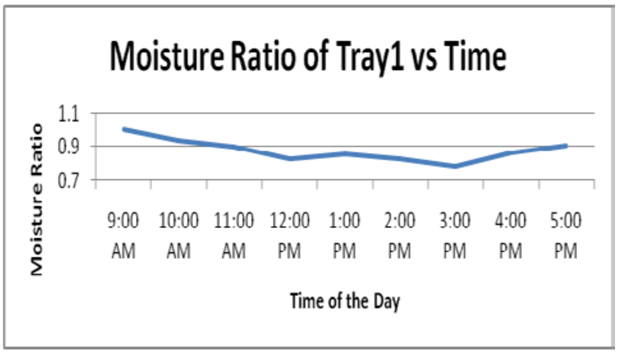

Figure 3. Moisture ratio of potato slices in tray1 (dry basis)

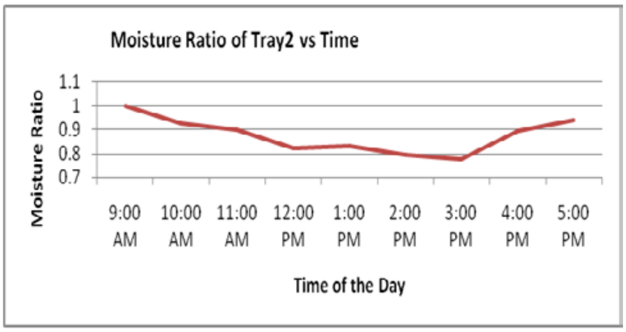

Figure 4 Moisture ratio (db) of potato slices in tray2

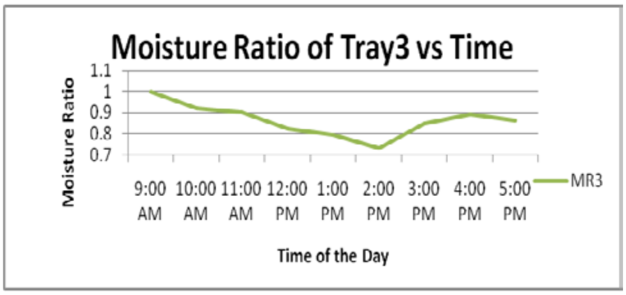

Figure 5 Moisture ratio (db) of potato slices in tray3

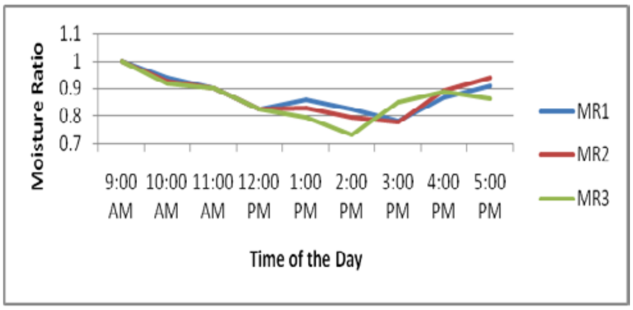

Figure 6. Moisture ratio (db) of potato slices in tray1, tray2 and tray3 respectively

Moisture ratio on dry basis for each tray has been computed and represented in Figure 3 to Figure 5. Further modeling. analysis and result discussion of moisture diffusivity and activation energy tray wise is being presented in 5.1 and 5.2 respectively.

5.1. Moisture Diffusivity Values and Models:

Best fit curves for ln(MR) verses time for each trays have been plotted and represented in Figure 7 to Figure 9 to predict the best possible thin layer drying behavior of potato slices. The logarithmic model was applied to best fit the ln(MR) verses time curve. The best fit logarithmic model with statistical fit parameters for each trays are given below-

Tray1: ln(MR) = -1.6101 log(t) – 0.1107

R^2 = 0.9937, RMSE = 0.09651

Tray1: ln(MR) = -1.497 log(t) – 0.09579

R^2 = 0.9937, RMSE = 0.09086

Tray1: ln(MR) = -1.432 log(t) – 0.07983

R^2 = 0.9923, RMSE = 0.09569

MATLAB 7.9 was used and slopes at each points of ln(MR) curve for each trays has been determined. Moisture diffusivity for potato slices of each trays were calculated by the formula (9) and results have been tabulated in Table 1.

Table 1. Result Table of Moisture Diffusivity (D_{eff}) and Activation Energy (E_a) for potato slices of Tray1, Tray2 and Tray3

Diffusivity for Tray1 (m2/s)	Diffusivity for Tray2 (m2/s)	Diffusivity for Tray3 (m2/s)	Ea (Tray1)	Ea (Tray2)	Ea (Tray3)
1.0088E-6	9.4340E-7	9.0286E-7	4.524734	4.524742	4.524734
5.0444E-7	4.7170E-7	4.5143E-7	3.885854	3.885863	3.885854
3.3629E-7	3.1446E-7	3.0095E-7	3.246975	3.246984	3.246975
2.5222E-7	2.3585E-7	2.2571E-7	2.608096	2.608096	2.608096
2.0177E-7	1.8868E-7	1.8057E-7	1.969217	1.969217	1.969217
1.6814E-7	1.5723E-7	1.5047E-7	1.330346	1.330338	1.330338
1.4412E-7	1.3477E-7	1.2898E-7	0.691464	0.691455	0.691461
1.2611E-7	1.1792E-7	1.1285E-7	0.052586	0.052573	0.052584

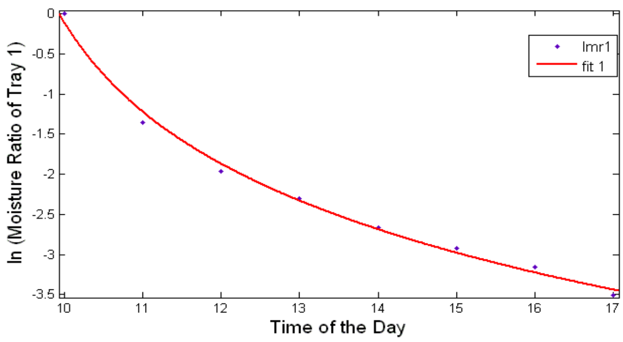

Figure 7. L_n(MR) verses Time curve For Potato Drying in Tray1

This study reveals that moisture diffusivity for tray1 varies from 1.2611exp (-7) m^2/ sec to 10.0889 exp(-7) m^2/ sec, for tray2. it varies from 1.1792 exp(- 7) m^2/ sec to 9.4306 exp(- 7) m^2/ sec and for tray3, D_{eff} varies from 1.12858exp(-7) m^2/ sec to 9.0286 exp (-7) m^2/sec. It can be observed from the results that the most effective factor which greatly affects the moisture diffusivity values in high moisture potato slices is the drying air temperature. Increase in air temperature caused increase in D_{eff} values which is evident from the result Table 1. Moisture diffusivity for tray2 and tray3 is observed in decreasing trend as compared to tray1 because air temperature gradually decreases for tray2 and tray3. Similar results regarding the effect of drying air temperature on moisture diffusivity during forced convection air drying have been reported for carrot slices (Aghbasshlo et al. 2009) and apricots (Doymaz et al. 2009).

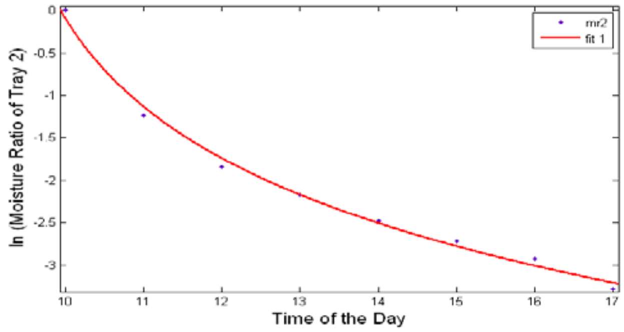

Figure 8. L_n(MR) verses Time curve For Potato Drying in Tray2

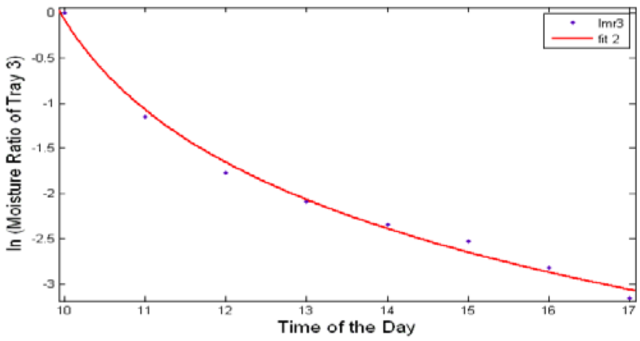

Figure 9. L_n(MR) verses Time curve For Potato Drying in Tray3

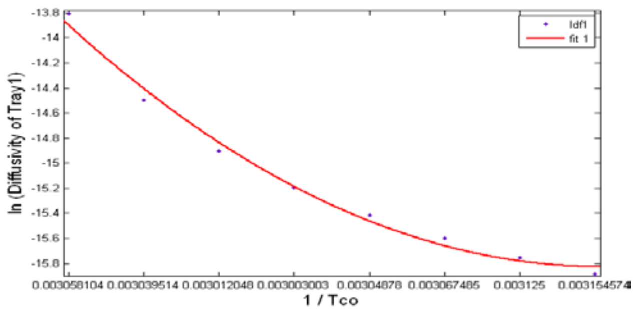

Figure 10. L_n(D_{eff}) against 1/T for thin- layer drying of high moisture potato slices 0f Tray1

5.2. Activation Energy Values and Models

As a first step towards the computation of activation of activation Energy (E_a), ln(D_{eff}) vrses 1/T curves were plotted for each trays and reprsented in Figure 10, Figure 11 and Figure 12 respectively. A quadratic model was applied to best fit the curves of drying potato chips of each trays. The best fit quadratic power models for ln(Deff) v/s 1/T curve with statistical fit parameters as obtained for each trays may be given as-

Tray1. f(x) = $0.03842\, x^2 - 0.6211\, x - 13.32$
$R^2 = 0.9905$, RMSE = 0.0811

Tray2. f(x) = $0.03842\, x^2 - 0.6211\, x - 13.38$
$R^2 = 0.9905$, RMSE = 0.08114

Tray3. f(x) = $0.03842\, x^2 - 0.6211\, x - 13.43$
$R^2 = 0.9905$, RMSE = 0.08114

The most general best fit power model which describes the drying kinetics of potato may be expressed as $f(x) = 0.03842\, x^2 - 0.6211x - 13.3$, $R^2 = 0.9905$.

As second step after getting best fit model, slopes at each points of ln(D_{eff}) curve for each trays have been determined and by using formula (12), activation energy (E_a) for potato slices of each trays has been computed and the result has been represented in Table 1.

Result Table 1 indicated the maximum and minimum value of activation energy as 4.524742 KJ/ mole and 0.052573 KJ/ mole.

Activation Energy of high moisture potato slices was relatively low as compared with other agricultural products. This is due to high moisture content, tissue of potato slices and starchy structure of potato slices. According to (Demirel and Turhan, 2003) less Activation Energy have been reported for banana slices as a result of high air temperature.

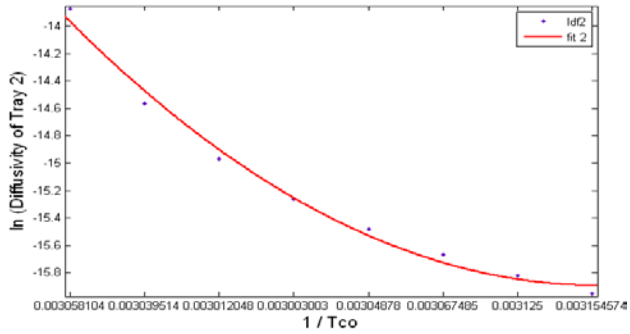

Figure 11. L_n(D_{eff}) against 1/T for thin- layer drying of high moisture potato slices of Tray2.

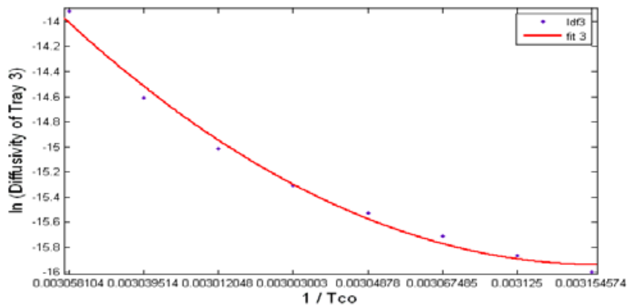

Figure 12. L_n(D_{eff}) against 1/T for thin- layer drying of high moisture potato slices of Tray3

6. Conclusion

Based on above studies and experimental results following conclusions can be made-

1) Logarithmic model has been found as the most appropriate mathematical model which may be used for the prediction of moisture diffusivity of potato slices of each tray in Indian climatic conditions.

2) Moisture diffusivity of tray1, tray2 and tray3 has been observed in decreasing trend. The result obtained is consistent and convincing as well with the decreasing trend of crop temperature of each trays and increasing

trend of moisture evaporation rate of each trays respectively.

3) Moisture diffusivity of each trays increases vertically in similar manner with respect to drying time.

4) Quadratic power model has been adjudged as the most appropriate mathematical model for predicting the activation energy of potato crops in Indian climatic conditions.

5) Experimental results indicate the maximum and minimum value of activation energy as 4.524742 KJ/ mole and 0.052573 KJ/ mole. Almost same average value of activation energy for potato slices of each tray has been found.

Nomenclature

D_{eff}	effective moisture diffusivity (m^2/ s)
t	drying time
$M.R$	moisture ratio (decimal)
M	moisture content at any specified time (dry basis)
M_e	equilibrium moisture content (dry basis)
M_i	initial moisture content (dry basis)
n	no. of terms taken
L	average half thickness of potato slice (m)
E_a	activation energy(KJ mole)
T	absolute temperature of air (K)
R	universal gas constant (8.314 Kj/mole K)
D_o	pre exponential factor.

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