

An experimental study on convective drying of quince

Tzempelikos Dimitrios¹, Bardakas Achilleas², Vouros Alexandros²,
Tsepenekas Dionysios³, Filios Andronikos², Margaris Dionissios¹

¹Laboratory of Fluid Mechanics and Applications, Department of Mechanical Engineering and Aeronautics, University of Patras

GR-26500 Patras, Greece

E-mail: dtzempelikos@meed-aspete.net

²Laboratory of Fluid Mechanics and Turbomachinery, Department of Mechanical Engineering Educators, School of Pedagogical and Technological Education (ASPETE)

GR-14121 Athens, Greece

E-mail: aefilios@meed-aspete.net

³Project Engineer, EKO

GR-15125 Marousi, Greece

E-mail: D.Tsepenekas@eko.gr

Abstract. *A laboratory convective drying unit (LCDU) has been designed, constructed and equipped with an integrated measurement and control instrumentation, in order to evaluate the essential drying characteristics of various horticultural and agricultural products. The current paper presents experimental results from tests with quince slices. Drying kinetics was investigated as a function of drying conditions. Experiments were conducted at air flow temperatures of 40, 50 and 60°C and average velocities of 1, 2 and 3 m/s. Temperature changes of the drying quince samples, the relative humidity and the temperature of the drying air were measured during the drying processes and finally the moisture ratio (MR) was calculated. The experimental MR data were fitted with three mathematical models available in the literature and a good agreement was observed. In the ranges measured, Fick's 2nd law of diffusion was used to fit the experimental data for the determination of the effective moisture diffusivity. The activation energy was determined, assuming an Arrhenius type temperature relationship with moisture diffusivity.*

Keywords: Convective drying, Quince, Experimental, Drying kinetics, Drying rate.

1. Introduction

The drying is used for the preservation and storage of different fruits and vegetables for long periods of time with the removal of moisture content. It is a complex process where a simultaneous heat and mass transfer in transient conditions occurs. Knowing the mechanism of heat and mass transfer of a product, the process drying parameters can be optimized with the ultimate aim of improving the product. The parameters which influence the drying process are the temperature, the velocity and the relative humidity of the drying air. There are many studies in the literature dealing with the aforementioned parameters and involves a variety of fruits and vegetables. Karathanos et al [1] dealt with drying of some fresh and semi-dried fruits.

Margaris et al [2] studied hot air dehydration of sultana grapes. Kaya et al [3] studied the drying kinetics of quince at low velocities. Babalis et al [4] studied the drying kinetics of figs. Aghbashlo et al [5] modeling potato slices in length continuous band dryer. Velic et al [6] & Zlatanovic et al [7] used a laboratory scale dryer equipment to study the influence of the airflow velocity on kinetics of apple drying. Sacilik et al [8] and Doymaz [9] also studied the drying kinetics of organic apple slices. Drying kinetics of some vegetables like pepper, pumpkin, green pea, carrot, etc. were studied by Krokida et al [10]. The purpose of this study is the experimental investigation of the drying kinetics of quince in accordance with predefined conditions (drying temperature 40, 50 and 60°C and air velocity value of 1, 2 and 3 m/s) that do not exist in the literature and the evaluation of the effective moisture diffusivity as well as the activation energy.

2. Materials and methods

2.1 Materials

Fresh quinces were purchased from a local market in Athens, Greece and used for the drying experiments. The samples were stored in a refrigerator at about 6°C until use. Before drying the quinces were cleaned and sliced manually to a thickness of 10 mm, in order to produce uniform quince pieces. The samples were used to form a thin-layer on a 440 x 400 mm tray with a net weight of 395,5 gr. The initial moisture content (M_0) of quince slices was measured to be around 81,04% in wet basis (w.b.) or 4,27 kg water / kg dry matter in dry basis (d.b.) and was determined by the oven-drying method [11] with repetition in order to assure accurate moisture content average values.

2.2 Experimental apparatus

Fig.1 shows the Laboratory Convective Drying Unit (LCDU) which has been designed and constructed in the Laboratory of Fluid Mechanics and Turbomachinery in ASPETE. 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 x 0,5 m) is of tower (vertical) type and is equipped with 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. Upstream of the drying chamber, the long rectangular diffuser with a total divergence angle of 6,7°, the tube heat exchanger in which the hot water is provided through a boiler of 58 kW thermal power, the transitional duct with observation window that includes the sprayer for humidifying purposes, the corner duct that incorporates four guide vanes and the flow straighteners section, are located. The flow straighteners consisting of an aluminum honeycomb are considered necessary aiming for flow uniformity in the drying section.

The flow rate is observed and controlled with a custom made and calibrated rake of pitot tubes, namely pitot rake, located at the inlet of the drying chamber.

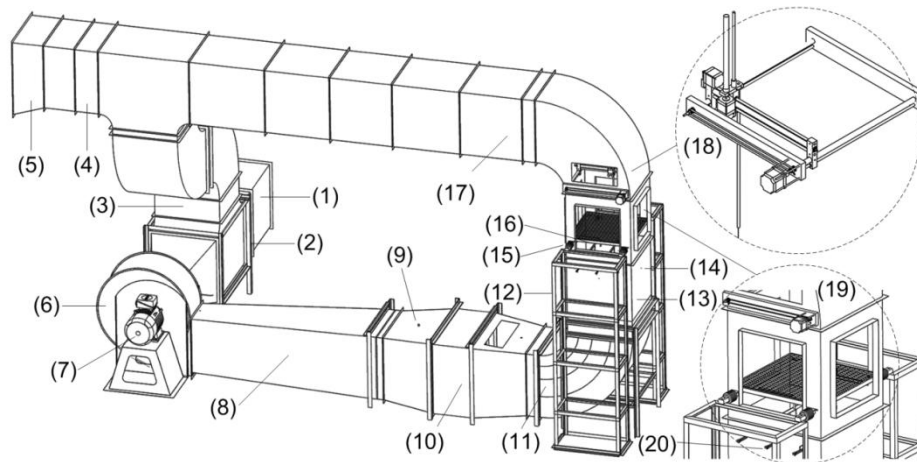


Fig. 1. Schematic diagram of the LCDU: (1) Air inlet, (2) Inlet damper, (3) By pass air damper, (4) Outlet damper, (5) Air outlet, (6) Centrifugal fan, (7) Three-phase electric motor regulated by an AC inverter, (8) Diffuser, (9) Temperature and humidity sensors, (10) Tube heat exchanger, (11) Guide vanes, (12) Metal frame for pressure cells, (13) Flow straighteners, (14) Temperature and humidity sensors, (15) Pressure cells, (16) Metal tray, (17) Temperature and humidity sensors, (18) Computer controlled 3-Axis traverse system, (19) Drying chamber, (20) Pitot rake.

Downstream of the vertical drying chamber, the second corner duct with guide vanes, the elevated horizontal modular constructed duct, the outlet dumper and the exit diffuser, are located. The modular design of the facility allows the easy placement of two or three horizontal drying chambers in tandem arrangement, on the elevated return or exit flow leg. The air flow is established and controlled through a centrifugal fan directly driven by a three phase electric motor of 3 kW with its speed regulated by an AC inverter. Adjusting the air dampers, the laboratory dryer can be used for thermal drying experimental studies in both open circuit and close circuit operations. The mean speed of the air flow at the inlet is the weighted average velocity of the 12 points collected from the pitot rake and the four pressure taps (same level with the contact tip of the pitot tube) in the side wall of the inlet of the drying chamber. Each pitot tube is connected via plastic tubing to a custom made pressure collector system equipped with solenoid valves (Tekmatic 24VDC, 6W) allowing its operation and control via pressure transmitter with the use of a custom application developed in Labview®.

2.3 Instrumentation and measurements

The air and drying product temperatures were measured using calibrated PT100 from UTECO Ltd. with class A tolerance and accuracy $\pm 0,15^{\circ}\text{C}$. A 3-wire transmitter from JUMO Ltd. (type 956533) with accuracy $\pm 0,2^{\circ}\text{C}$ was used for the above PT100's. The relative humidity of the drying air was determined using calibrated humidity transmitters from KIMO Instruments, models TH100 & TH200, with accuracy $\pm 2,95\%$ and $\pm 2,36\%$ respectively. A differential pressure transmitter (Dwyer, model MS-121-LCD) with a calibrated accuracy $\pm 2\%$ of the selected range of 25 Pa was used to measure air drying velocity. The weight was quantified using four load cells (total nominal load 10 kg) of model F1, class C2, with accuracy $\pm 0,05\%$ and TA4/2

analog transmitter with accuracy $\pm 0,03\%$, from AEP Ltd. All transmitters are connected to a PC with a PCIe-6321 DAQ device (National Instruments®) via NI SCXI-1000 and NI SCXI-1302 modules with accuracy $\pm 0,134\%$ and sampling frequency 3,2 kHz. Custom application in Labview® was used to interface with data acquisition.

2.4 Experimental procedure

The LCDU was started 2h before each experiment in order to achieve the desired steady state conditions. Then the metal tray of the drying chamber was regularly filled with about 700 gr sliced quinces in thin-layer form. Experiments were performed at air drying conditions of 40, 50 and 60 °C with 4, 8 and 12 % relative humidity respectively. The air velocity was adjusted to 1, 2 and 3 m/s in the drying chamber. The volumetric flow rate varied from 900 to 2.700 m³/h, corresponding to a range of Reynolds number varying from $2,64 \times 10^4$ to $8,82 \times 10^4$. Weight, air temperature, probe-surface temperature and relative humidity were automatically monitored and acquisitioned by a PC. Measurements were taken 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.

2.5 Theoretical considerations

2.5.1 Modeling of drying kinetics

The moisture content of the samples and the dimensionless moisture ratio (MR) during the drying processes were found applying the following equations:

$$M(t) = \frac{w(t) - w_d}{w_d}, \quad MR = \frac{M(t) - M_{eq}}{M_0 - M_{eq}} \quad (1)$$

where $M(t)$ is the moisture content at any moment t (kg water / kg dry matter), $w(t)$ is the dry matter at any moment t (kg) and w_d is the dry matter (kg), M_0 , M_{eq} are initial and equilibrium moisture content (kg water / kg dry matter) respectively. M_{eq} is quite small compared with M_0 and $M(t)$ and in the MR definition may be ignored [12]. The following assumptions were taken into account in order to establish the equations of mass transfer during convective drying: i) The process was isothermal, ii) The main transfer mechanism was diffusion and iii) deformations and shrinkage during drying were negligible [13]. The experimental data were fitted in three, state-of-the art, thin-layer drying models: i) Newton, $MR = \exp(-kt)$ [14], ii) Henderson – Rabis, $MR = \alpha \exp(-kt)$ [15] and iii) Page, $MR = \exp(-kt^n)$ [16], in order to find the best suitable model for describing the drying behavior of a quince slice in LCDU. In the aforementioned models the moisture ratio is a function of the drying time. In order to determine each constant for the tested model, non-linear regression was used. The effectiveness of each model fit was evaluated via statistical criteria such as coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the experimental and the predicted moisture ratio values. 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.

2.5.2 Effective moisture diffusivity estimations

An analytical solution of Fick's model mass-diffusion equation for drying biological products in a falling-rate period was developed by Crank (1975). For long drying times a limiting of Crank equation is obtained and expressed in a logarithmic form:

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

where D_{eff} is the effective moisture diffusivity (m^2/s), t is the time (s), L is the half-thickness of samples (m), and n is a positive integer. D_{eff} is determined by the slope of the relationships between the experimental drying data in terms of $\ln MR$ and drying time.

2.5.3 Calculation of the activation energy

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:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_{abs}}\right), \quad \ln D_{eff} = \ln D_0 - \frac{E_a}{RT_{abs}} \quad (3)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (kJ/mol K), and T_{abs} is the absolute temperature (K). A plot of $\ln D_{eff}$ versus $1/T_{abs}$ from the Eq. (3) gives a straight slope and consequently, the energy activation (E_a).

3. Results and discussion

The drying curves for all drying experiments performed are reported in Fig. 2. In Fig. 2a to 2c the MR was plotted versus the drying time for different values of air drying temperature, while the air velocity value was kept constant. As it can be seen increasing the temperature of the drying air from 40 to 60 °C for all drying velocities, the total drying time decreased about 30%. This effect became less important after approximately 10 – 15 h.

Fig. 2d to 2f show the drying curves for different drying velocities, keeping the drying temperature constant. In these figures the effect of varying the air velocity on the drying rate is shown clearly. The increased air velocity of the air in the drying process results in a reduction of the drying time, a phenomenon that is more pronounced at higher drying temperatures, since heat transfer was increased due to the increasing temperature difference which is the driving cause of the heat transfer. It was observed that after a period of 4 to 5 h, the velocity increase does not affect the drying rate, i.e. the curve for the 3 m/s coincides with the curve of 2 m/s. The reason for this effect can be explained by the flow pattern inside the drying chamber and the dried product that directly affect the heat and mass transfer coefficients.

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 V is the air velocity and T is the temperature. The models of Henderson – Rabis and Page (bold numbers in Table 1) obtain an $R^2 > 0,99$ while the small values for the other criteria, show a very good consistence with the experiments.

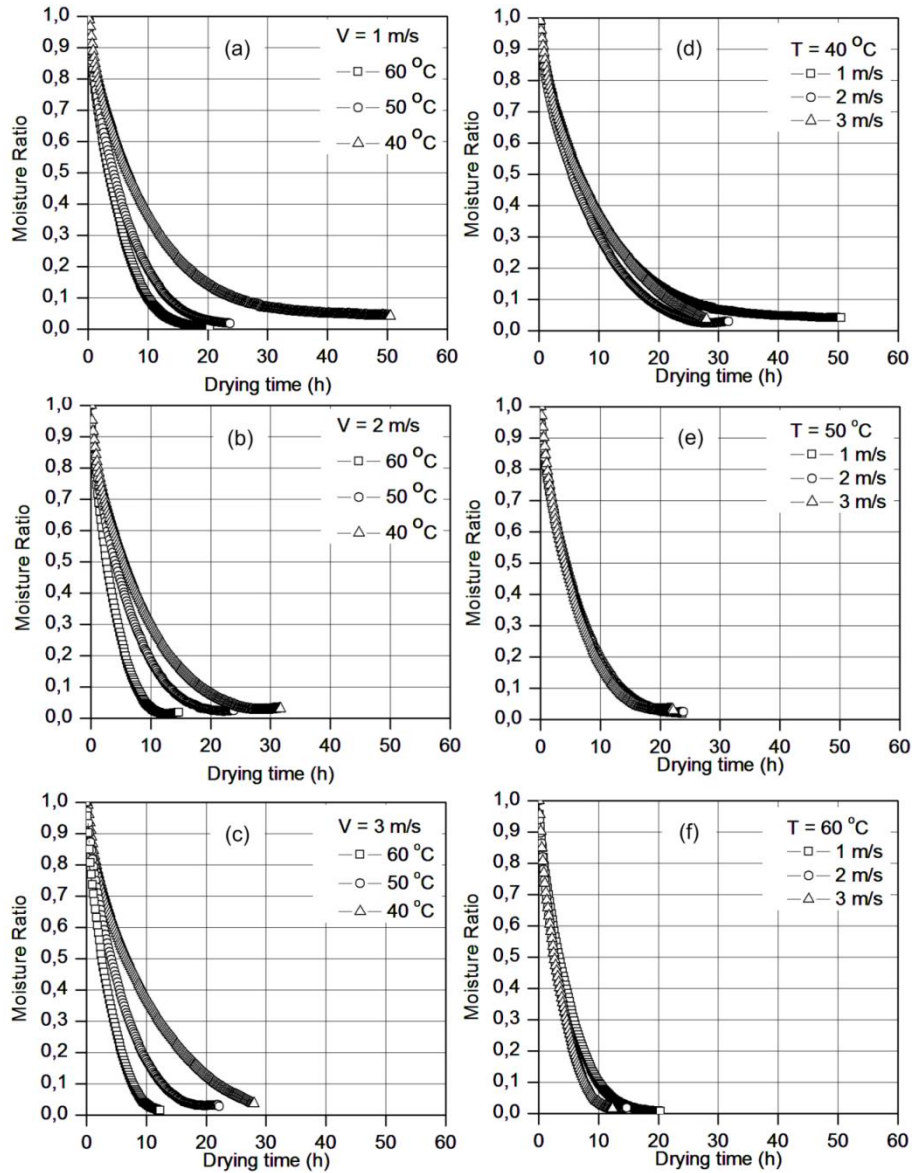


Fig 2. Air temperature (a,b and c) and air velocity (d, e and f) effects on the drying curves.

Table 2 shows the effective moisture diffusivity (D_{eff}) for each test. D_{eff} values varied from $2,67 \times 10^{-10}$ to $8,17 \times 10^{-10}$. These values are in a good agreement with those reported in the literature. As can be seen an increase in either the velocity or temperature increases moisture diffusivity due to the higher mass transfer.

The energy activation (E_a) 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_a and D_0 . The value of energy activation ranged between 36,996 kJ/mol and 42,593 kJ/mol, similar to those given in the literature for the drying of different foods.

Table 1

Fitting results for different drying conditions

V(m/s)	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			0,9981	1,23	0,0110
		Page	0,1727			0,9974	1,68	0,0129
	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			0,9975	1,57	0,0125
		Page	0,1434			0,9955	2,81	0,0167
	50	Newton	0,1736	0,9562	0,9616	0,9955	2,85	0,0168
		Henderson - Rabis	0,1660			0,9975	1,56	0,0124
		Page	0,1874			0,9961	2,49	0,0157
	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			0,9966	2,18	0,0147
		Page	0,1155			0,9956	2,83	0,0167
	50	Newton	0,1745	0,9903	1,0123	0,9979	1,42	0,0119
		Henderson - Rabis	0,1728			0,9980	1,37	0,0116
		Page	0,1703			0,9980	1,40	0,0117
	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

Table 2

Effective moisture diffusivity coefficient, D_{eff}

Air velocity (m/s)	Temperature (°C)	D _{eff} x 10 ⁻¹⁰ (m ² /s)	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_a and Arrhenius coefficient D₀

Air velocity (m/s)	E _a (kJ/mol)	R ²	D ₀ (m ² /s)
1	36,996	0,9925	4,04E-04
2	38,291	0,9976	7,78E-04
3	42,593	0,9959	3,97E-03

4. Conclusions

The drying kinetics of the quince slices were studied as a function of the drying conditions. Experiments were carried out for three values of the drying air temperature and the averaged velocity. Increasing the temperature or the velocity of the drying air decreases the total drying time. In order to describe the drying behavior of the quince slices, three drying models were fitted to the drying data. The Henderson – Rabis and Page model predicted adequately the moisture ratio, according to the values of R^2 , χ^2 and RMSE. The effective moisture diffusivity was obtained from Fick's 2nd law and observed that increase either velocity or temperature reduces D_{eff} . Finally, the Arrhenius equation was used to describe the energy activation and to increase the drying velocity caused increase E_a .

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