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Case studies on the effect of the air drying conditions on the convective drying of quinces

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A B S T R A C T

The objective of the current study is to examine experimentally the thin-layer drying behavior of quince slices as a function of drying conditions. In a laboratory thermal convective dryer, experiments were conducted at air temperatures of 40, 50 and 60 °C and average air velocities of 1, 2 and 3 ms^{-1}. Increasing temperature and velocity resulted to a decrease of the total time of drying. The experimental data in terms of moisture ratio were fitted with three state-of-the-art thin-layer drying models. In the ranges measured, the values of the effective moisture diffusivity (D_{eff}) were obtained between 2.67 × 10^{-10} and 8.17 × 10^{-10} m^2 s^{-1}. The activation energy (E_a) varied between 36.99 and 42.59 kJ mol^{-1}.

1. Introduction

The drying is used for the removal of moisture content of different fruits and vegetables, aiming to the efficient preservation and storage for long periods of time. It is a complex process where a simultaneous heat and mass transfer in transient conditions occurs. Knowledge of the heat and mass transfer mechanisms related to the process and the role of the drying parameters has a direct impact on the improvement of the quality of the dehydrated product. The main parameters affecting the drying process are temperature, velocity and relative humidity of the drying air.

There are many published studies dealing with the effect of the drying parameters during the drying process of vegetables and fruits. Drying kinetics of vegetables such as potato, carrot, pepper, garlic, mushroom etc. were studied by Krokida et al. [1]. The authors studied the effect of air drying conditions i.e. air temperature, humidity and velocity, and characteristic sample size on drying kinetics and they concluded that the drying constant and the equilibrium moisture content of the dehydrated product increases with temperature. For the examined cases, the temperature of the drying air was the most important factor affecting the drying rate. Sacilik et al. [2] studied the thin layer characteristics of organic apples slices in a convective hot air dryer as a single layer with thickness of 5 and 9 mm. Temperatures ranged from 40 to 60 °C while a single air velocity of 0.8 ms^{-1} was utilized. They noticed that both moisture content and drying rate were affected by the drying air temperature and slice thickness and they observed a decrease in the drying time, with the increase of the air drying temperature and an increase in the drying rate, with the decrease of the slice thickness. Babalis et al. [3]

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Nomenclature

a, n	coefficients in thin layer drying models
D_0	pre-exponential factor of the Arrhenius equation ($m^2\ s^{-1}$)
D_{eff}	effective moisture diffusivity ($m^2\ s^{-1}$)
DR	drying rate (g water/h)
E_α	activation energy (kJ mol^{-1})
k	constants in thin layer drying models (h^{-1})
L	half-thickness of samples (m)
N	integer number of terms in Fick's equation
M_0	initial moisture content (g water/g dry matter)
M_{eq}	equilibrium moisture content (g water/g dry matter)
MR	moisture ratio (dimensionless)
M_t	moisture content at any time t (g water/g dry matter)
R^2	coefficient of determination
R_g	gas constant (8.3143 kJ $mol^{-1}\ K^{-1}$)
RMSE	root mean square error
T	drying temperature (°C)
t	drying time (h)
T_{abs}	absolute temperature (K)
w	weight loss (g)
w_d	dry matter (g)
w_t	dry matter at any time t (g)
w_{t+dt}	dry matter at time $t+dt$ (g)

Greek symbols

χ^2	reduced chi-square

studied the influence of the drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. The authors stated that air velocities greater than 2 ms^{-1} has no significant effect on the drying rate and they concluded that the drying kinetics is most significantly affected by the air temperature, with the airflow velocity having a limited influence on the drying process.

Focusing on the drying of quince slices, Kaya et al. [4] and Barroca et al. [5] studied the effect of the temperature and velocity of the air stream. The former also conducted measurements by altering the humidity of the drying air. In the study of Kaya et al. [4], the values of the imposed temperatures varied from 35 °C to 55 °C, the relative humidity values from 40% to 70% while air velocities from 0.2 ms^{-1} to 0.6 ms^{-1}. The authors concluded that increasing the temperature or the velocity of the drying air, the total drying time is decreased, while the relative humidity and the total drying time are related in vice-versa manner. Barroca et al. [5] carried out experiments in temperatures ranging from 40 °C to 60 °C and velocities from 0.7 ms^{-1} to 1.2 ms^{-1}. The authors stated that the moisture curves followed sigmoidal shape characteristic of the drying processes and gave evidence of a reduction in drying time with the increase in temperature. They also concluded that an increase in air velocities resulted to a higher drying rate; however, the effect of the drying velocity on the drying rate was nearly negligible for lower moisture ratios.

The purpose of the present study is the experimental investigation of the drying kinetics of quinces for air drying conditions (temperature 40, 50 and 60 °C, velocity of 1, 2 and 3 ms^{-1}, humidity 10%) that have not been studied in the earlier literature and the determination of the effective moisture diffusivity as well as the activation energy for the above conditions.

2. Experimental methods

Fresh quinces were stored in a refrigerator at about 6 °C. Before drying, the quinces were cleaned and sliced manually to a thickness of 12 mm. The initial net weight of the quince slices was about 700 g and the initial moisture content (M_0) was measured to be 81.04% in wet basis (w.b.) or 4.27 g water/g dry matter in dry basis (d.b.) and was determined by the oven-drying method, for the fresh and for the final dehydrated products at 70 °C for 24 h [6] with repetition in order to assure accurate moisture content average values.

The laboratory thermal convective dryer (LTCD) unit was starting 2 h before each experiment in order to achieve the desired steady state conditions of the drying air flow. Experiments were performed at air drying conditions of 40, 50 and 60 °C, air velocities 1, 2 and 3 ms^{-1}, while the relative humidity remained constant at 10%. Product weight, air drying temperature, probe-surface temperature and relative humidity were acquired every 10 min. All experiments were twice repeated and the means of measurements were averaged and used to express the data of the moisture content.

Fig. 1 shows the LTCD unit which is equipped with an integrated measurement and control instrumentation. The overall dimensions of the facility are 4.7 m (length), 2.5 m (width) and 2.5 m (height). The air ducts are made from steel of 0.8 mm thickness. All the ducts were insulated with 10 mm of Alveolen (Frelen). The square section drying chamber (0.5 m × 0.5 m) is of tower (vertical) type and contains a metal tray which is supported on four, side wall mounted, load cells. A set of four refractory glasses of 10 mm thickness are available to replace the side steel walls when optical clarity and precise visual observations are required. A detailed description of the components and the operational characteristics has been presented in a previous publication [7].

The air and drying product temperatures were measured using calibrated PT100 with class A tolerance and accuracy ±0.15 °C. A 3-wire transmitter used to connect the probes to the card interface with accuracy ±0.2 °C was used.

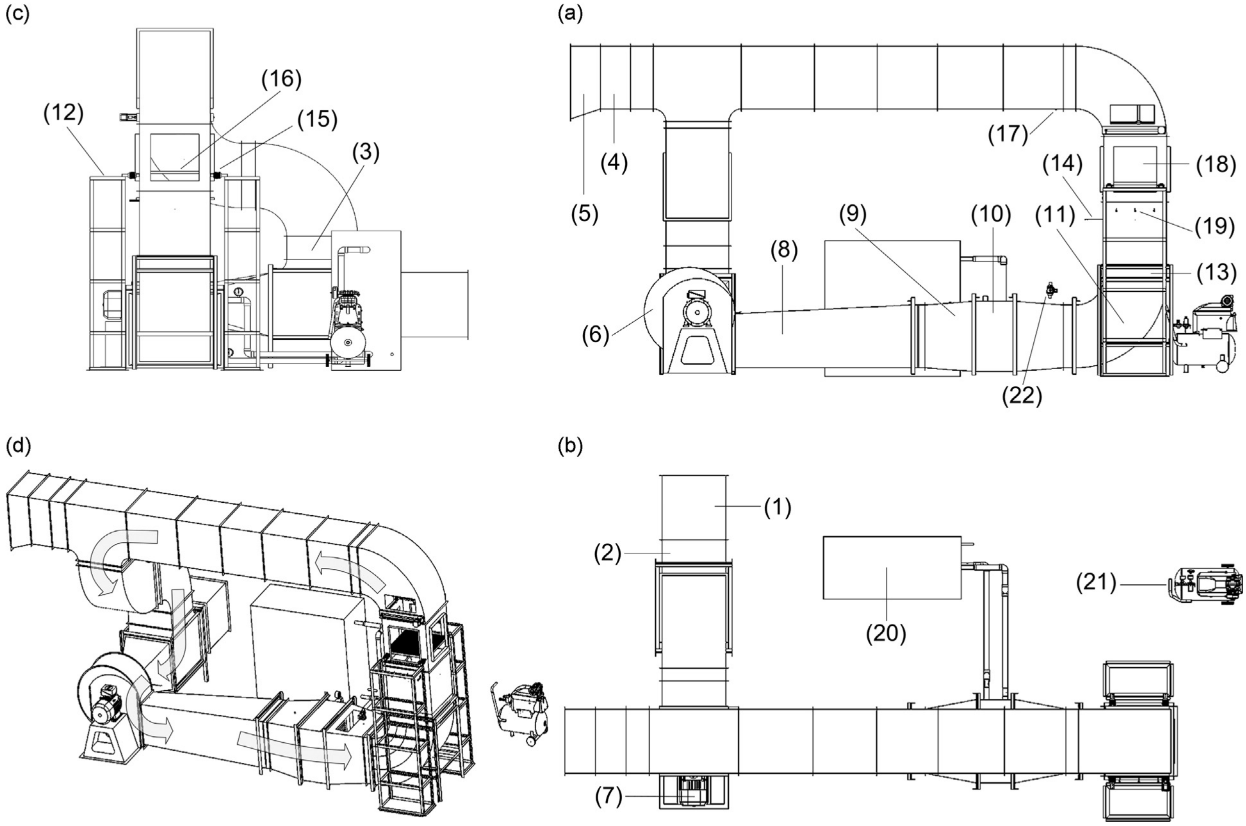

Fig. 1. Schematic diagram of the LTCD unit (curved arrow indicate the flow direction when dryer is in full recirculation operation): (a) front view, (b) top view, (c) right side view and (d) perspective view. Numbered items: (1) Ambient air inlet, (2) inlet damper, (3) by pass air damper, (4) outlet damper, (5) air outlet, (6) centrifugal fan, (7) three-phase electric motor regulated by an AC inverter, (8) diffuser, (9) temperature and humidity sensors, (10) tube heat exchanger, (11) guide vanes, (12) metal frame for pressure cells, (13) flow straightener, (14) temperature and humidity sensors, (15) pressure cells, (16) metal tray, (17) temperature and humidity sensors, (18) drying chamber, (19) pitot rake, (20) boiler, (21) air compressor, (22) water and air spray nozzle.

The relative humidity of the drying air was determined using calibrated humidity transmitter with accuracy $\pm 2.95\%$. A differential pressure transmitter with a calibrated accuracy $\pm 2\%$ of the selected range of 25 Pa was used to measure dynamic pressure and hence air drying velocity. The weight was quantified using four load cells (total nominal load 10 kg) with accuracy $\pm 0.05\%$ and an analog transmitter with accuracy $\pm 0.03\%$. A custom application in Labview® was used to operate and control the LTCD device.

3. Engineering analysis

The moisture content of the samples during the drying process is calculated according to the following formula:

$$M_t = \frac{w_t - w_d}{w_d} \tag{1}$$

where M_t is the moisture content at any time t, g water/g dry matter; w_t is the dry matter at any time t, g; w_d is the dry matter, g. It is used however to present moisture data in non-dimensional form involving the moisture ratio defined by the following equation:

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} \tag{2}$$

where M_0 and M_{eq} are the initial and equilibrium moisture contents, g water/g dry matter, respectively. M_{eq} is quite small compared with M_0 and M_t and in the MR definition may be ignored [8].

The drying rate DR of quince slices was calculated using the following equation:

$$DR = -\frac{M_{t+dt} - M_t}{dt} \tag{3}$$

where M_{t+dt} is the moisture content at time $t+dt$, g water/g dry matter and t is time, h.

The experimental data were fitted using the following three, thin-layer drying models: (i) Newton, $MR=\exp(-kt)$ [9], (ii) Henderson–Rabis, $MR=\alpha\times\exp(-kt)$ [10] and (iii) Page: $MR=\exp(-kt^n)$ [11], in order to find the best suitable model for describing the drying behavior of a quince slice in LTCD unit. Non-linear regression analysis was used for the determination of the constants of each model. The effectiveness of each model was evaluated based on statistical criteria i.e. coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE). The best model describing the thin-layer drying characteristics of quince slices was chosen based on the higher R^2 value and the lower χ^2 and RMSE values. An analytical solution of Fick's model of mass-diffusion equation for drying biological products in a falling-rate period was developed by Crank [12]. The assumption for the analytical solution were recently reviewed by Lopez [13]. For long drying times a limiting of Crank's equation is expressed in a logarithmic form:

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

where D_{eff} is the effective moisture diffusivity, m^2 s^{-1}; t is the drying time, h; L is the half-thickness of the samples. To determine D_{eff}, firstly the slope (θ) of the relationship between the experimental drying data in terms of lnMR and drying time, Eq. (4), is computed, and then D_{eff}, is calculated by:

$$\theta = \frac{\pi^2 D_{eff}}{4L^2} \tag{5}$$

The activation energy can be obtained from the Arrhenius correlation, which demonstrates the effective diffusivity reliance on temperature, and taking the natural logarithmic exponential form of Arrhenius, can be expressed as:

$$D_{eff} = D_0 \exp\left(\frac{-E_\alpha}{R_g T_{abs}}\right) \tag{6}$$

where D_0 is the pre-exponential factor of the Arrhenious equation, m^2 s^{-1}; E_α is the activation energy, kJ mol^{-1}; R_g is the gas constant, kJ mol^{-1} K^{-1}; T_{abs} is the absolute temperature. The above exponential form of Arrhenius can be expressed as:

$$\ln D_{eff} = \ln D_0 - \frac{E_\alpha}{R_g T_{abs}} \tag{7}$$

A plot of lnD_{eff} versus $1/T_{abs}$, gives a straight line of slope E_α/R_g slope and consequently, the energy activation (E_α).

4. Results and discussion

The drying curves for all the drying experiments performed are reported in Figs. 2 and 3. Fig. 2a shows the variation of moisture content with time for different temperatures at 2 ms^{-1} air velocity. Increasing the temperature from 40 °C to

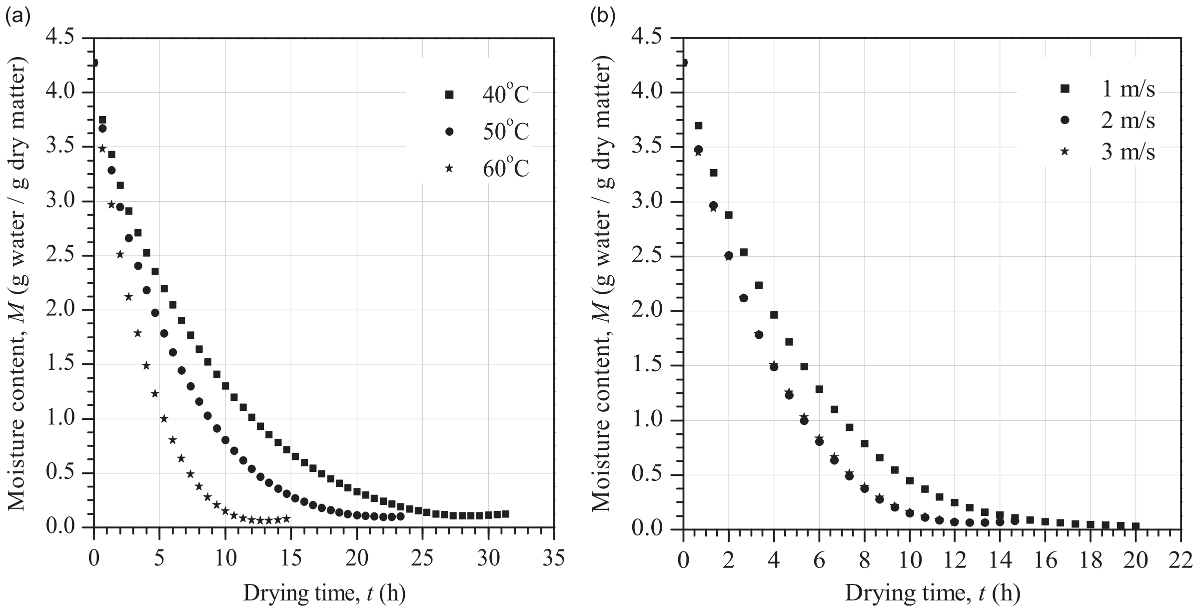

Fig. 2. The variation of moisture content with drying time for (a) different temperatures at air velocity of 2 ms^{-1} (b) different air velocities at temperature of 60 °C.

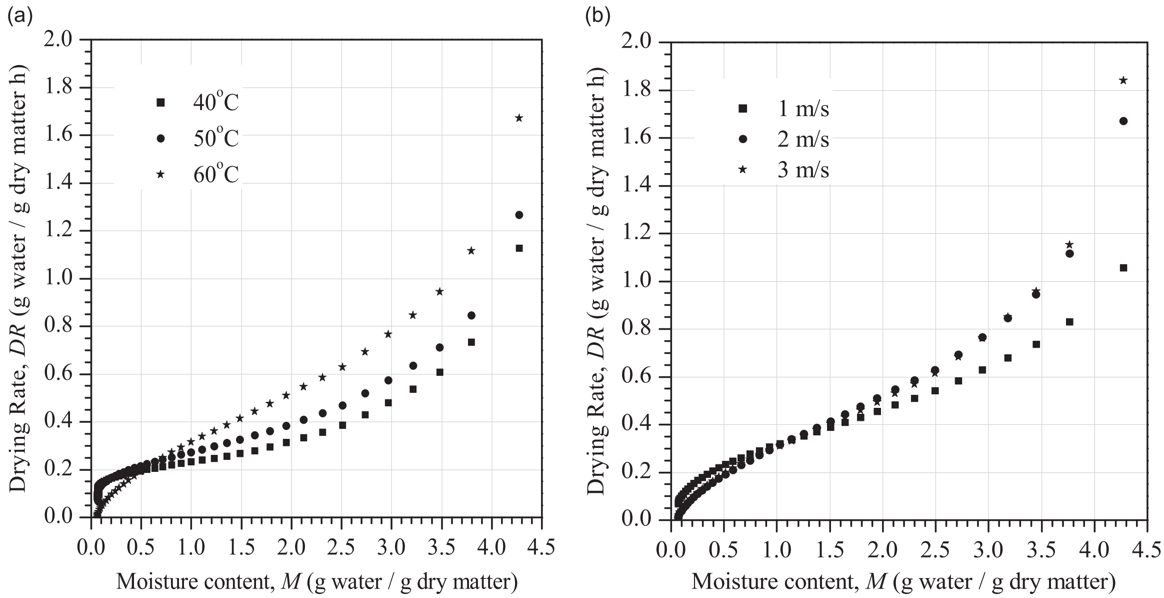

Fig. 3. The infulence of drying temperatures on the variation of the drying rate with moisture content at (a) air velocity of 2 ms^{-1} (b) temperature of 60 °C.

Table 1
Fitting results for different drying conditions.

Air velocity (ms^{-1})	T (°C)	Model	k	α	n	R^2	$\chi^2 \times 10^{-4}$	RMSE
1	40	Newton	0.0986	0.9386	0.8721	0.9907	4.92	0.0221
		Henderson–Rabis	0.0922			0.9943	3.01	0.0173
		Page	0.1363			**0.9972**	**1.50**	**0.0122**
	50	Newton	0.1676	0.9734	0.9852	0.9974	1.71	0.0130
		Henderson–Rabis	0.1631			0.9974	1.68	0.0129
		Page	0.1727			**0.9981**	**1.23**	**0.0110**
	60	Newton	0.2139	1.0094	1.0716	0.9958	2.97	0.0172
		Henderson–Rabis	0.2158			0.9958	2.96	0.0171
		Page	0.1882			**0.9971**	**2.04**	**0.0142**
2	40	Newton	0.1254	0.9448	0.9423	0.9942	3.59	0.0189
		Henderson–Rabis	0.1184			0.9955	2.81	0.0167
		Page	0.1434			**0.9975**	**1.57**	**0.0125**
	50	Newton	0.1736	0.9562	0.9616	0.9955	2.85	0.0168
		Henderson–Rabis	0.1660			0.9961	2.49	0.0157
		Page	0.1874			**0.9975**	**1.56**	**0.0124**
	60	Newton	0.2805	1.0112	1.0768	0.9951	3.57	0.0188
		Henderson–Rabis	0.2835			0.9952	3.53	0.0186
		Page	0.2497			**0.9967**	**2.40**	**0.0153**
3	40	Newton	0.1031	0.9628	0.9536	0.9946	3.41	0.0184
		Henderson–Rabis	0.0990			0.9956	2.83	0.0167
		Page	0.1155			**0.9966**	**2.18**	**0.0147**
	50	Newton	0.1745	0.9903	1.0123	0.9979	1.42	0.0119
		Henderson–Rabis	0.1728			0.9980	1.40	0.0117
		Page	0.1703			**0.9980**	**1.37**	**0.0116**
	60	Newton	0.2782	1.0024	1.0507	0.9946	3.97	0.0198
		Henderson–Rabis	0.2789			0.9946	4.03	0.0198
		Page	0.2578			**0.9954**	**3.45**	**0.0183**

50 °C, the drying time is decreased about 25%. A further increase in 60 °C decreased the drying time about 36%, while the total drying time is reduced about 54% in respect of an increase of the drying temperature from 40 °C to 60 °C.

Fig. 2b presents the variation of moisture content for different air velocities at constant air temperature of 60 °C. In this way, the effect of the air drying velocity in the drying time is evident. An increase in the air velocity from 1 to 2 ms^{-1} results to a decrease of the drying time about 30%. It is interesting to note that the curves corresponding to 2 and 3 ms^{-1} coincide during the experiments, showing that for values greater than 2 ms^{-1}, the velocity has not a significant effect on the drying process. The results of the above figures indicate that the increase of temperature and velocity affect the heat and mass transfer which seems to be most significant for higher temperature differences of drying air and product and also for higher air drying velocities. However, for large values of velocity, the most important parameter is the temperature difference, while the effect of the velocity diminishes.

Fig. 3a presents the influence of drying temperature on the variation of the drying rate with moisture content at air velocity 2 ms^{-1}. Increasing the drying temperature results in an increase of the drying rate and a decrease of the total time of drying. In agreement to the previous plots, the higher temperature difference between the air and the quince accelerates the removal of water. All the curves of the diagram indicate four zones which are characterized by the different rates of drying rate decrease with the decrease of moisture content. Initially, a significant decrease of the drying rates occurs until a moisture content value close to 3.8 g water/g dry matter for all the drying temperatures. After this value of moisture, an intermediate region is observed before a third zone, in which an almost linear decrease occurs, leads to low moisture contents. The third region can be considered to extend from 3 to 0.5 g water/g dry matter for all the temperatures examined. After this value of moisture content, the rates of decrease are sharp, denoting the final stage of drying. For the three different temperatures, two different routes to the equivalent moisture are apparent. The main feature of this plot is evidently the presence of the falling rate period, a behavior which has been also observed in Ref. [2].

Fig. 3b presents the influence of air drying velocity on the variation of the drying rate with moisture content at air temperature 60 °C. It can be observed that the higher the air drying velocity the higher the drying rate especially for greater moisture content (4.27 to 1.5 g water/g dry matter). At lower moisture content, the effect of the velocity on the drying rate seems to be insignificant. In particular, it is evident that the effect of air velocity can be considered negligible for values higher than 2 ms^{-1}, since after that limit the drying curves are practically identical.

The statistical results in terms of R^2, χ^2 and RMSE, as well as drying constants k for Newton, a and k for Henderson–Rabis and k, n for Page models, are shown in Table 1, where T is the drying temperature. All the three thin-layer drying models obtain an $R^2 > 0.99$ while the small values for the other criteria, show a very good consistence with the experiments. Among

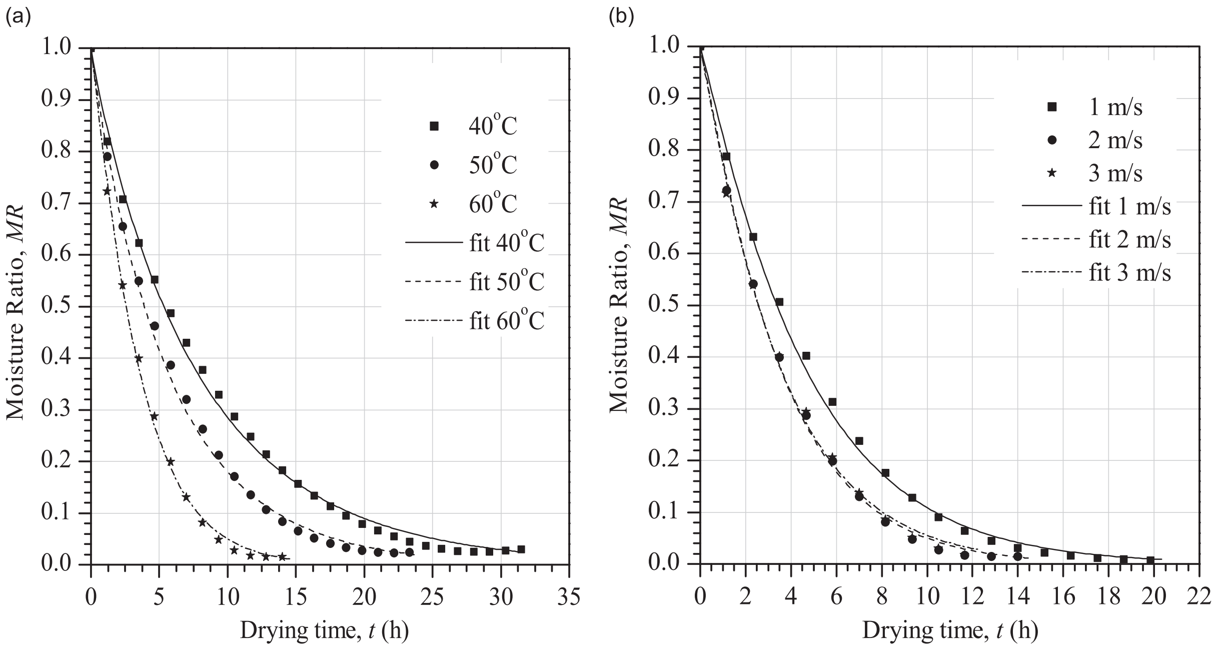

Fig. 4. Fitting the moisture ratio with the Page thin-layer drying model for (a) different temperatures at air velocity of 2 ms^{-1} (b) different air velocities at temperature of 60 °C.

Table 2
Effective moisture diffusivity coefficient, D_{eff}.

Air velocity (ms^{-1})	Temperature (°C)	$D_{eff} \times 10^{-10}$ ($m^2 s^{-1}$)	R^2
1	40	2.67	0.9993
	50	4.42	0.9989
	60	6.26	0.9933
2	40	3.23	0.9982
	50	4.91	0.9951
	60	7.82	0.9958
3	40	3.06	0.9901
	50	5.36	0.9940
	60	8.17	0.9903

Table 3
Energy of activation E_α and Arrhenius coefficient D_0.

Air velocity (ms^{-1})	E_α ($kJ\,mol^{-1}$)	R^2	D_0 ($m^2\,s^{-1}$)
1	36.99	0.9925	4.04×10^{-4}
2	38.29	0.9976	7.78×10^{-4}
3	42.59	0.9959	3.97×10^{-3}

the selected models, the Page model implies an excellent consistency in all the ranges of the drying air temperatures and velocities (bold numbers in Table 1) and thus this model may be assumed to represent the drying behavior of quince slices in a convective dryer within the examined range. All the experimental values of the moisture ratio for the different drying air temperatures and velocities, as well the fittings obtained for each case using the Page model are illustrated in Fig. 4a and b, respectively.

Table 2 shows the effective moisture diffusivity (D_{eff}) for each test. D_{eff} values varied from 2.67×10^{-10} to 8.17×10^{-10}. These values are in a good agreement with those reported in the literature [4,14]. An increase in either the velocity or temperature increases moisture diffusivity due to the higher mass transfer.

The energy activation (E_α) and the Arrhenius coefficient (D_0) for each value of drying air velocity are presented in Table 3. An increase in air velocity increases both E_α and D_0. The value of energy activation ranged between 36.99 kJ mol^{-1} and 42.59 kJ mol^{-1}, similar to those given in the literature for the drying of different foods [4,15].

5. Conclusion

In the present study, a LTCD unit was used to assess the drying kinetics of quince. Experiments were carried out at three different drying air temperatures (40 °C, 50 °C and 60 °C) and three drying air velocities (1 ms^{-1}, 2 ms^{-1} and 3 ms^{-1}) while relative humidity remained constant at 10%. The following conclusions can be drawn from the experimental study:

i. Increasing the drying temperature or the velocity of the drying air decreases the total drying time. In particular, an increase from 40 °C to 60 °C in temperature, at 2 ms^{-1} drying velocity resulted to a decrease of the total time of drying of about 54%. On the other hand at air drying temperature of 60 °C, an increase from 1 ms^{-1} to 2 ms^{-1} in drying velocity resulted to a decrease of the total time of drying of about 30%.
ii. At lower moisture content the effect of the air drying velocity on the drying rate is nearly insignificant.
iii. A nonlinear regression analysis was performed, indicating that Page's thin-layer drying model is best-fitted to the experimental results.
iv. Using the experimental data, the values of D_{eff} were estimated, showing that an increase in drying velocity or temperature increases effective moisture diffusivity.
v. The estimated values of E_a and D_0 lie within the range reported in the earlier literature for quince slices drying while an increase in drying velocity increases energy of activation.

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