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Drying kinetics and activation energy for solar drying of ginger slices

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Abstract

Drying is one of the oldest and most important preservation method for food in which by reducing the water activity the shelf life can be increased. In the present investigation, fresh ginger was pretreated in calcium oxide solution at different concentrations. Solar drying at three temperature levels *viz.*, 55, 65 and 75^{o} C at loading densities of 0.147 g/cm^2, 0.176 g/cm^2, 0.206 g/cm^2 respectively were used for the investigation. Results of study revealed that the total time required for ginger drying in solar dryer curtails with rise in drying air temperature and increased as loading density increased. The activation energy was observed to be 20.45 kJ mol^{-1}, 29.06 kJ mol^{-1} and 17.6 kJ mol^{-1} for 0.147 g/cm^2, 0.176 g/cm^2 and 0.206 g/cm^2 loading density respectively. Also, the diffusivity increased with increase in temperature from 45 to 65 ^{o}C.

Keywords: activation energy, drying kinetics, effective moisture diffusivity, *Zingiber officinale*

Introduction

Ginger (*Zingiber officinale*) a herbaceous perennial plant which belongs to the family *Zingiberaceae.* It is a major cash crop in the world and one of the earliest oriental spices. It comes in a variety of forms, including raw ginger, dried ginger, ginger powder, and bleached dry ginger and also in the form of ginger oleoresin, ginger oil, brined ginger and many more. Ginger and its products have numerous applications in culinary preparation, bakery products and perfumes as well as in the meat product industries (Deshmukh *et al.* 2014). Ginger is not only used to increase palatability of food but also widely used in ayurveda as medicine. (Ali *et al.* 2008). Drying or dehydration is one of the most prominent and oldest ways of food preservation. It preserves food by removing free water and hence reducing the water activity of food material which hinder the development and multiplication of deteriorative microorganisms (Kohli *et al.* 2017). The energy required for drying of product is a cost factor because of the high price of fossil fuels. Thin layer drying equations can be used to determine the drying time and for the generalization of the drying curves for several food products. The temperature of the drying air, its velocity, the thickness of the material (size) have a significant impact on drying kinetics (Vardia *et al.* 2019; Erenturk & Erenturk 2007; Kohli *et al.* 2022). Physico-thermal properties of the food products, like heat and mass transfer and moisture diffusivity information are the basic requirements for the design of dryer and in mass transfer modeling i.e., drying or adsorption of moisture during storage (Aghbashlo *et al.* 2008). Drying kinetics of various fruits and vegetables such as (Zielinska & Markowski, 2010), yam (Xiao *et al.* 2010), asparagus (Kohli *et al.* 2017; Kohli *et al.* 2018), cauliflower (Gupta *et al.* 2013), ginger (Deshmukh *et al.* 2014), okra (Doymaz 2005) and potato (Onu *et al.* 2016) were reported. The objective of this work was to study the drying behavior of ginger in PID (Proportional-Integral-derivative) control poly tunnel solar dryer and also to determine the effective diffusivity and activation energy of ginger.

Materials and Methods

Material

Fresh ginger (Rio De Janeiro variety) was procured from the local market of Pantnagar, Uttarakhand. Samples for drying were carefully selected on the basis of uniformity in shape and size and visually inspected for any defects. Samples were then washed, cleaned peeled and sliced into 2-3 mm thin slices with the help of a slicer. The initial moisture content of sliced ginger was estimated by hot air oven drying method (Ranganna 1986).

PID controlled solar dryer

The solar tunnel dryer was developed as a portable, batch type, solar operated forced convection type dryer. It was fabricated at the Development Laboratory of Department of Post Harvest Process and Food Engineering, College of Technology, Pantnagar. It consisted base frame, drying chamber (semi cylindrical shape), solar collector, an absorber and an air distribution system with chimney. The overall dimensions of the dryer were 1.60 m×0.90 m× 0.90 m (L×W×H) and the dimension of the chamber was 1.60 m×0.90 m×0.40 m (L×W×H) with the tray area of 1.2 m^2. It had a PID (proportional-integral-derivative) feedback controller, with temperature sensor of 0-200°C. Power supply was 200V AC, 50/60 Hz (Shahi *et al.* 2011).

Pre-treatment

Sliced ginger samples were pretreated for 10 minutes in a solution containing 1.5 g CaO and 3 g CaO per litre of distilled water in solid to solution ratio of 1:3. Treating ginger with calcium oxide (lime solution) is one of the common pre-treatment methods which improves colour, and also increases the drying rate (Kohli *et al.* 2018). The completely drained samples were utilized in experiments (Zhang *et al.* 2006).

Experimental procedure

The pretreated samples were dried in thin layer in the PID controlled solar dryers at temperature ranging from 55-75 °C with an increment of 10 °C (Singh *et al.* 2008; Alam *et al.* 2014; Tiroutchelvame 2000). The independent variables and their range for experiments are shown in Table. 1. For the steady-state condition during the experiment, the dryer was started 60 min prior to the drying process. The pre-treated samples of ginger were dried in single thin layer and weight of samples was continuously measured at every 1 hour interval. The drying was carried till the samples attained constant weight. The initial moisture value of the sample was represented on dry basis (d.b.) by the equation given by (Kohli *et al.* 2018).

Table 1. Independent variables during Experiment

Variable parameter	Levels
Loading density (g/cm^2)	0.147, 0.176 & 0.206
Drying temperature (°C)	55, 65 & 75
CaO concentration for pre-treatment (g L^{-1})	0, 1.5 & 3

$$M_c = \frac{W_1 - W_2}{W} \times 100 \quad (1)$$

Where, W is bone dry weight of sample (g), W_1 is weight of sample before drying (g) and W_2 is sample weight after drying (g).

Equilibrium moisture content

The moisture content at which the partial water vapour pressure of the surroundings is in equilibrium with material is represented as equilibrium moisture content. Since equilibrium moisture content (EMC) is used in equation used for determination of the moisture ratio (MR), EMC calculations were done by the method, in which last three moisture content values of drying process were used. The equilibrium moisture content was determined using the formula (Mujumdar 1995).

$$M_e = \frac{M_1 \times M_3 - (M_2)^2}{M_1 + M_3 - 2M_2} \quad (2)$$

Where, M_1, M_2 and M_3 are the moisture content (% d.b.) at time t_1, t_2 and t_3, respectively. Moisture content should be considered with the following condition

Moisture ratio and drying rate

The moisture content of ginger was expressed in dimension less form i.e. moisture ratios (MR) by using following equation (Erenturk *et al.* 2004; Midilli 2001).

$$MR = \frac{M_t \times M_e}{M_o - M_e} \quad (3)$$

Where, MR is the moisture ratio and M_o, M_t and M_e are the initial moisture content moisture content at particular time, and equilibrium moisture content, respectively.

Drying rate was defined as follows (Kohli *et al.* 2017).

$$\frac{dm}{dt} = \frac{M_2 - M_1}{\Delta t} \quad (4)$$

where Δ, is difference in time.

Overall drying rate

The overall rate of drying is the ratio of difference between initial and final moisture content and total drying time which was calculated using the equation (Kohli *et al.* 2017).

$$\frac{dm}{dt} = \frac{M_o - M_F}{t_T} \quad (5)$$

Effective moisture diffusivity

The efficiency of moisture removal rate of any material is represented by its diffusivity. The drying of food product generally follows the falling rate period. In order to predict the moisture transfer during this falling phase, various mathematical models based on Fick's Law of diffusion (for slab geometry) have been proposed (Kohli *et al.* 2017). Crank (1975) proposed an equation to evaluate the effective moisture diffusivity of an infinite slab by using the Fick's second law. The equation proposed by Crank (1975) and modified equation by Lopez *et al.* (2000) was used for calculation of effective moisture diffusivity. Slices of ginger were assumed to be of slab geometry. The equation used for estimation is as follows

$$MR = \frac{8}{\pi^2} \exp\left(-\pi^2 \frac{D_{eff} t}{4L^2}\right) \quad (6)$$

where, D_{eff} = effective moisture diffusivity ($m^2 s^{-1}$), L = thickness of slice (m) and, t = time of drying (sec).

The equation (6) was rearranged and rewritten as follows;

$$\text{In } MR = k_o t + \text{In } \frac{8}{\pi^2} \quad (7)$$

The equation (7) is similar with general linear or straight-line equation i.e. Y= mX+C, where m is the slope of the straight line. So, in the equation (7) the graphical relation between ln (Moisture Ratio) and time gives the slope i.e. k_o which was calculated as follows

$$k_o = -\frac{\pi^2 D_{eff}}{4L^2} \quad (8)$$

$$D_{eff} = -\frac{4L^2 k_0}{\pi^2} \quad (9)$$

Activation energy

The initiation of moisture diffusion by drying from a food material needs some amount of energy termed as activation energy. For ginger it was calculated from an Arrhenius type equation given as under (Akpinar & Toraman 2013; Akpinar *et al.* 2003).

$$D_{eff} = D_o \exp\left[-\frac{E_a}{R(T+273.15)}\right] \quad (10)$$

Where, D_o is the constant in Arrhenius equation ($m^2 s^{-1}$), R is the universal gas constant (kJ mol^{-1} k), T is the temperature (°C), and E_a is the activation energy (kJ mol^{-1}).

The above equation can also be written as:

$$\ln(D_{eff}) = \ln(D_o) - \frac{E_a}{R(T+273.15)} \quad (11)$$

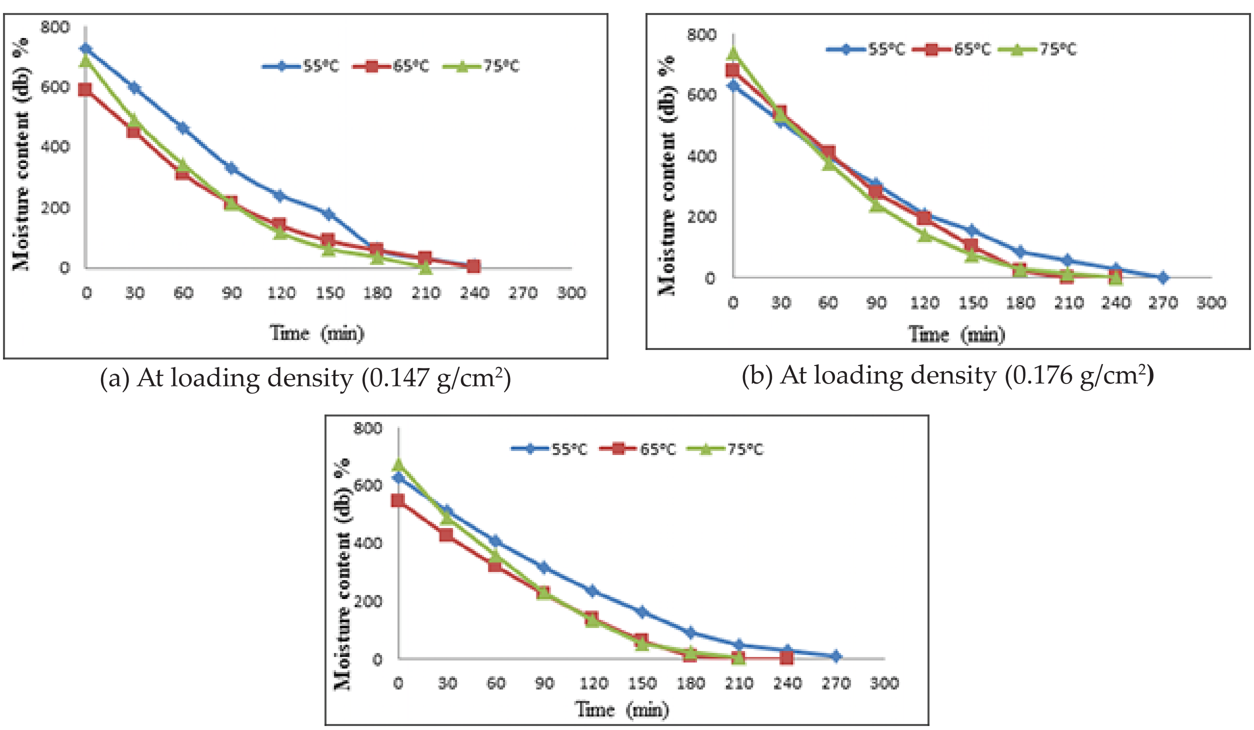
Now, the activation energy was calculated by using graphical relation of ln (D_{eff}) and 1/(T+273.15).

Results and Discussion

The average moisture content of ginger samples was found to be 86.77% (wb) or 655.79% (db) which showed that it is a highly perishable commodity.

Drying characteristics of ginger

The initial moisture content was observed to be 724.28 % (db). Fig. 1 depicts the variation in moisture content (d.b. percent) with drying time in treated samples with various loading densities. It shows a non-linear reduction in moisture content as drying time increases.



(a) At loading density (0.147 g/cm^2)

(b) At loading density (0.176 g/cm^2)

(c) At loading density (0.206 g/cm^2)

Fig. 1. Variation in moisture content (% db) with drying time at different loading densities

Firstly, there was rapid decrease in moisture and then the decrease slowed down considerably for all loading densities. The time required for drying depends on drying temperature and loading densities and generally it was found to be low for higher drying temperatures. It was minimum of 210 min for 0.147 g/cm^2 loading density at temperature of 75^{o}C and maximum of 270 min for 0.206 g/cm^2 loading densities at 55^{o}C. The final moisture content of dried samples varied from 4% to 6% (d.b.). It was also observed that as the loading density increased, the time required for drying also increased.

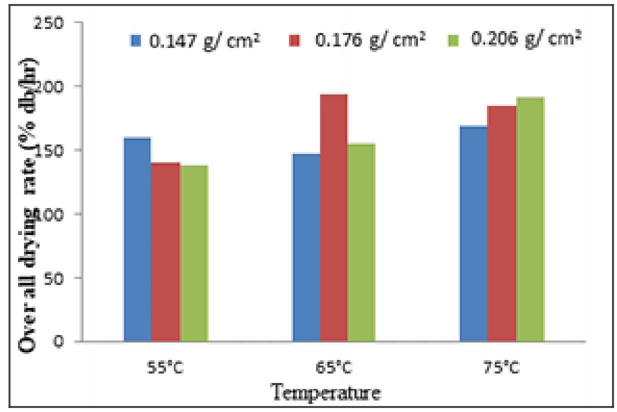
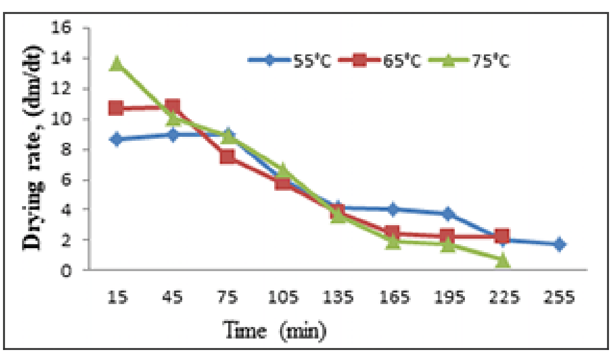
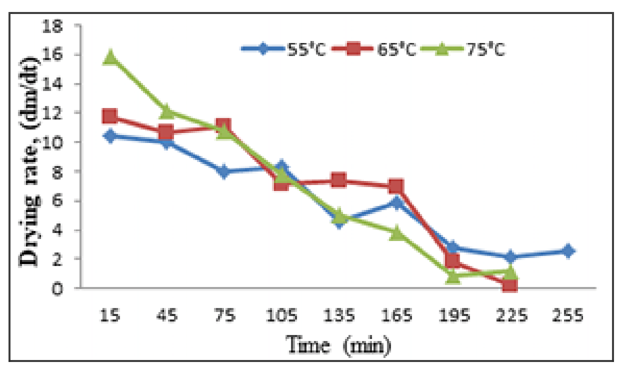


Fig. 3. Variation in overall drying rate at different temperatures and loading densities

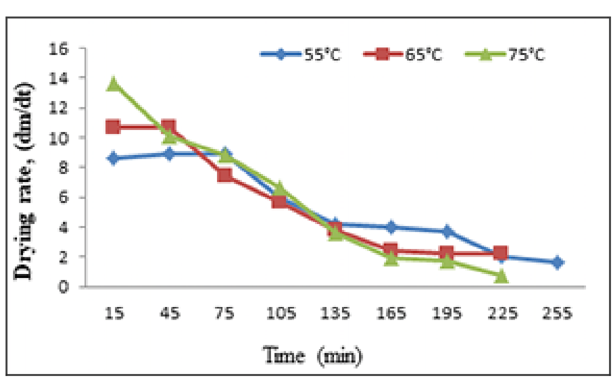
The average rate of drying decreased with increase in time. It was faster at higher drying temperature and decreased with drying time non-linearly. It was observed that at higher loading densities the drying rate was low. The graph between drying rate and time at different loading densities is shown in Fig. 2. Normally, it is also expected that at higher temperature the overall drying rate is also higher. Overall, it linearly increased with increase in temperature from 55 to 75°C. The graph between overall drying rate and temperature at different loading densities is shown in Fig. 3. Earlier studies also reported similar findings (Kohli *et al.* 2017; Vardia *et al.* 2018).



(a) At loading density (0.147 g/cm^2)

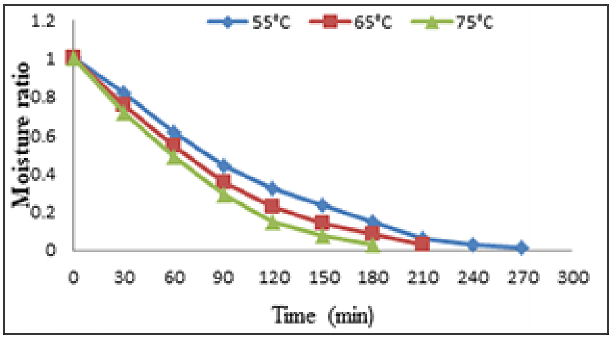


(b) At loading density (0.176 g/cm^2)

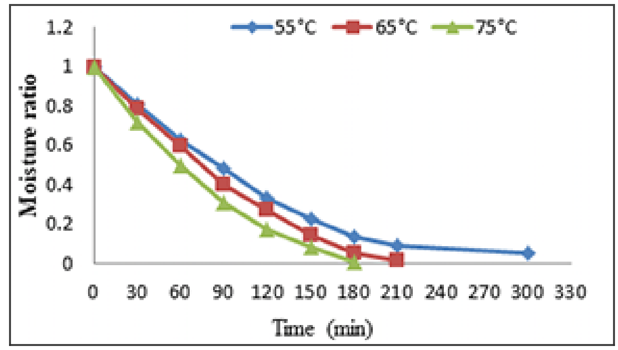


(c) At loading density (0.206 g/cm^2)

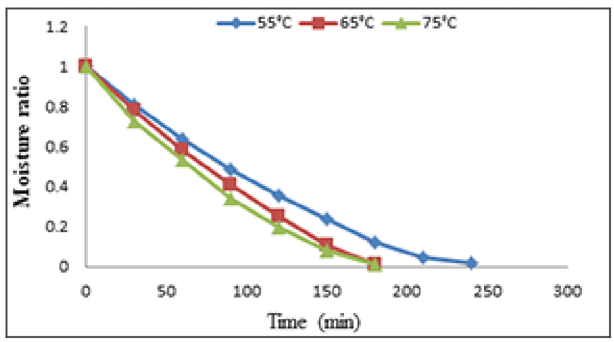
Fig. 2. Variation in drying rate with drying time at different loading densities



(a) At loading density (0.147 g/cm^2)



(b) At loading density (0.176 g/cm^2)



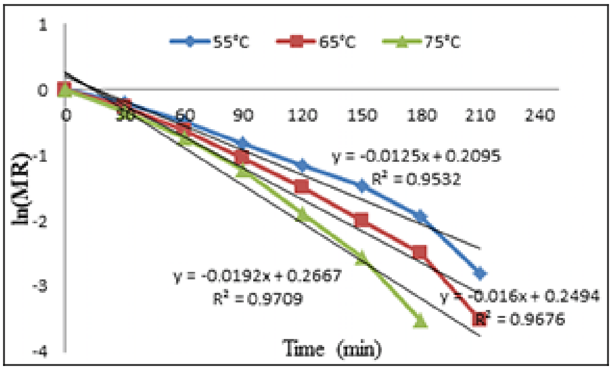
(c) At loading density (0.206 g/cm^2)

Fig. 4. Variation in moisture ratio with drying time at different loading densities

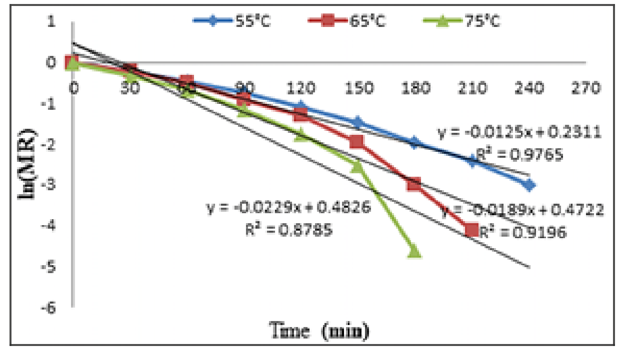
The change in moisture ratio over time for different temperature range (55-75° C) at different loading densities is shown in Fig. 4. In the initial stage of drying (i.e. 60 to 120 minutes) the moisture ratio decreased rapidly; however, in later stage of drying the moisture content approached the equilibrium moisture content (EMC) and hence the moisture ratio decreased slowly. The curves of moisture ratio of all drying temperatures showed that the drying was faster at 75°C. The curves did not show a constant drying rate period, and the entire drying process followed only a declining rate period which represent that the moisture mobility in samples is governed by diffusion, which is the major physical mechanism.

Effective moisture diffusivity and activation energy

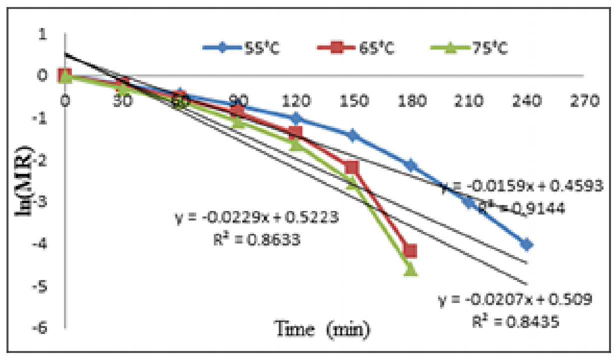
The results indicated that internal mass transfer resistance controls the drying time due to which falling rate drying period dominate the drying process (Fig. 5). The values of effective moisture diffusivity for different drying conditions are shown in Table 2. The effective diffusivity was in the range of 1.896×10^{-10} m^2 s^{-1} to 3.480×10^{-10} m^2 s^{-1} for different temperatures (55 -75°C) and different loading densities in solar drying. The minimum and maximum were obtained for drying condition of 55^{o}C at 0.176 g/cm^2 loading density and 75^{o}C at 0.176 g/cm^2, respectively. The mean diffusivity for 55°C, 65°C and 75°C was 2.069×10^{-10} m^2 s^{-1}, 2.811×10^{-10} m^2 s^{-1} and 3.294×10^{-10} m^2 s^{-1} respectively. It was also observed that there was increase in the effective diffusivity with increase in drying temperature, which may be due to the increase in diffusion with the increase in sample temperature (Diamante 1994**)**. Effective moisture diffusivity for fruits and vegetables including grape, carrot, potato, apple, cassava, mango and fish reported by Zogzas *et al*. (1996) showed that moisture diffusivity varies between 2.2×10^{-10} and 9.4×10^{-10} m^2 s^{-1}.



(a) At Loading density (0.147 g/cm²)



(b) At loading density (0.176 g/cm²)



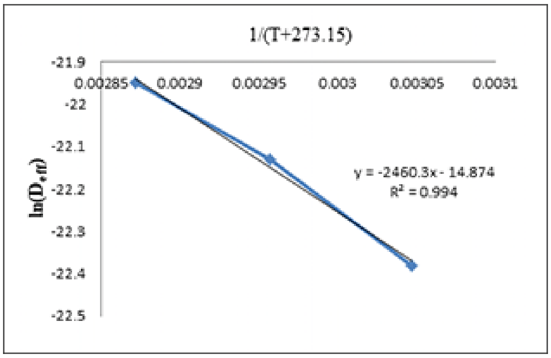
(c) At loading density (0.206 g/cm²)

Fig. 5. Experimental and predicted ln (MR) vs time at different conditions

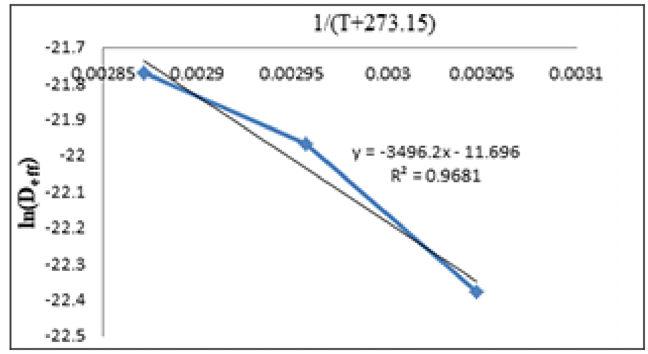
Table 2. Effective moisture diffusivity under different conditions

Temperature (°C)	Sample weight (g)	Equation	k_o	D_{eff} ($m^2 s^{-1}$)
55	25	y= -0.012x+0.209	-0.012	1.902×10^{-10}
	30	y= -0.012x+0.231	-0.012	1.896×10^{-10}
	35	y= -0.015x+0.459	-0.015	2.411×10^{-10}
65	25	y= -0.016x+0.249	-0.016	2.426×10^{-10}
	30	y= -0.018x+0.472	-0.018	2.866×10^{-10}
	35	y=-0.020x+0.509	-0.020	3.141×10^{-10}
75	25	y= -0.019x+0.266	-0.019	2.925×10^{-10}
	30	y= -0.022x+0.482	-0.022	3.480×10^{-10}
	35	y= -0.020x+0.522	-0.020	3.477×10^{-10}

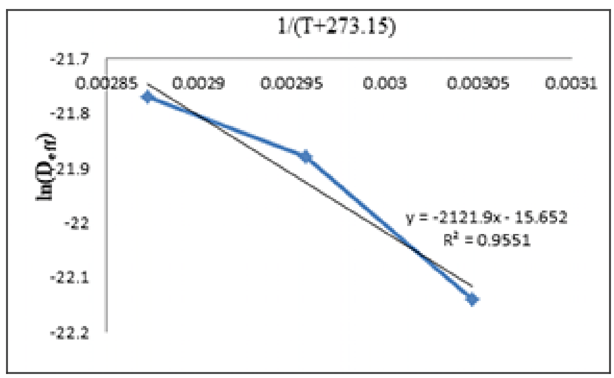
The activation energy was calculated using Arrhenius equation (Yaldiz *et al.* 2001). The activation energy was estimated to be 20.45, 29.06 and 17.6 kJ mol^{-1} for 0.147, 0.176 and 0.206 g/cm² loading density respectively (Fig. 6). Higher air temperature levels increases the effective moisture diffusion due to increasing heat and mass transfer. Similar results were also reported by other researchers working with different foods (Kohli *et al.* 2017).



(a)At loading density (0.147 g/cm^2)



(b) At loading density (0.176 g/cm^2)



(c) At loading density (0.206 g/cm^2)

Fig. 6. Effective diffusivity vs reciprocal of absolute temperature at different loading densities

Conclusion

In conclusion, ginger slices dried under the solar drying methods did not have any constant rate drying period and the drying took place only in falling rate period which shows that moisture removed by drying from the product was governed by diffusion phenomenon. It was also observed that the pre-treatment of CaO to ginger slices influenced the drying rate in all the drying methods. The drying time of ginger decreased and the effective diffusivity increased as the drying air temperature increased. Drying reduced the weight of ginger slices to nearly one fifth of its original value. The highest effective diffusion was found to be 3.294×10^{-10} m^2 s^{-1} at 75°C and the lowest effective diffusion was 2.069×10^{-10} m^2 s^{-1} at 55°C. For loading density of 0.206 g/cm^2, the activation energy (17.6 kJ mol^{-1}) was found minimum and diffusivity (3.294×10^{-10} m^2 s^{-1}) was maximum for 75^{o}C.

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