Drying kinetics, modeling and quality of quince slices in thin layer air impingement jet dryer

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Abstract: Quince is a nutritionally important fruit, which is not much appreciated for fresh consumption. Drying of quince is one of the methods which is suited for preserving it against deterioration. In this paper, an experimental investigation was conducted to study the drying kinetics, modeling and quality of quince slices in an air impingement dryer under different drying temperatures, air velocities and relative nozzle-to-product distance (*H/D*) values. The results indicated that increasing drying air temperature and velocity can reduce the drying time. In addition, the impact of drying temperature on the drying time was more significant than that of the air velocity. It was also observed that the maximum heat and mass transfer occurs at the *H/D* ratio of 4 as Reynolds number varies between 4000 and 7500. The effective moisture diffusivity of quince slices ranged from 3.04×10^{-10} to 7.85×10^{-10} m^2 s^{-1} and the activation energy of quince slices were 23.570, 24.825 and 33.430 kJ mol^{-1} at different velocities of air. Based on the results reported in this study, the Midilli model provided the best fit to describe the experimental drying data of quince slices. Furthermore, the results showed that the rehydration ratio of dried slices increased as *H/D* ratio rose and dropped with increase of the drying temperature and air velocity. Also results of color change of dried samples demonstrated that drying temperature and air velocity significantly affected the overall color change of quince slices, while the interaction between drying temperature and air velocity beside main effect of *H/D* ratio did not show any statistically significant difference in color change of dried samples. From the point of view of the drying time, rehydration ratio and color change of the dried slices, the optimum drying conditions were proposed.

Keywords: air impingement jet dryer, drying kinetics, quince slices, rehydration ratio, color change.

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1 Introduction

Quince is a delicious fruit which has a rich source of organic acids, sugars, fiber, minerals and phenolic compounds with antioxidant activity. The quince fruit is not much suitable for fresh consumption because of the hardness and bitterness of the pulp. Drying of the quinces is one of the preserving methods and extends their shelf lives by reducing moisture content to a safe level (Akpinar and Bicer, 2005). Dried quince is mainly considered to make jam, marmalade, jelly, cake and ingredients of foods.

Several methods of drying are applied to reduce the water content of fruits and vegetables. Sun drying is conventional and oldest method which is free and uses renewable source of energy (Tiwari, 2016). Disadvantages of this method such as long drying time, contamination by dust and insects, non-uniform drying and rewetting of products due to bad weather result in poor quality of dried products (Xiao et al., 2015). The air

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impingement jet drying with high heat and mass transfer rates has been considered as one of the relatively quick methods. In this technic, the high values of heat transfer coefficient are achieved at lower temperatures and in a shorter drying time (Xiao and Mujumdar, 2014). The range of impingement jets use in industrial applications is wide (Mujumdar, 2006). Since high heat and mass transfer can extensively reduce drying time, this technology is applied in thin layer drying of food products (Wang et al., 2015). The air impingement jet drying due to high heat transfer coefficient in lower temperatures, shorter processing time and better drying quality of products is preferred to conventional methods of drying, at the same temperature (Mujumdar, 2006; Jung et al., 2015).

In recent years, this technology has been employed by researchers in the field of food and agricultural product processing such as baking and drying. This method has been used to blanch apple quarters and seedless grapes (Bai and Gao et al., 2013; Bai and Sun et al., 2013). Banooni et al. (2009) and Sumnu et al. (2007) used this technology to bake bread; Anderson and Singh (2006) handled it to thawing of frozen foods; Wahlby et al. (2000) applied it to cook yeast buns and pork cutlet; Li and Walker (1996) used it to bake cake. In the case of drying, it has been applied to dry pressed fish cake (Bórquez et al., 1999), tortilla chips (Li et al., 1999), corn tortillas (Braud et al., 2001), tortilla and potato chips (Caixeta et al., 2002; Moreira, 2001), fish particles (Bórquez, 2003), coriander seeds (Merino et al., 2008), seedless grapes, carrot cubes and yam slices (Xiao and Gao et al., 2010; Xiao and Pang et al., 2010; Xiao et al., 2012), ganoderma lucidum (Bai and Xiao et al., 2013), onion slices (Li et al., 2015), kiwifruit slices (Huang et al., 2017; Li et al., 2016), ginseng slices (Wang et al., 2015; Xiao et al., 2015), hami melon (Zhang et al., 2011; Zheng et al., 2014). In these researches, the only effects of temperature and air velocity on drying kinetics and quality characteristics have been investigated, while the effect of relative nozzle-to-product distance (*H/D*) as an effective parameter in the air impingement jet dryers is important.

The drying kinetics parameters are key factors to design and control of the drying process (Vega-Gálvez et al., 2008). Mathematical models have been widely used to describe and predict the drying kinetics of food materials (Akpinar, 2006; Kaya et al., 2007).

Air impingement drying is one of the best methods for drying fruit slices, if the quality of the final product is acceptable. Rehydration ratio and color change of dried products are two important quality aspect. The color of dried product is mentioned as a one of the first quality attributes assessed by consumes and can convince consumers to purchase the product. By rehydration, the product represents similar characteristics to the fresh product. Therefore, least color change and higher rehydration ratio of the products are good. Several researches have been carried out to investigate change of quality attributes of the quince during osmotic drying (Babić et al., 2008; Babić et al., 2007; Radojčin et al., 2010; Radojčin et al., 2015) and to study thin layer of the quince dried in convective hot air dryer (Izli and Polat, 2019; Kaya et al., 2007), but none have been reported for the quince dried by air impingement jet technology. This study was focused on use of air impingement jet technic and investigates the impact of different drying conditions on drying kinetics and quality attributes of the quince slices.

The objectives of this study were to investigate the effects of drying air temperature, air velocity and relative nozzle-to-product distance (*H/D*) on the drying kinetics of the quince slices in an air impingement jet dryer. They will enable us to evaluate a suitable mathematical drying model for describing the drying characteristics and to compute the drying rate, effective moisture diffusivity and activation energy of the dried quince slices. Furthermore, rehydration ratio and color change of dried slices was evaluated.

2 Materials and methods

2.1 Raw materials

The quince fruits used in this study were obtained from a local agricultural market in Sanandaj, Iran. The quinces of uniform color and regular size were selected and stored in a refrigerator at +4 ℃ prior to the drying experiments. The average initial moisture content of the quince samples was 84.1% w.b. (5.28 d.b.), as determined by vacuum drying at 70 ℃ for 24 h following Associations of Official Analytical Chemists procedures [no. 934.06]. The samples were cut into slices having 5 mm thickness using the kitchen slicer (Siemens MS42006N Slicer).

2.2 Experimental apparatus

The air impingement drying equipment, designed and manufactured to study drying kinetics of different fruits, is illustrated in Figure 1. This apparatus basically consists of a side channel blower to supply and circulate the air flow, an electric heater to heat the air, a T-SSR relay (GOLD, China) and a *TC4W* controller (Autonics, South Korea) to keep the temperature of air discharged from nozzles constant, and series of linear circular nozzles. A *VSD2* frequency converter (Vynckier, USA) was used to vary the air velocity. The bolt and screw mechanism were applied for adjusting the distance between circular nozzles and drying tray. Each plenum has an array of 3×3 nozzles. The diameter (*D*) of each nozzle is 15 mm. Air outlet velocity was measured with Hot Film Anemometer (Smart Sensor AR866 model with the accuracy of 0.3-30 ±1% m s^{-1}). An electronic balance with accuracy of ±0.01 g (Sartorius TE1502S, England) was applied to measure weight loss of samples.

1. Upper plenum 2; Plenum air temperature display; 3. Plenum temperature sensor; 4. Drying tray and quince slices being dried; 5. Series of circular nozzles; 6. Lower plenum; 7. Air flow valve; 8. Electric heater; 9. Side channel blower; 10. Frequency converter; 11. Temperature PID controller; 12. Control unit.

Figure 1 The air impingement jet dryer

2.3 Experimental procedure

The experiments were conducted in two sections: The first section was carried out based on a factorial layout in a completely randomized design (CRD) with two factors including temperature at three levels of 50 ℃, 60 ℃ and 70 ℃ and velocity with 3 levels of 5, 7 and 9 m s^{-1}. The second section was done based on a single-factor to explore the effect of *H/D* ratio at 3 levels of 4, 5 and 6.

The experiments were repeated three times and the drying kinetics are calculated using average of the three experiments. The temperature of surroundings during drying experiments was in the range of 17 ℃-21 ℃. After the temperature reached to the set point, the quince slices were spread in a single layer on the stainless-steel wire mesh in the drying chamber. Weight loss of samples was measured at 5-minute intervals during drying. The time of sample weighing was less than 15 seconds. The drying continued until the samples reached a constant weight. The samples were cooled and packed in low density polyethylene bags that were heat-sealed.

2.4 Mathematical modelling of drying curves

The moisture ratio (*MR*) of quince slices during the thin layer drying process was calculated based on the application of the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

Since the values of equilibrium moisture content M_e are relatively small compared to M_t or M_0, the Equation 1 can be written in a simplified form as Equation 2 (Xiao and Pang et al., 2010).

$$MR = \frac{M_t}{M_0} \quad (2)$$

The drying rate (*DR*) of quince slices during drying experiments was calculated using Equation 3:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

The drying data obtained were fitted by several different moisture ratio models (Henderson and Pabis (Zhang and Litchfield, 1991), Lewis (Roberts et al., 2008), Logarithmic (Kingsly et al., 2006), Midilli et al. (Midilli et al., 2002) and Page (Hassan-Beygi et al., 2009)) that are widely applied in most food and biological materials. The coefficient of determination (R^2) and root mean square error (*RMSE*) were used to select the best model. The model with highest R^2 and lowest *RMSE* values, is considered as the best suitable model representing the drying kinetics (Akpinar and Bicer, 2005).

2.5 Effective moisture diffusivity

Effective moisture diffusivity is defined as moisture movement and closely related to drying rate. The effective moisture diffusivity is relatively related to moisture velocity within the material, while the drying rate is the moisture evaporation rate and depends directly on the pressure gradient that exists between material and the air caused by temperature gradient (Ahmad et al., 2017).

It has been commonly accepted that the drying process of most agricultural products during the falling rate period can be described by Fick's second law of diffusion (Falade and Solademi, 2010; Xiao and Gao et al., 2010). In thin layer drying, the curves of moisture ratio as a function of time are plotted based on Fick's second law of diffusion to estimate the effective moisture diffusivity (Saxena and Dash, 2015). The Fick's second law of diffusion is shown in Equation 4:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (4)$$

With some assumption, the solution of the Fick's second law for a long drying time of infinite slab materials can be written as Equation 5: (Doymaz, 2012)

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2}\left[\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right)\right] \quad (5)$$

Taking the natural logarithm of both sides of Equation 6, resulted in Equation 6:

$$\ln MR = \mathrm{Ln}\frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (6)$$

The slope (K_1) can be given by plotting experimental drying data in terms of ln *MR* versus time and fitting a linear regression, finally the D_{eff} can be calculated as Equation 7:

$$K_1 = \frac{\pi^2 D_{eff}}{4L^2} \quad (7)$$

2.6 Activation energy

The activation energy for drying process is the minimum energy to initiate moisture diffusion during drying (Wang et al., 2015). It is inversely proportional to the effective moisture diffusivity where low activation energy means less energy required to split moisture particle bonding and coincide with a higher value of effective moisture diffusivity (Ahmad et al., 2017). The activation energy can be computed from the Arrhenius relation as shown in Equation 8:

$$D_{eff} = D_0 \exp\left[-\frac{E_a}{R(T+273.15)}\right] \quad (8)$$

The Equation 9 has been obtained by taking the natural logarithm of both sides of the Equation 8.

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{R}\frac{1}{T+273.15} \quad (9)$$

Plotting the calculated data in terms of ln D_{eff} versus *1/ (T+273.15)* and finding a regression line to fit the data, would give slope (K_2) as shown in Equation 10:

$$K_2 = \frac{E_a}{R} \quad (10)$$

2.7 Measurement of rehydration ratio

The rehydration ratio of the dried quince slices was measured by the following procedure. 300 ml of distilled water with a constant temperature equal to 90 ℃ was prepared in a 400 ml beaker. Approximately 5 g dried quince slices were weighed and placed into beaker for 30 minutes, following the methodology has been described by Lin et al. (2007) with some modification. After this stage was completed, the rehydrated samples were removed from the beaker and the excess water on their surfaces was absorbed with blotter paper. Weights of rehydrated samples were determined using a digital balance (Sartorius ED323S, England) with accuracy of 0.001 g. All experiments were executed in triplicate and the rehydration ratio (*RR*) was determined, as shown in Equation (11):

$$RR = \frac{\text{weight of sample after rehydration (g)}}{\text{weight of dry sample (g)}} \quad (11)$$

2.8 Color change measurement

The color measurement carried out for dried and fresh quince slices using a simple digital imaging method. A digital camera (Sony Cyber shot DSC-H3, 8.1 Mega Pixel, 10x optical zoom) was used to measure color by capturing the color image of the sample under two 40 W florescent light. The captured images were analyzed using the ImageJ software. This software can convert an image from RGB color space to L*a*b* color space and display the L*, a* and b* images in the separated images. However, they can be measured easily. L*, a*, and b* color scale was measured for all images. All measurements were replicated thrice and the mean readings were taken. The color change of quince slices was calculated by the Equation 12. In this equation, the subscripts 0 and 1 correspond to fresh and dried samples respectively.

$$\Delta E = [(L_1^* - L_0^*)^2 + (a_1^* - a_0^*)^2 + (b_1^* - b_0^*)^2]^{0.5} \quad (12)$$

2.9 Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) and mean comparison operations were conducted by Tukey method at 0.05 probability level. The statistical operations were done by Minitab 16 software. The statistical analysis of moisture ratio versus drying time for model fitting was performed using MATLAB software (Version 8.4.0) and ImageJ software (Version 1.40g) was applied to analyze and determine color parameters.

3 Results and discussion

The effects of different drying air temperatures (50 ℃, 60 ℃ and 70 ℃), air velocities (5, 7 and 9 m s^{-1}) and *H/D* ratios (4, 5 and 6) on drying kinetics of quince slices are illustrated in Figures 2, 3 and 4 respectively.

3.1 Effects of air temperature and velocity on moisture ratio

The moisture ratio of the quince slices as a function of time and drying rate with respect to moisture content are shown in Figures 2 and 3. The influence of air temperature (*T*) and air velocity (*V*) on the variation of moisture ratio with drying time, are shown in the part of a in these Figures. The H/D was kept constant at 5. As it can be seen, the moisture ratio of quince slices decreased with the increase of drying time. The drying time to reach the final moisture content (0.168 d.b.) for quince slices decreased with increasing drying temperature and air velocity.

The analysis of variance for drying time indicated that increasing drying temperature and air velocity could reduce the drying time (Table 1). In addition, the effect of drying temperature on drying time was more significant than that of the air velocity (Table 2). Similar results have been found during drying of Chinese jujube (Lou et al., 2013), Monukka seedless grapes (Xiao and Pang et al., 2010) and American Ginseng (Wang et al., 2015).

3.2 Effects of air temperature and velocity on drying rate

Figures 2 (b) and 3 (b) exhibit the distribution of drying rate with respect to moisture content. It is clear that the drying rate decreases with moisture content. There is a rapid decrease in drying rate during the initial period and slow decrease at the later stages of the drying process. It is also found that a constant rate period is not observed in drying of quince slices and the drying process generally takes place in the falling rate period, depending on diffusion of moisture from the interior of the quince slices to the surface and then mass transfer from the surface. Similar results have been reported in previous investigations on drying of various agricultural products drying (Akpinar and Bicer, 2005; Kaya et al., 2007; Lou et al., 2013; Xiao and Pang et al., 2010).

3.3 Effect of H/D ratio on the moisture ratio and drying rate

Figure 4 presents the effect of *H/D* ratios on the variation of moisture ratio with drying time and drying rate versus moisture content, respectively. From the experimental results, it is observed that the moisture ratio decreases as *H/D* ratio falls. A decrease in the value of *H/D* ratio results in drying time reduction due to increased convective heat and mass transfer between the quince slices and drying air. Similar trends have also been reported by Li et al. (2016), Xiao and Pang et al. (2010).

As shown in Table 1, the response of drying time was affected significantly ($p < 0.01$) by *H/D* ratio. The means comparisons (Figure 5) shows that the total drying time decreased when H/D value varied from 6 to 4. Decreasing *H/D* from 6 to 5 reduces the total drying time by 12.6% and further decrease in *H/D* ratio to 4 represents 11.7% save in drying time. In general, dropping the *H/D* from 6 to 4 results in 22.8% reduction in drying time.

Figure 4 indicates that the maximum heat and mass transfer occurs at *H/D* ratio of 4 as Reynolds number varies between 4000 and 7500. The results are in good agreement with Chakron et al. (1998), where they found the maximum heat transfer occurs at *H/D* ratio between 4 and 6 for Reynolds number between 6500 and 19000. Also, Obot and Trabold (1987) demonstrated the narrow H/D ratios give better heat transfer performance. They found that the H/D ratio of 4 exhibits maximum heat transfer for some experiments. Additional discussion on H/D ratio effects is provided by Lee et al. (2014), who found the maximum heat transfer appears to be associated with H/D ratio of 5 for the Reynolds number 8000.

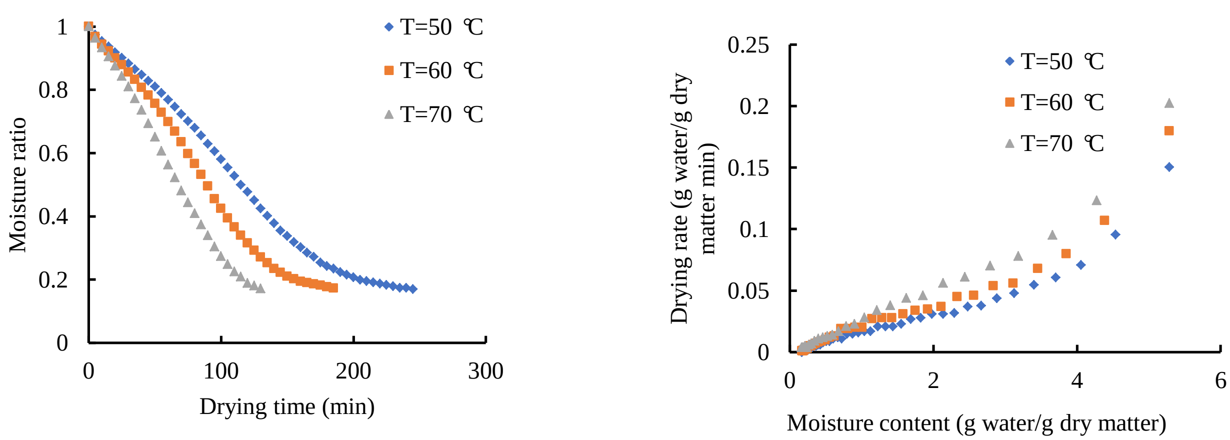

Figure 2 Influence of air temperatures on moisture ratio and drying rate at *V*=7 m/s (a and b respectively).

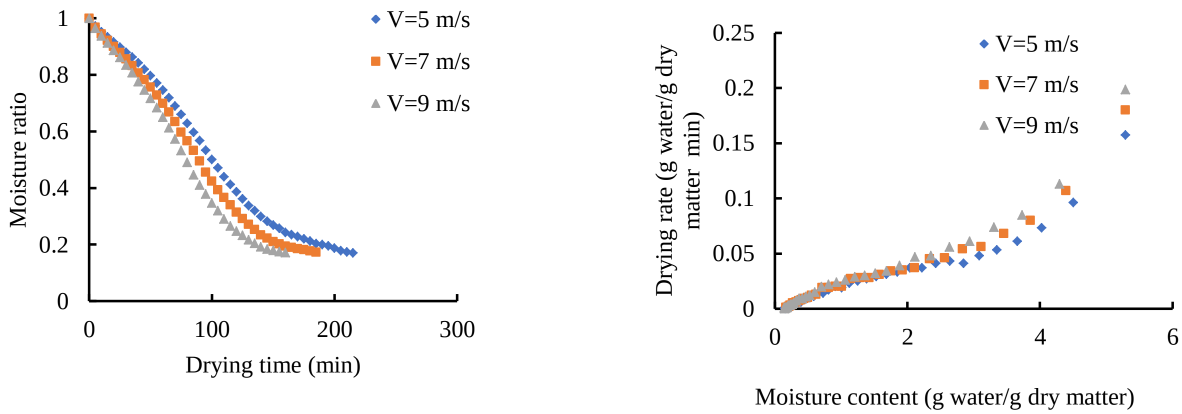

Figure 3 Influence of air velocities on moisture ratio and drying rate at T=60 ℃ (a and b respectively).

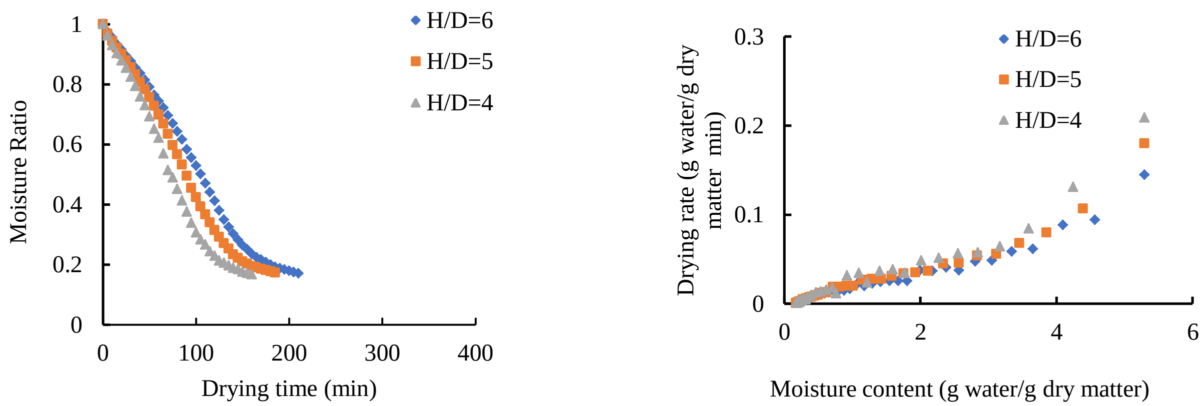

Figure 4 Influence of H/D values on moisture ratio and drying rate at T=60 ℃, V=7 m s^{-1} (a and b respectively)

Table 1 ANOVA results of the effects of drying temperature, air velocity and H/D on drying time

Source	Degree of freedom	Mean square	F	P
T	2	27317.6	1017.34	0.000
V	2	7895.4	294.03	0.000
T× *V*	4	42.6	1.59	0.221
Error	18	26.9		
H/D	2	1758.3	19.78	0.002
Error	6	88.9		

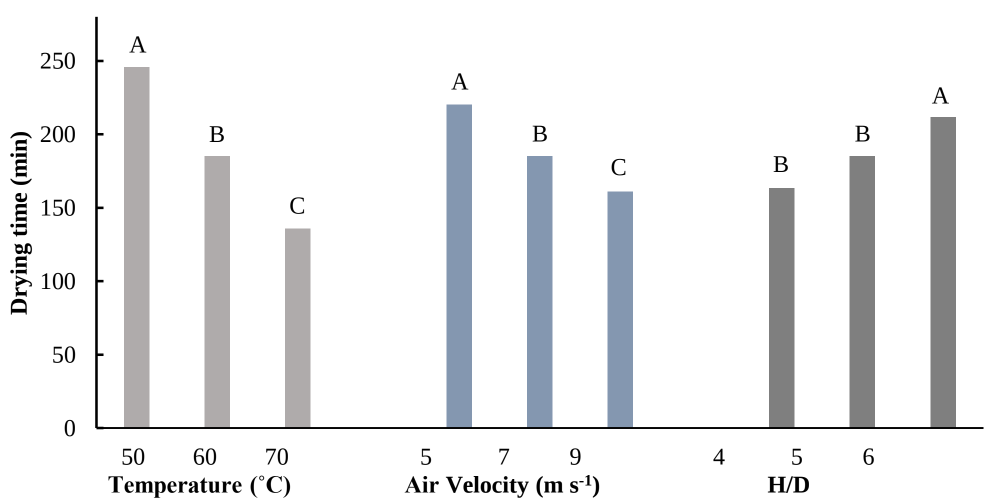

Figure 5 Means comparison of drying temperature, air velocity and H/D levels in terms of drying time

Means that share a letter are not significantly different at 5% probability level.

Table 2 Coefficients of different drying models for each experimental treatment

Model	Treatment	Model parameter				R^2	*RMSE*
Henderson and Pabis	No. 1	a= 1.1	k= 0.000114			0.9748	0.0449
	No. 2	a= 1.106	k= 0.008342			0.9708	0.0487
	No. 3	a= 1.096	k= 0.01086			0.9745	0.0459
MR = a exp(-kt)	N0. 4	a= 1.099	k= 0.007345			0.9727	0.0466
	No. 5	a= 1.102	k= 0.00952			0.9678	0.0513
	No. 6	a= 1.095	k= 0.01234			0.9684	0.0502
	N0. 7	a= 1.097	k= 0.007799			0.9715	0.0471
	No. 8	a= 1.1	k= 0.01079			0.9664	0.0526
	N0. 9	a= 1.103	k= 0.015			0.9532	0.0632
	No. 10	a= 1.107	k= 0.008254			0.965	0.0533
	No. 11	a= 1.095	k= 0.01141			0.9715	0.0487
Lewis	No. 1	k= 0.000102				0.9579	0.0576
	No. 2	k= 0.007374				0.9508	0.0624
	No. 3	k= 0.009724				0.9583	0.0578
	N0. 4	k= 0.006548				0.9553	0.0589
MR = exp(-kt)	No. 5	k= 0.00845				0.949	0.0637
	No. 6	k= 0.01097				0.9495	0.0622
	N0. 7	k= 0.00694				0.9536	0.0594
	No. 8	k= 0.009592				0.9478	0.0645
	N0. 9	k= 0.0132				0.9312	0.0749
	No. 10	k= 0.007278				0.9442	0.0665
	No. 11	k= 0.01023				0.9555	0.0599
Logarithmic	No. 1	a= 1.366	k= 0.004304	c= -0.3092		0.9843	0.0358
	No. 2	a= 1.53	k= 0.004441	c= -0.4743		0.9837	0.036
	No. 3	a= 1.401	k= 0.006536	c= -0.348		0.9851	0.0357
	N0. 4	a= 1.56	k= 0.003744	c= -0.5145		0.9875	0.0318
MR=a exp(-kt) + c	No. 5	a= 1.704	k= 0.00431	c= -0.6591		0.9859	0.0344
	No. 6	a= 2.497	k= 0.003467	c= -1.466		0.9941	0.0222
	N0. 7	a= 1.736	k= 0.003441	c= -0.6959		0.9891	0.0295
	No. 8	a= 1.87	k= 0.004307	c= -0.8303		0.9874	0.0327
	N0. 9	a= 5.153	k= 0.00187	c= -4.124		0.9909	0.0286
	No. 10	a= 1.914	k= 0.003207	c= -0.8704		0.9868	0.0332
	No. 11	a= 1.486	k= 0.006243	c= -0.4389		0.9849	0.036
Midilli et al.	No. 1	a= 0.9539	k= 0.000138	n= 1.802	b= 0.000495	0.9983	0.0118
	No. 2	a= 0.9582	k= 0.000167	n= 1.837	b= 0.000629	0.9986	0.0111
	No. 3	a= 0.959	k= 0.000361	n= 1.773	b= 0.00077	0.9982	0.0124
	N0. 4	a= 0.955	k= 0.000182	n= 1.761	b= 0.000443	0.9982	0.0122
MR= a exp(-kt^n) + bt	No. 5	a= 0.954	k= 0.000216	n= 1.824	b= 0.000605	0.9978	0.0137
	No. 6	a= 0.9746	k= 0.000816	n= 1.599	b= 0.000148	0.999	0.0091
	N0. 7	a= 0.958	k= 0.000225	n= 1.739	b= 0.000447	0.9984	0.0116
	No. 8	a= 0.956	k= 0.000395	n= 1.792	b= 0.000588	0.9976	0.0146
	N0. 9	a= 0.9666	k= 0.000551	n= 1.763	b= 0.000168	0.9975	0.0155
	No. 10	a= 0.9552	k= 0.000162	n= 1.824	b= 0.000462	0.9974	0.015
	No. 11	a= 0.9542	k= 0.000346	n= 1.798	b= 0.000764	0.9977	0.0143
Page	No. 1	k= 0.000877	n= 1.389			0.9931	0.0235

	No. 2	k= 0.000876	n= 1.446	0.9941	0.0219
	No. 3	k= 0.00163	n= 1.394	0.9937	0.0227
	N0. 4	k= 0.000818	n= 1.424	0.9953	0.0193
MR= exp(-kt^n)	No. 5	k= 0.000964	n= 1.468	0.9947	0.0208
	No. 6	k= 0.001322	n= 1.488	0.9983	0.0117
	N0. 7	k= 0.000829	n= 1.441	0.9962	0.0173
	No. 8	k= 0.001091	n= 1.482	0.9953	0.0198
	N0. 9	k= 0.001053	n= 1.611	0.996	0.0186
	No. 10	k= 0.000662	n= 1.502	0.9906	0.0276
	No. 11	k= 0.001156	n= 1.399	0.9949	0.0203

3.4 Modelling of drying kinetics

In this study, 5 different mathematical models were used to represent the moisture ratio data. Nonlinear regression analysis was used to estimate the parameters of these models. The statistical results are shown in Table 2. In all cases, the value of R^2 is greater than 0.93 and the *RMSE* is lower than 0.08. The Midilli et al. model with the highest R^2 (0.9974-0.999) and the lowest RMSE (0.0091-0.0155) gave the best results in describing the drying curves of quince slices under experimental conditions. This finding is in agreement with earlier results reported for quince dried in convective oven (Izli and Polat, 2019).

3.5 Effective moisture diffusivity

The results of effective moisture diffusivity (D_{eff}) of quince slices at different air temperatures, air velocities and H/D ratio values are presented in Table 3. As it can be seen, an increase in either temperature or velocity, or a decrease in H/D ratio increased D_{eff}, which might be caused by the increase in heating energy inside the samples. It would intensify the activity of water molecules and lead to higher D_{eff} (Li et al., 2015). Table 3, also shows the effective moisture diffusivity values change from 3.04 to 7.85×10^{-10} m^{2}s^{-1} which are in good agreement with those of existing in the literature, e.g. 0.65 to 6.92×10^{-10} m^{2}s^{-1} for quince (Kaya et al., 2007), 3.32 to 9.0×10^{-10} m^{2}s^{-1} for berberis (Aghbashlo et al., 2008), 4.44 to 8.60×10^{-10} m^{2}s^{-1} for chayote slices (Ruiz-López et al., 2012) and 1.264 to 4.56×10^{-10} m^{2}s^{-1} for ripe jackfruit (Saxena and Dash, 2015).

Table 3 Effective moisture diffusivity values at different conditions

Experimental treatment	Temperature (℃)	Velocity (m s^{-1})	H/D	D_{eff} ×10^{-10} (m^2 s^{-1})	R^2
No. 1	50	5	5	3.04	0.9814
No. 2	60	5	5	4.05	0.9834
No. 3	70	5	5	5.07	0.9838
No. 4	50	7	5	3.55	0.9821
No. 5	60	7	5	4.56	0.9787
No. 6	70	7	5	6.08	0.9754
N0. 7	50	9	5	3.8	0.9825
No. 8	60	9	5	5.32	0.9778
No. 9	70	9	5	7.85	0.9615
No. 10	60	7	6	4.07	0.9758
No. 11	60	7	4	5.33	0.9815

3.6 Activation energy

The variations of ln D_{eff} with 1/($T+273.15$) were plotted at different air velocities as shown in Figure 6. The slope and intercept of the straight line are equal to -E_a/R and ln D_0, respectively, therefore, E_a and D_0 can be easily estimated. Equations 12 to 14 show the effect of temperature on D_{eff} for the quince slices:

$$D_{eff} = 1.98 \times 10^{-6} \exp\left[-\frac{2835}{(T+273.15)}\right] \quad (R^2=0.9969), \text{ for } V=5 \text{ m s}^{-1} \quad (12)$$

$$D_{eff} = 3.67 \times 10^{-6} \exp\left[-\frac{2986}{(T+273.15)}\right] \quad (R^2=0.9968), \text{ for } V=7 \text{ m s}^{-1} \quad (13)$$

$$D_{eff} = 9.51 \times 10^{-5} \exp\left[-\frac{4021}{(T+273.15)}\right] \quad (R^2=0.9965), \text{ for } V=9 \text{ m s}^{-1} \quad (14)$$

The activation energy values are equal to 23.570, 24.825 and 33.430 kJ mol^{-1} for air velocities of 5, 7 and 9 m s^{-1}, respectively. The data are in agreement with the results representing increased activation energy with increase in air velocity (Zheng et al., 2005). Also, these values are within the general range of 12.7 to 110 kJ mol^{-1} for most food materials (Zogzas et al., 1996). The activation energy values in the current study are consistent with those proposed in the previous studies for different fruits such as 33.832-41.515 kJ mol^{-1} for quince (Kaya et al., 2007), 22.66-30.92 kJ mol^{-1} for apples (Meisami-Asl et al., 2010) and 30.46-35.57 kJ mol^{-1} for strawberry (Lee and Hsieh, 2008).

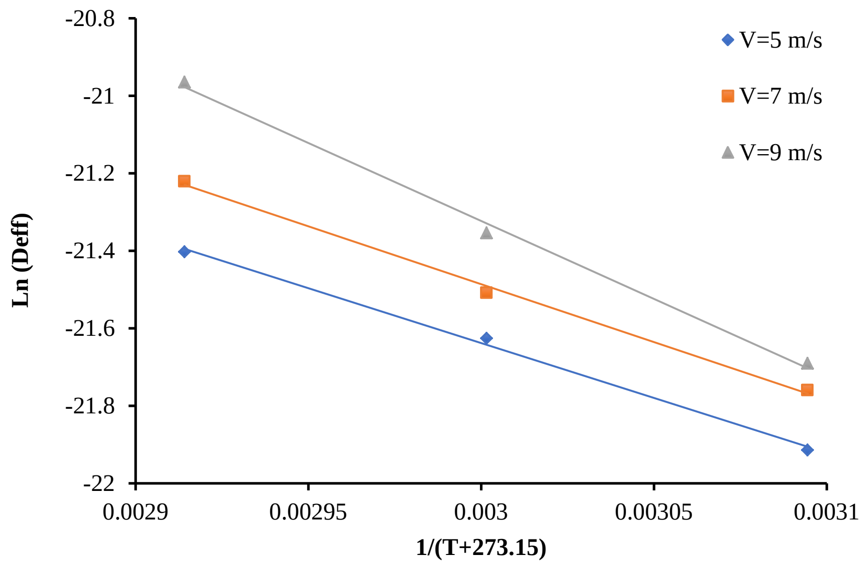

Figure 6 Arrhenius- type relationship between effective moisture diffusivity and temperature for quince slices

3.7 Rehydration ratio

The statistical analysis (Table 4) shows that drying temperature (*T*) and air velocity (*V*) have significant ($p <$ 0.000) effect on the rehydration ratio (*RR*) of quince slices, while the interaction effect was not significant. Also, the results show that the response of rehydration ratio was affected significantly ($p < 0.05$) by *H/D* ratio.

The means comparison (Figure 7) shows that the RR of dried slices decreased as drying temperature rose from 50℃ to 70℃, which decreased from 3.0956±0.0477 to 3.0033±0.0450. This might be due to physicochemical changes in the dried slices caused by temperature. Similar results have been reported by Cunningham et al. (2008). The increase of the air velocity resulted in the rehydration ratio to drop. This might be due to case hardening on the surface, which limited water movement from the exterior to the interior of the dried slices during rehydration process. These results are in good agreement with those obtained by Xiao et al. (2015). As shown in Figure 7, the rehydration ratio increased when *H/D* value varied from 4 to 6. The rehydration ratio is more at *H/D*=6.

3.8 Color change

Color is considered to be one of the most important criteria determining product quality and consumer preference. The color change of product takes place due to enzymatic reaction and non-enzymatic reactions such as caramelization and the Millard reaction (Vadivambal and Jayas, 2007). The values *ΔE* are used for comparison of fruit colors during drying. This value defines the overall color change, but not the values of the changes of individual colors. (Maskan, 2000). On the basis of the experimental results in Table 5 it can be observed that both drying temperature (*T*) and air velocity (*V*) significantly affected the overall color change (Δ*E*) of quince slices, while the H/D ratio and interaction effects were not significant. The mean comparisons in Figure 8 show that drying temperature and air velocity had a direct relationship with ΔE. At the lower drying temperatures, i.e. 50 ℃, the changes in color value of high moisture content materials was small. Then, the changes in color value went faster, especially in samples dried at high drying temperatures, i.e. 60 ℃ and 70 ℃. It can be explained by the fact that the higher temperatures can speed up Maillard reaction and lead to greater color change. The rate of color change can also increase with the decrease of moisture content. Similar result was reached also by Izli and Polat, (2019) for drying of quince and Xiao et al. (2012) for drying yam slices. Also, the changes in color as a result of higher air velocities can probably be due to the increment in the moisture diffusion and enhanced browning reactions. These findings are in compliance with the results reported for color changes of apple slices during drying (Nadian et al., 2015).

Table 4 ANOVA results of the effects of drying temperature, air velocity and *H/D* on *RR*

Source	Degree of freedom	Mean square	F	P
T	2	0.0192111	32.42	0.000
V	2	0.0124778	21.06	0.000
T×V	4	0.0009556	1.61	0.214
Error	18	0.0005926		
H/D	2	0.001244	10.18	0.012
Error	6	0.000122		

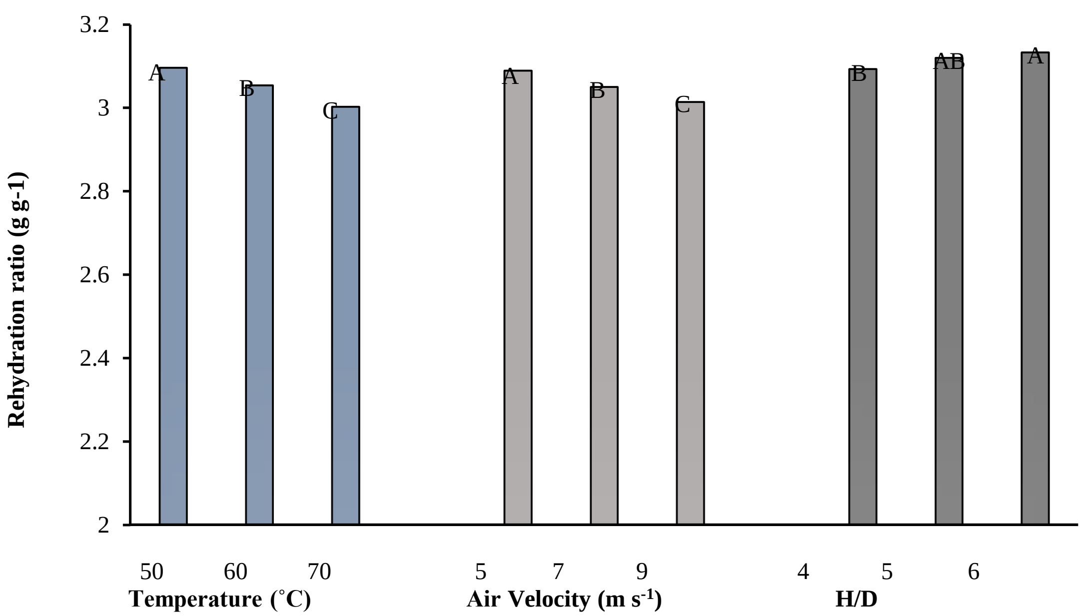

Figure 7 Means comparison of drying temperature, air velocity and *H/D* levels in terms of *RR*

Note: Means that share a letter are not significantly different at 5% probability level

Table 5 ANOVA results of the effects of drying temperature, air velocity and *H/D* on color change (ΔE)

Source	Degree of freedom	Mean square	F	P
T	2	52.206	225.63	0.000
V	2	1.335	5.77	0.012
T×V	4	0.356	1.54	0.233
Error	18	0.231		
H/D	2	3.044	4.89	0.055
Error	6	0.623		

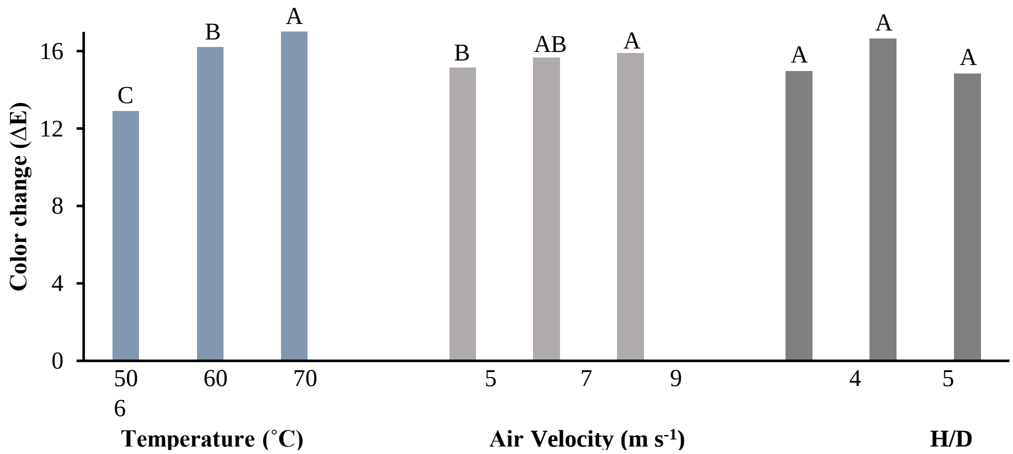

Figure 8 Means comparison of drying temperature, air velocity and *H/D* levels in terms of color change (Δ*E*)

Note: Means that share a letter are not significantly different at 5% probability level

3 Conclusions

In this experimental study, the effect of drying variables on the drying characteristics, rehydration ratio and modeling of quince slices were investigated. The following findings were obtained from the results of this study:

a) Increasing drying air temperature and velocity dropped the drying time. In addition, the effect of drying temperature on drying time was more significant than that of the air velocity.

b) A constant rate period was not observed in drying of quince slices. This implies that the drying process of quince slices was generally carried out in the falling rate period.

c) The moisture ratio decreases as *H/D* ratio drops, which in turn results in saving drying times due to increasing convective heat and mass transfer between the quince slices and drying air. The maximum heat and mass transfer occurs at *H/D* ratio equal to 4 as Reynolds number varies between 4000 and 7500.

d) The Midilli et al. model was found to be the best model to describe the drying behavior of quince slices because of higher R^2 and lower RMSE under all experimental conditions.

e) The effective moisture diffusivity computed by Fick's second law varied between 3.04×10^{-10} and 7.85×10^{-10} $m^2 s^{-1}$.

f) The values of activation energy of quince slices were found to be 23.570, 24.825 and 33.430 kJ mol^{-1} for air velocities of 5, 7 and 9 ms^{-1}, respectively.

g) The rehydration ratio of dried quince slices significantly increased as the drying temperature and air velocity rose. Also, grow at *H/D* ratio of 4 to 6 significantly increased the rehydration ratio of dried slices, while increase of the air velocity caused the rehydration ratio to drop.

h) Both drying temperature and air velocity significantly affected the overall color change of quince slices, while there was no statistically significant interaction between these process variables. Also, the changes in *H/D* ratio did not show any statistically significant difference in color change of dried samples.

Taking into consideration drying time, rehydration ratio and overall color change of dried slices it was suggested that a drying temperature at 50℃ with an air velocity of 9 ms^{-1} and *H/D* ratio of 4 should be applied for thin layer air impingement drying of quince slices.

Conflict of interest

The authors declare that there are no conflict interests associated with the publication of this paper.

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Appendix

Nomenclature

D	nozzle-exit diameter (mm)	M_0	initial moisture content (g g^{-1})
D_0	constant diffusivity ($m^2 s^{-1}$)	$M_{t+\Delta t}$	moisture content at $t+\Delta t$
D_{eff}	effective moisture diffusivity ($m^2 s^{-1}$)	$\partial M/\partial t$	change in moisture with time
DR	drying rate (g g^{-1}. min)	R	universal gas constant (J mol^{-1} K^{-1})
E_a	activation energy (kJ mol^{-1})	R^2	coefficient of determination
H	distance between the nozzle-exit and the quince slices (mm)	$RMSE$	root mean square error
H/D	relative nozzle-to-product distance	RR	rehydration ratio (g g^{-1})
K_1, K_2	Slope of trend lines	SD	standard deviation
L	half thickness of quince slice (m)	t	drying time (s)
L^*, a^*, b^*	Color parameters	Δt	time difference
M	moisture content of quince slice (g water/g dry matter)	ΔE	color change of samples
MR	moisture ratio	∇	gradient operator, which generalizes the first derivative,
M_e	equilibrium moisture content	∇^2	second derivative
M_t	moisture content at time t (g g^{-1})	T	drying temperature (℃)