KINETIC PARAMETERS IDENTIFICATION OF CONDUCTIVE ENHANCED HOT AIR DRYING PROCESS OF FOOD WASTE

by

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Original scientific paper
https://doi.org/10.2298/TSCI200312223M

The efficient utilization of waste from food industry is possible after thermal treatment of the material. This treatment should be economically feasible and compromise the energy efficient drying process. The main goal of this investigation is to determine drying characteristics of nectarine pomace as a waste from food industry. The measurements were performed in an experimental dryer by combined conductive-convective drying method with disk-shaped samples of 5, 7, and 10 mm thickness and 100 mm in diameter at the air temperatures of 30, 40, 50, 60, and 70 °C, hot plate temperatures of 50, 60, and 70 °C and air velocity of 1.5 m/s. The drying curves were compared to a few semi-theoretical mathematical models. The Logarithmic model showed the best correlation. On the basis of experiments, it is determined that the drying process takes place in a falling rate period and it is accepted that the main mechanism of moisture removal is diffusion. The effective coefficient of diffusion was determined using experimental results by calculating the slope of the drying curves. Drying time and equilibrium moisture are determined for each experiment. Analysis of drying curves showed that the conductive-enhanced drying method reduces drying times and increases the diffusivity coefficient. The character of drying rate curves for conductive-enhanced drying was analysed and compared with pure convective drying of nectarine pomace.

Key words*: nectarine pomace, convective-conductive drying, drying rate, effective diffusivity, drying models*

Introduction

Nectarine (*Promus Persica* (*L.*) *Batsch*, var. nectarine) is smooth-skinned peach of the family *Rosaceae*. The annual peach and nectarine production worldwide in 2017 was 24.67 million tons (MT) compared to 11 MT in 2005 which shows the trend of growing production of nectarines [1]. China is leading producer of peaches and nectarines with 14.3 MT

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produced in 2017, while the EU produced 4.086 MT in the same year. The biggest EU-28 producers of peaches and nectarines are Spain, Italy, Greece, and France, respectively. In 2017 Serbia produced 0.0806 MT peaches and nectarines and holds the 5th place in Europe. Although most peaches and nectarines are still consumed fresh, total peach and nectarine juice consumption in EU comprises 3.5% of total consumption [2, 3]. In juice production, the majority of the fruit mass is converted to juice, while the rest is a waste product comprised of skin and stem, known in the literature as pomace [2, 4-7]. This pomace is usually thrown away on the land fields which causes environment pollution and, on the other hand, represents a waste of usable material, which could be converted to value-added products. There are many promising ways in which the pomace can be used, for example animal food, beverages, flour, processing for nutrient recovery, or even packaging [8].

Drying is one of the most cost-effective ways of preserving foods of all variety [9]. Drying of moist materials is a complicated process involving simultaneous heat and mass transfer within the material being dried [10]. In literature can be found three approaches to evaluating and analysing the drying processes, namely: theoretical, semi-theoretical, and empirical approach [11]. Theoretical approach implies set of differential equations taking into account internal moisture movement mechanisms, external conditions, and material properties. Semi-theoretical models are derived from Fick's Second law of diffusion or Newton's law of cooling using certain simplifications and these models need fewer assumptions because of use of experimental data. On the other hand, the empirical models are based on experimental data and dimension analysis, and they are obtained from experimental drying curves by the means of regression analysis, tab. 1.

Table 1. Empirical and semi-theoretical expressions of drying curves for thin layer drying

Model name	Mathematical expression	Number of parameters
Lewis [12, 13]	$MR = \exp(-k\tau)$	1
Midilli *et al.* [14]	$MR = a \cdot \exp(-k\tau^n) + b\tau$	4
Page [15]	$MR = \exp(-k\tau^n)$	2
Henderson and Pabis [16, 17]	$MR = a \cdot \exp(-k\tau)$	2
Logarithmic [18]	$MR = a \cdot \exp(-k\tau) + c$	3
Simplified Fick's diffusion [11]	$MR = a \cdot \exp[-c(\tau/\delta^2)]$	3

Several investigations have been published on nectarine drying [4, 19-24]. The focus of these studies was on nectarine drying with microwave, hot air and infrared technology, as well as combination of them. The influence of the temperature, sample thickness was studied.

Regarding studies on conductive enhanced drying of foodstuff, there are certain data in literature. In [25] the model for combined conductive-convective drying on hot isothermal surface was developed. All thermophysical coefficients, such as specific heat capacity, thermal conductivity, thermal diffusivity, density, *etc.* are assumed to be dependent on the temperature and moisture content of the dried material, and that the shrinkage of the material during drying can be neglected. In [26] the authors have investigated drying of pumpkin slices (10 mm thickness) with *conductive hydro-drying* method where the heat was supplied both by convection and conduction. In [27] was evaluated the influence of conductive heating and forced air convection on the drying rate and temperature of tomato pulp using cast-tape drying method.

However, very few literature data are available on combined conductive-convective drying of nectarine pomace. That is why it was necessary, in order to get reliable data, to design a semi-industrial installation and conduct extensive experimental research. In this work, the accent was on kinetics of conductive enhanced drying process and finding the best model describing conductive-convective drying of nectarine pomace. The samples were in the shape of thin discs for easier mathematical modelling.

The novelty of this research is the use of conductive enhanced drying method for fruit waste drying. Nectarine pomace could be very useful value-added material for number of purposes, and therefore the study on nectarine pomace drying could be beneficial for industrial uses. Another innovation of this paper lies in the possibility to explore the effect of parameter variation, i.e. in obtaining specific curve characters with different combinations of the hot plate and hot air temperatures. Combined conductive-convective drying method was used to determine the influence of conductive enhanced drying on drying characteristics, such as drying rate, drying time and effective moisture diffusivity.

This study can be used in industrial facilities to improve the energy efficiency of the drying process of fruit waste and similar products. The conductive enhanced drying of nectarine pomace is more energy efficient than widely used convective drying, and it can be optimized with the combination of the process parameters. The results show savings can be made with lowering the temperature of the air at certain moment and thus directly reducing the costs of the drying.

Theoretical considerations

Nectarine pomace drying takes place in a falling rate period, except for a short period of sample warming up period at the beginning of the process. When drying takes place in the falling rate period, internal resistances of moisture transfer through the material are greater than convective resistance at the surface of the material [16]. Therefore, it is widely accepted that the moisture diffusion is the main controlling mechanism during drying of agricultural products [18, 24, 28-31]. The change of moisture content in time assuming 1-D moisture transfer is formulated through Fick's Second law of diffusion:

$$\frac{\partial MR}{\partial \tau} = D_{\text{eff}} \left(\frac{\partial^2 MR}{\partial z^2} \right) \tag{1}$$

where MR is dimensionless moisture content, [= $(M - Me)/(M_0 - Me)$] and D_{eff} is the effective diffusion coefficient. Analytical solutions of Fick's Second law of diffusion have been given in [32] for certain geometries, initial and boundary conditions.

Assuming the moisture transfer takes place in axial direction only (*i.e.* the radial diffusion can be neglected), the formula used for the determination of the effective diffusivity for a thin slab with the thickness of 2δ, where the moisture transfer occurs from both upper and lower surface, is:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp\left[-\frac{(2n+1)^2 \pi^2 D_{\text{eff}} \tau}{4\delta^2} \right] \tag{2}$$

However, when moisture is removed from the upper surface only, which is the case in this work, δ stands for the thickness of sample. When the process of drying is isothermal, shrinkage is considered negligible, initial moisture distribution uniform and diffusion coefficient is assumed constant, eq. (1) can be used for determination of the effective diffusivity [33]. The equation can be simplified and only the first term of the sum (n = 0) can be taken into account for the long drying times [16, 30, 33, 34]. Then, after further simplification, we can obtain:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{\text{eff}} \tau}{4\delta^2}\right) \tag{3}$$

In order to determine the effective diffusivity, the experimental drying data are plotted against time, *i.e.* $\ln(MR) - t$, and the plot is a straight line. The slope of the line can be expressed as:

$$k_0 = \frac{\pi^2 D_{\text{eff}}}{4\delta^2} \tag{4}$$

The line $\ln(MR) - t$ is fitted against a straight line using regression analysis tools. From the slope of the fitted line, the D_{eff} can be calculated.

During drying, several moisture transport phenomena are occurring simultaneously: diffusion caused by concentration gradient, capillary moisture movement caused by capillary forces, thermo-diffusion caused by temperature gradient, evaporation and condensation within the material, pressure gradient moisture movement and gravitational forces [16]. Effective diffusion coefficient, D_{eff}, takes into account these transport phenomena. The values of D_{eff} for foodstuffs range from 10^{-12} to 10^{-8} [18]. The D_{eff} depends on drying temperature, and in several studies it is shown that the effective diffusivity increases with the thickness of material [28, 30]. One possible way of explaining the increase of effective diffusivity with material thickness is to attribute it to the moisture diffusion in radial direction. In [30] the theoretical model for effective diffusion coefficient dependence on the sample thickness for three types of fruit was proposed. It is concluded that for thin samples (<10 mm) the diffusion in radial and side directions can be neglected, whereas for the thicker samples, *i.e.* (>10 mm) the diffusion in other directions must also be taken into account when calculating effective diffusion.

Theoretical drying models give holistic approach to the drying processes, however, they can be analytically solved only for a few combinations of boundary and initial conditions. Therefore, in practice it is common to use semi-theoretical and empirical models for describing the drying processes. Models in tab. 1 are derived from the Fick's Second law of diffusion or Newton's law of cooling with the correlating parameters taking into account external conditions, such as hot air velocity, temperature, relative humidity and internal parameters, such as mechanisms of moisture transport through the material. The experimental data is fitted with proposed drying model and the goodness of fit is estimated. The best correlating model is then used to describe the character of the drying process.

The goodness of fit of the tested mathematical models to the experimental data is evaluated with the correlation coefficient, R^2. The higher the R^2 values, the better are the goodness of fit [18]. In this work nonlinear regression analysis was performed with statistical software OriginPro2018.

Drying rate represents first derivative of the dimensionless moisture with time:

$$DR = \frac{\mathrm{d}M}{\mathrm{d}\tau} \tag{5}$$

In order to verify the model and to determine the experimental parameters and the generality of the model (so it could be applied to other similar materials and cases), experimental investigations are carried out.

The experimental research was designed and conducted to correspond with the reality as much as possible.

Material and methods

In this chapter were described theoretical aspects of drying, nectarine pomace preparation and methods of drying. Dried nectarine pomace is a prospective material for various uses. Thin discs were dried to investigate the drying kinetics and parameters such as drying time, equilibrium moisture content and effective diffusivity coefficient.

Experimental material

The nectarine pomace was obtained from the juice factory *Nectar* from city of Bačka Palanka, Serbia which is the biggest commercial fruit juice producer in Serbia. Fresh nectarine pomace was transported to the laboratory, where the samples were shaped in thin discs, put in the freezer for couple of hours to stiffen and then put in the plastic bags, vacuumed and frozen again. For the thin disk shaping the special module was used, constructed for this purpose with 3-D printer, shown in fig. 1. The module can be used to shape discs up to 20 mm thickness and 100 mm radius. The samples were preserved in the freezer at the temperature of –21 °C. Although the nectarines are susceptible to chilling injury, it has a little influence in fruit stored at 0 °C or below [3]. Therefore, in this case it can be neglected. The moisture content was controlled periodically and it was concluded that the moisture content loss due to the material storage is negligible, but it was noticed that the biggest influence on the moisture content of the samples has the non-homogenous structure of the material. In order to mitigate the effect of the material non-homogeneity, the samples were made of the same bulk mass of material right upon the arrival. Furthermore, prior to experiments, additional measurements have been performed to evaluate the extent of non-homogeneity of the material. It was concluded that three repetitions are enough to neglect the effect of non-homogeneity. Therefore, all experimental measurements were done in triplicates.

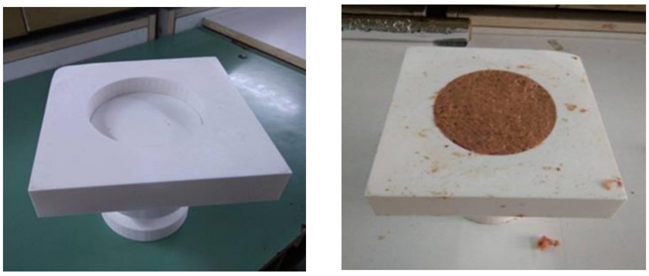

Figure 1. The module for shaping the samples

Prior to drying, each sample was exposed shortly (15 minute) to the ambient air. The initial moisture content of the nectarine pomace samples was determined by the standard procedure at 105 °C for 12 hours [35]. The average initial moisture content of fresh nectarine pomace was 82.24% wet basis (wb).

Experimental installation and procedure

For the purpose of the experiments, the experimental (semi-industrial) installation was constructed, shown in fig. 2. The installation was constructed to be able to precisely measure the mass change in time, and hold the set temperatures and air velocity. Additionally, the values of RH were monitored during the experiments.

Fresh air is pushed through the installation by a fan and heated with electric heater. After removing the moisture from material in drying chamber, the exhaust air was released to the atmosphere. The experimental dryer has mixing chamber, which is an air re-circulation system, however during all measurements, the installation was operating with 100% fresh air, *i.e.* without re-circulation.

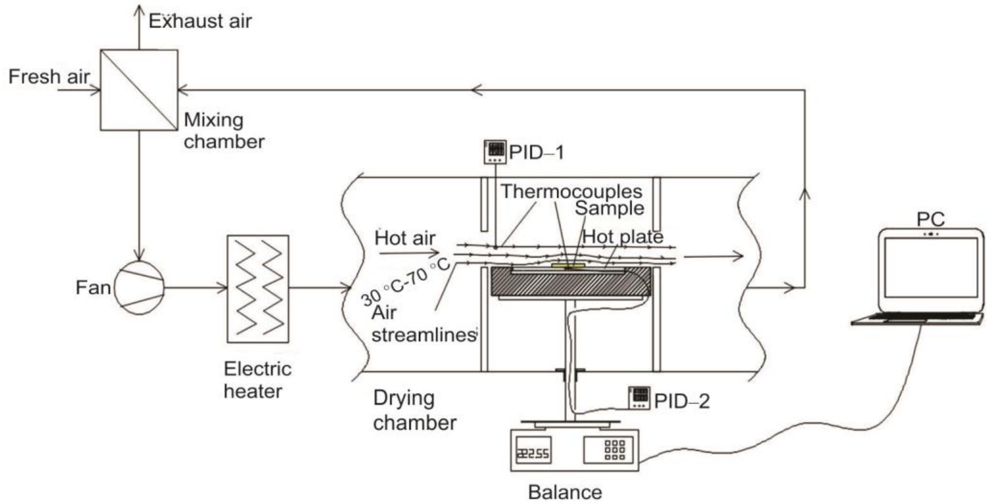

Figure 2. Experimental dryer

The experimental measurements were carried out in the drying chamber. The material to be dried is placed on the sheet metal heating plate, which was thermally insulated from all sides accept from the upper one. The heating plate is placed on the balance (positioned below the chamber). The balance used is Kernel (Kernel S232) with the accuracy of ±0.01 g. Hot air temperature is measured and regulated by the PID-1 thermoregulator, and the thermocouple was positioned just before the hot air reaches the material. The samples were placed on the heated sheet metal plate with temperature controlled by PID-2. With heat fluxes from hot air circulating above the material (convection), and heating plate from below (conduction), this construction enables combined conductive-convective drying of material.

The air velocity was controlled by frequency regulator connected to the fan electromotor. The velocity of the air was verified by the hot wire anemometer Airflow^{TM} TA35 with the accuracy of ±0.05 m/s. For most foodstuff exists the *critical velocity*, *i.e.* the velocity above which the velocity has negligible effect on the drying rate, which is proposed to be 1.5 m/s for pomace-like products [36]. Therefore, separate measurements were performed to investigate the influence of velocity on drying process. Mass change in time of nectarine samples was monitored for air velocities 1.5-3 m/s with 0.5 m/s step and 50 °C air temperature, and it was determined that increasing the air velocity above 1.5 m/s does not have much influence on the drying time and drying curves, which is in correlation with several studies related to pomace drying [36, 37]. This can be explained by the fact the drying is taking place in the falling rate period, and internal resistances have much greater influence then the external forces.

The temperatures of the air and the hot plate were controlled by PID regulators (REX C-100), accuracy ±0.1 °C, thermocouple accuracy ±0.1 °C. Temperatures for the experiments were chosen based on the recommendations for nectarine drying in the literature and they were 30 °C, 40 °C, 50 °C, and 70 °C for hot air, and 50-70 °C for hot plate, with 10 °C step difference. The temperature of the hot plate could not be lower than hot air temperature, since the hot plate surface exposed to the air was not insulated, and the hot plate could not be kept at the set temperature.

Samples were placed on a hot plate of constant temperature with a convective air stream being blown over the opposite free surface of the sample. When dried in experimental dryer the temperatures of the hot plate and hot air were kept constant during each experiment. The hot plate temperatures were 50 °C, 60 °C, 70 °C, or without heating (WH), while the temperatures of the air were kept at 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C. Three series of experiments were performed with the nectarine pomace disks thicknesses of 5, 7, and 10 mm, with the variations of hot plate and hot air temperatures. During the experiments the air velocity was kept constant at 1.5 m/s. Experiments were marked as *P*-*A*-*T*, where *P* is the hot plate temperature [°C], *A* – th air temperature [°C], and *T* – the sample thickness [mm]. For example, WHP-30-10 stands for a sample of 10 mm thickness being dried at 30 °C without use of hot plate.

During each experiment mass change of the sample in time and relative humidity of the air were measured. The average net weights of the nectarine samples were 82.5 g, 56.8 g, and 45.5 g for the sample thicknesses of 10 mm, 7 mm, and 5 mm, respectively. To ensure contact between the hot plate and material and prevent deformation of the sample, steel wire mesh of known and unchangeable mass was placed on top of each sample during drying. The density of the wire mesh was chosen not to interfere or affect convection or air flow pattern across the sample, fig. 3. During the experiments the change in mass of the samples was weighted by the electronic balance and monitored and recorded on the PC connected to it at 5 minute interval. The drying was stopped when the sample mass between two consecutive measurements has not changed.

Figure 3. Sample during drying with wire mesh on top of it

Results and discussion

The initial moisture content, M_0. of nectarine pomace was 4.63 ± 0.01 kg water per kg dry matter. Other authors have obtained similar results for initial moisture content of foodstuff [24]. The equilibrium moisture content, *Me*, values, tab. 2, varied with the hot plate and air temperatures and ranged from 0.08 to 0.35 kg water per kg dry matter. The values in tab. 2 were obtained by averaging the equilibrium moisture content values of the samples with thicknesses 5, 7, and 10 mm for each drying regime. However, for each experimental regime, the samples with 10 mm thickness showed the highest equilibrium moisture content values, while the samples of 5 mm thickness showed the lowest values. It can be concluded that the equilibrium moisture depends on both drying temperatures of the hot plate and air, temperature difference between them, as well as on thickness of the samples. Highest values of *Me* were obtained for WHP-30, while the lowest for 70-30 regime. The RH values of hot air were 21, 14, 10, 5.8, and 0.7% for air temperatures of 30 °C, 40 °C, 50 °C, 60 °C, and 70 °C, respectively.

Table 2. Equilibrium moisture content

		Air temperature [°C]				
		30	**40**	**50**	**60**	**70**
Hot plate temperature [°C]	**WHP**	0.35	0.27	0.23	0.18	0.13
	50	0.16	0.21	0.25	–	–
	60	0.13	0.17	0.20	0.23	–
	70	0.08	0.09	0.11	–	0.14

Drying times varied with the drying conditions and sample thickness, fig. 4. For purely convective drying, drying time decreases with the increase of air temperature because of the faster moisture migration through samples, and lower RH values of the drying air, which is in agreement with other studies on nectarine drying [21, 22, 24]. However, when combined hot air and hot plate method was used, the drying time was influenced not only by the temperatures of the air and hot plate, but also by temperature difference between them. Longest drying times were obtained for WHP-30-10 regime, while the lowest for 70-30-5 regime.

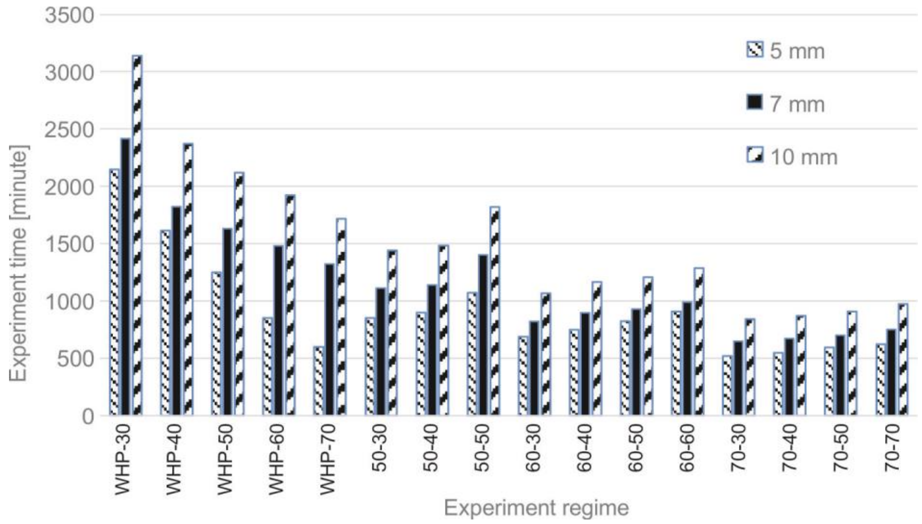

Figure 4. Drying times for each experiment for different material thicknesses

The hot plate temperature has predominant influence on drying time. If the air temperature was kept constant, increasing the temperature of the hot plate significantly shortened the drying time, fig. 5. For example, for sample thickness of 7 mm, and air temperature set to 40 °C, conductive enhanced drying with temperatures of the hot plate set to 50 °C, 60 °C, and 70 °C led to the reduction of drying times by 37.5%, 51%, and 63%, respectively, in comparison with pure convective drying at 40 °C. Effectiveness of conduction enhanced drying can be explained by the fact the heat flux provided through the hot plate is much greater than the heat flux brought by hot air [16, 17].

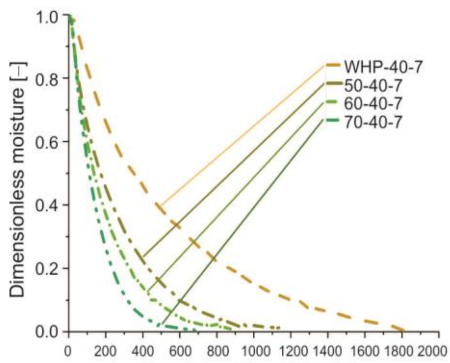

Figure 5. Influence of the heating plate temperature on drying curve for constant air temperature

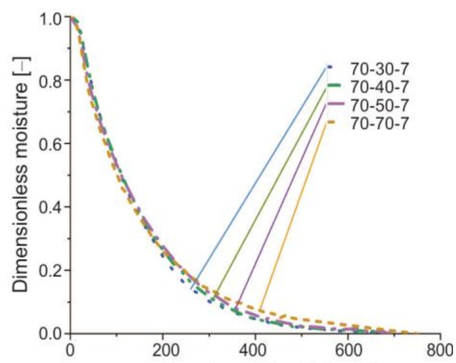

Figure 6. Influence of the hot air temperature on drying curve for constant hot plate temperature

On the other hand, when the hot plate is kept at constant temperature, it is observed that air temperature has little effect on drying times, fig. 6. However, we noticed slight differences that are consistent with all material thicknesses. Namely, the regimes where the temperatures of the hot plate and hot air were the same have shown the lowest values of effective coefficient of diffusion and consequently the longest drying times, in comparison with the regimes where the temperature difference between hot plate and the air existed. This indicates that heat fluxes and temperature field had significant effect on the drying process and moisture removal from material. In materials with colloidal-capillary structure, such as fresh nectarine pomace, the majority of moisture in falling rate period is transferred through material mainly in the form of liquid moisture. During combined conductive-convective drying, liquid moisture flux, and heat flux have the same directions, which indicate that one of the main mechanisms of liquid moisture transfer in falling rate period is liquid thermal diffusion [38, 39]. When drying conditions were such that the temperatures of the inner layers of material close to the free surface were lower than the temperature of the air, then the heat fluxes from the hot plate and hot air had opposite directions, which led to forming moisture vapour front inside the material, causing resistance to moisture transfer [25]. This is especially true during latter phases of drying when vapour moisture transfer is the controlling mechanism of moisture transfer. This could explain why the regimes with higher hot air temperature have slightly longer drying times and lower diffusion coefficients. The regimes with no temperature gradients, *i.e.* with the same temperature of the air and hot plate had the longest drying times. Another phenomena to take into consideration is case hardening, *i.e.* formation of the crust on the surface of the sample, which could reduce the moisture removal from the free surface of the material, and has stronger effect with increasing air temperature.

At the beginning of the drying, higher air temperatures influence quicker heating of material which leads to faster moisture removal, higher drying rates and steeper drying curves, fig. 6. However, as the experiment progressed, the effect of vapour fronts is becoming more dominant, and at one point 70-70 regime is turning into slower regime than 70-30, 70-40, and 70-30, fig. 7. For 70 $^{\circ}$C heating plate temperature, curve 70-70 starts intersecting other lines at MR = 0.34. From that point on, air temperature can be lowered to 30 $^{\circ}$C in order to gain energy savings.

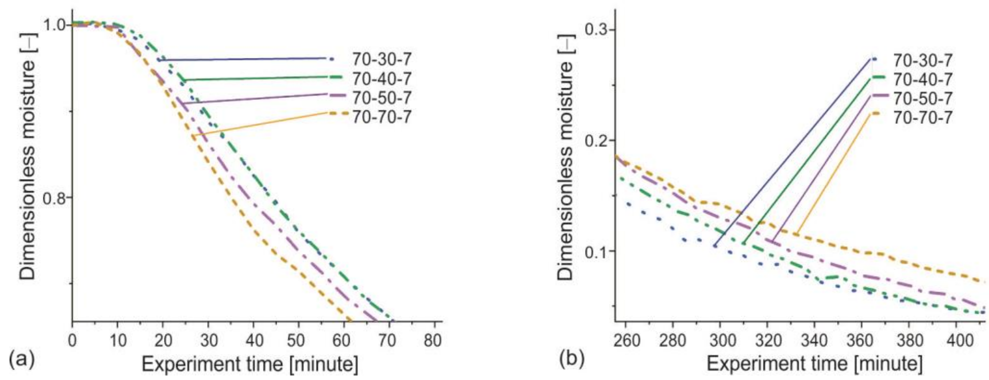

Figure 7. Drying curves' character at the beginning (a) and the end (b) of the measurements for 7 mm samples dried at 70 $^{\circ}$C heating plate and 30 $^{\circ}$C, 40 $^{\circ}$C, 50 $^{\circ}$C, and 70 $^{\circ}$C air temperatures

Drying rates calculated using eq. (5) for pure convective and conductive enhanced drying are plotted on the same diagram, fig. 8. As it can be seen, the nectarine pomace drying takes place in the falling rate period, except for very short period of warming-up at the beginning of the drying process. Character of 60-30-10 and WHP-30-10 curves are significantly different. Combined conductive-convective drying reaches much higher (approximately 3.2 times greater) values of drying rate compared to convective one.

The conductive enhanced drying rate curve has abrupt rise till the pick at the beginning and then steep fall compared too much lower pick and mild constant fall during convective drying. Hot plate is heating the material much faster which leads to faster moisture migration during whole experiment. During the initial phase of drying the moisture gradient is the greatest, and the intensity of moisture transport is the highest. Later on, as the evaporation effect is taking place, the gradient of temperatures and moisture front has bigger influence, causing regimes with bigger temperature difference to have better diffusion coefficient and lower drying times.

In fig. 9 it can be seen the influence of material thickness on drying rate for 70-40 regime. Samples of 5 mm thickness are showing the highest drying rate values at the beginning of the drying. This is because the thinner the sample is, easier is to warm it up, which directly caused faster moisture removal at the beginning of the drying. At approximately 240 min after the beginning of the drying, curves intersect and have the same drying rate value.

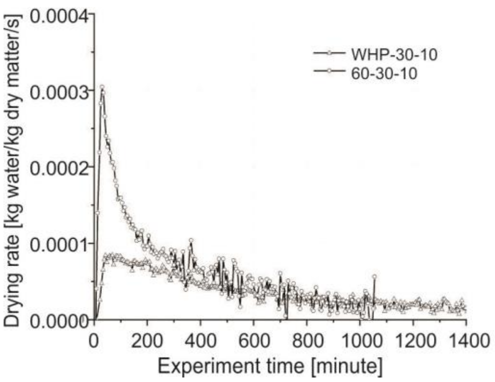

Figure 8. Comparison of drying rate characters between pure convective drying at 30 °C and conductive enhanced drying with 60 °C hot plate temperature for sample thickness of 10 mm

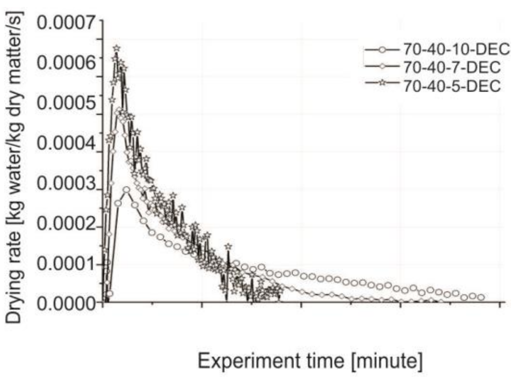

Figure 9. Influence of the sample thickness (5, 7, and 10 mm) on drying rates at 70 °C hot plate and 40 °C hot air temperatures

Fitting of the drying curves

The MR *vs*. time curves are fitted to the 6 models listed in tab. 1. The statistical results of the models, including model, coefficients and goodness of fit, R^2 are listed in tab. 3. The R^2 values of logarithmic model were the highest with average value of 0.99795, which indicates this model fits very well to the experimental data, and is adopted as satisfactory for nectarine pomace drying.

Determination of effective diffusivities

The results have shown that internal mass transfer resistance controls the drying time due to the presence of a falling rate drying period. The values of effective diffusivity, D_{eff}, for different drying regimes are obtained by using eq. (2). The average values of effective diffusivities of nectarine pomace in the drying process varied in the range of $0.279\text{-}3.15 \cdot 10^{-9}$ m^2/s, fig. 10.

Table 3. Goodness of the fit for models in tab. 1

Thickness [mm]	Model name					
	[12]	[14]	[15]	[17]	Logarithmic	Simplified fick diffusion
	R^2					
5	0.98949	0.70351	0.99809	0.99339	0.99822	0.99726
7	0.99336	0.74033	0.99834	0.99622	0.99837	0.99722
10	0.99171	0.80535	0.99707	0.99517	0.99725	0.99319
Average R^2	0.99152	0.74973	0.99783	0.99493	0.99795	0.99589

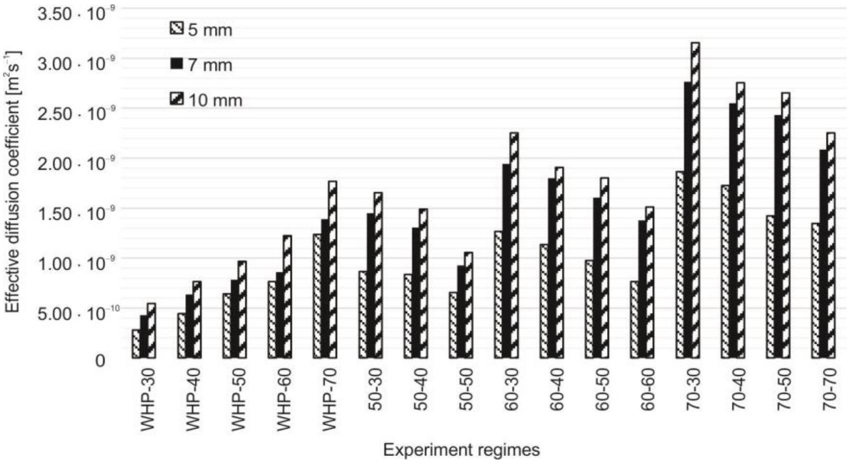

Figure 10. Effective diffusion coefficients for different material thicknesses

These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of 10^{-12} to 10^{-8} m^2/s for food materials [28].

Conclusions

Kinetic parameters of thin layer nectarine pomace were evaluated in a laboratory scale dryer. Thin disk-shaped samples of nectarine pomace with 5, 7, and 10 mm thickness and 100 mm in diameter were subjected to the simultaneous hot air and hot plate heating, thus allowing for combined conductive-convective drying process.

The kinetics of nectarine pomace drying was examined in detail. It was concluded that the hot plate has much more influence on drying curves than the hot air during entire experiment. However, hot air plays significant role during the initial stages of drying when the material is being warmed up, while as the drying progresses, the effect of hot air decreases, and even has negative impact on drying times. Therefore, one recommendation is to decrease air temperature at certain point, which would lead to shorter drying times and consequently energy savings. The exact determination of the moment where the hot air temperature should be lowered is a subject to further investigations. The results were fitted against few empirical models found in literature. For conductive-convective drying, logarithmic fit was satisfactory with R^2 value of 0.99795.

The significance of this work is in evaluating the drying kinetics by varying the temperatures of the hot plate and hot air, thus drying under the temperature gradient. Combined conductive-convective drying method changes the moisture removal mechanisms typically present in pure convective drying. Practical application in industry is the possibility of obtaining the optimum between the drying time and energy consumption. The results of this study could be applied for thin film drying of nectarine pomace or similar fruit pomaces.

In future work it is planned to determine the energy efficiency of the conductive-enhanced drying and the optimal regime of food waste products with respect to energy consumption and drying times.

Nomenclature

a,b,c,k,n – drying model coefficients
D_{eff} – effective diffusion coefficient, [m^2s^{-1}]
DR – drying rate, [$kg_w kg_{dm}^{-1} s^{-1}$]
k_0 – slope of the line, [–]
M – moisture content, [$kg_w kg_{dm}^{-1}$]
Me – equilibriummoisture content, [$kg_w kg_{dm}^{-1}$]
M_0 – initial moisutre content, [$kg_w kg_{dm}^{-1}$]
MR – moisture ratio [= $(M – Me)/(M_0 – Me)$], [–]
n – counter
R^2 – correlation coefficient, [–]
RH – Relative humidity, [%]

Greek symbols

τ – time [s]
δ – thickness of the sample[m]

Acronyms

WHP – without hot plate
P – hot plate temperature
A – air temperature
T – sample thickness

Subscripts

dm – dry basis
w – water

Acknowledgment

The results presented in this paper are the result of the research supported by MPNTR RS, Contract No. 451-03-68/2020-14/200105.

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Paper submitted: March 12, 2020
Paper revised: July 18, 2020
Paper accepted: July 28, 2020