Optimization of Convective Drying of Apricots

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***Abstract* – The purpose of this study is to realize multi-criterial optimization of the parameters of apricot drying. The drying experiments were conducted at a temperature of *T*=50÷80°C and velocity of *v*=0.5÷2m/s of the drying agent. The dependence of the modified Page model's parameters to the temperature and the velocity of the drying agent were obtained. The impact of the drying parameters on the quality indicators colour, β-carotene and vitamin C content in the dried apricots was studied. The optimal values of the drying parameters were determined applying different criteria: the quality of the final product, the quality of the final product and process duration, the quality of the final product and minimum energy consumption. The optimal values of the temperature and velocity of the drying agent according the criteria for the quality of the final product, the process duration and the energy consumption are *T*=63.5°C and *v*=0.5m/s.**

***Keywords* – apricots, drying, energy consumption, optimization, quality.**

1. Introduction

Drying is a typical heat and mass exchange process, which is widely used in agriculture. This method of preserving agricultural production has been known since ancient times. At the beginning of the 20th century, an intensive development and research of forced drying, using classical energy sources began. Industrial dryers have a high productivity and provide constant parameters of the drying process, regardless of the ambient air's parameters, but they are characterized with high energy costs. Therefore, studies are needed to determine the regime parameters for specific fruits and vegetables, in order to reduce energy costs [4].

Apricots (Prunus armeniaca L.) are the primarily grown fruit in Northeast Bulgaria. The fresh fruit contain vitamins B2, B3, B9, C, and E and are an excellent source of provitamin A (β-carotene). The main method of apricot drying is the convective drying. To preserve the quality characteristics of the final product, the most frequently used method is the preliminary treatment of the raw material, using sulfation. In many of the cases, the consumption of such dried fruit leads to allergic reactions. As an alternative to such apricots, organic apricots are increasingly more frequently offered in the market – dried fruit without preliminary treatment or treated in advance with ascorbic acid. The impact of the drying agent's parameters on the quality of the final product is substantial in them. There is a number of publications on the sulfation impact over the quality of the dried apricots [3, 5, 7]. The studies on the impact of the drying agent's parameters over the β-carotene and vitamin C content and the loss of colour in the dried apricots, treated preliminarily with ascorbic acid, are insufficient.

Another significant characteristic of the drying processes is their duration. The parameters of the drying agent have a substantial impact on the process duration. In order to define the process of moisture separation, more than 16 kinetic models have been developed [9]. In some studies, the dependence of the mathematical models parameters on the drying agent's parameters are obtained [9, 6], so that they can be used for a further optimization of the process.

The above discussed characteristics of the drying process - energy consumption, duration, and the high quality of the final product, are however, in conflict. For example, increasing the temperature of the drying agent will accelerate the process, but it may

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lead to increased energy consumption. The higher velocity of the drying agent in the initial drying phase leads to a better separation of the moisture from the surface layer of the material; however, the high velocity in the final phase can result in a loss of some dried material and excessive energy consumption. Therefore, a comprehensive approach is needed in the optimization of fruit and vegetable drying processes, in order to meet the increasing demands of the European Union, with respect to the food-product quality, and the reduction of the energy consumption, needed for its implementing.

The aim of this study is the optimization of convective drying of apricots under criteria, considered the quality of the final product, the process duration and the energy consumption for its implementation.

2. Materials and Methods

Samples

Fresh apricots (*Prunus armeniaca* L.) were purchased, selected without defects and with similar size and colour. Prior to their drying, a kilogram of apricots was washed, pitted, and split into two halves. The halves of the apricots were preliminarily treated by soaking them for 10 minutes in 0.2% solution of ascorbic acid.

Drying experiments

The drying processes were implemented in July 2013. An experimental set-up to capture the kinetic curves of the drying consists of a chamber with shelves, a fan, heaters, a computer, a controller, a digital scale, sensors of the relative humidity and temperature, and an anemometer. During the experiments the temperature and the humidity of the ambient air and the electric energy consumption were recorded, and the temperature and the velocity of the drying agent were controlled. The experiments were conducted with apricots arranged on the shelves and dried at temperatures of 50, 60, 70 and 80°C and velocities of the drying agent 0.5, 1, 1.5 and 2m/s. During the drying, the mass of apricots was recorded every 15 min, by electronic scale with class of Accuracy III. The initial moisture content of the apricots was 86% and they were dried until a condition in which there was no further change in the mass was reached - about 16÷18% moisture content.

Quality analysis

Another set of experiments was carried out in the summer of 2016 to determine the change of colour and the content of β-carotene and vitamin C.

The colour values L^*, a^* and b^* of the fresh and dried apricots were measured using Imaging source DFK 31AU03 camera. The total colour difference ΔE was determined as

$$\Delta E = \left[\left(L_f^* - L_i^*\right)^2 + \left(a_f^* - a_i^*\right)^2 + \left(b_f^* - b_i^*\right)^2 \right]^{\frac{1}{2}}$$

where L_f^*, a_f^* and b_f^* are the colour values of fresh samples and L_i^*, a_i^* and b_i^* are the colour values of the dried samples.

The total β-carotene content was determined using the Park's method [2]. The vitamin C content was determined according to the method of Klein & Perry [2]. The analysis was conducted with a triple measurement of a sample of dried apricots.

Statistical analysis and optimization

Drying processes under plan B_2 - a symmetric composition plan with a central point - were implemented in the summer of 2016 for the purposes of qualitative analysis. The values of the temperature and velocity are shown in Table 1. The regression equations were obtained as a result of the statistical analysis with the StatSoft bundle of STATISTIKA.

The optimization of the mathematical model of the drying curve and the optimization of the processing conditions were implemented using GA and GAMULTIOBJ in MATLAB.

3. Results and Discussions

Mathematical modelling of drying curves

The moisture ratio *MR* for different fruits and vegetables is calculated as

$$MR = \frac{u - u_e}{u_o - u_e} \qquad (1)$$

where u is the moisture content of the material at time t, kg/kg;

u_o - initial moisture content, kg/kg;

u_e - equilibrium moisture content, kg/kg.

Research for the model, which best describes the experimental data, has been conducted and described in Ivanova et al., [6].

Modified Page model

$$MR = e^{-(kt)^n} \qquad (2)$$

gives the highest value of the correlation coefficient *R* and the lowest value of the root mean square error *RMSE* for all of the experimental drying air conditions T=50÷80°C and v=0.5÷2m/s.

Based on the multiple regression analysis, the values of the drying rate constant k and the drying parameter n of the modified Page model, were regressed against those of drying air temperature and velocity. The dependence of both parameters on the air variables was expressed as an Arrhenius type equation [1]. The genetic algorithm was used to optimize the obtained drying rate constant k and the drying parameter n of the modified Page model. As unknown variables it was considered to be parameters k and n. The aim was to obtain the minimum of the fitness function which consists of the reciprocal of the correlation coefficient R and root mean square error $RMSE$. The fitness function had been saved in M-file. It was necessary to pass a function handle as the first argument to the GA function, as well as specifying the number of variables as the second arguments. Lower and upper bounds of the air parameters were provided as LB and UB respectively. No need to manually input another restrictive condition.

The obtained drying rate constant k and drying parameter n for the temperature T=50÷80°C and the velocity v=0.5÷2m/s of the drying agent are

$$k = 0.0155 v^{0.3258} e^{-\frac{105}{T}}, \qquad R = 0.9957$$

$$n = 2.0848 v^{-0.0659} e^{-\frac{25.3279}{T}}, \qquad R = 0.9272$$

The effect of drying on quality indicators

The evaluation of the change in colour of the dried apricots was conducted using the colour values L^*, a^* and b^*. The measured colour values of fresh and dried apricots are shown in Table 1. and are close to those published in [5].

The impact of the drying agent's temperature on the colour value L^* is significant – for fresh apricots it is 69.0 and for dried ones drops from 43.8 at T=65°C and to 30.2 at T=50°C.

The impact of the drying agent‘s velocity was considerable at lower temperatures of drying. The value a^* increased more than twice with the increase in the temperature of the drying agent. Ihns et al., [5], argue that the value a^* decreases with the increase in the temperature, whereas Karabulut et al., [7], also claims that a^* increases with the increase in the temperature of the drying agent, which confirms the blackening of the dried apricots. The value b^* changes in the range of 9 at T=50°C and v=0.5m/s to 25.1 at T=65°C and v=0.5m/s.

The last column of Table 1. shows the total colour change ΔE. It is evident that with the increase of the drying agent's temperature to T=65°C the losses of colour in the dried apricots decrease.

The colour change of the dried apricots can be described with the mathematical model

$$\Delta E = 283.3708 - 7.165T + 1.793v + 0.0526T^2$$

The model is adequate.

Table 1. Colour values, β-carotene and vitamin C of dried apricots

	T	v	T, °C	v, m/s	β-c.	vit.C	L^*	a^*	b^*	ΔE
fresh					41	17	69.0	6.2	51.8	85.50
1	-1	-1	50	0.5	24	5.28	30.2	6	9	57.77
2	-1	0	50	1.25	26	7.2	34.4	9.7	9.6	54.68
3	-1	1	50	2	26	8.54	37.8	10.3	10.2	52.16
4	0	-1	65	0.5	29	5.06	41.2	12.2	25.1	39.01
5	0	0	65	1.25	30	6.05	43.8	12.8	24.8	37.52
6	0	1	65	2	31	6.78	43.4	12.6	24.6	37.90
7	1	-1	80	0.5	35	4.75	35.2	11.9	21	46.08
8	1	0	80	1.25	35	4.4	36.5	12.2	22.2	44.37
9	1	1	80	2	37	4.4	36.4	12.4	21.8	44.73

The β-carotene content in apricots dried at different temperatures and velocities of the drying agent is shown in Table 1. The β-carotene content in fresh fruits is 41mg/100g, larger than the values for the different varieties published by Ruiz et al., [8]. The β-carotene value at temperature T=50°C and velocity v=0.5m/s of the drying agent is 24mg/100g, and at T=80°C and v=0.5m/s is 35mg/100g, i.e. with the increase of the drying agent's temperature, the β-carotene content increases. In [5, 7] also is shown that the β-carotene content in the dried apricots increases with the increase in the temperature of the drying agent. For them, the results also show that apricots dried for a longer period of time have lower β-carotene content. This is also confirmed by Table 1., where, albeit in smaller bounds, the increase in the drying agent's velocity at one and the same temperature increases the β-carotene content.

The model describing the dependence of the β-carotene content in dried apricots of the drying agent's temperature and velocity is

$$\beta = 15.3332 + 0.0555T + 1.3333v + 0.0022T^2$$

The model is adequate.

The vitamin C content in fresh apricots is 17mg/100g. The vitamin C values in dried apricots at different temperatures and velocities are shown in Table 1. They range from 4.4mg/100g to 8.54mg/100g. The vitamin C content decreases with the increase in the temperature of the drying agent. At T=50°C, the impact of the velocity of the drying agent is considerable – the decrease in the velocity also decreases the vitamin C content. At T=80°C of the drying agent, the impact of the velocity is very weak.

The model of the vitamin C content in dried apricots depending on the drying agent's temperature and velocity is

$C = 3.6085 + 0.0173T + 6.2433v + 0.08022vT$.

The model is adequate.

Definition of a multi-criterial optimization of the drying process

Determining the minimum energy consumption

The energy efficiency of the moisture-separation process is evaluated mainly with the energy, input for its implementation. The energy, required to carry out the process, is determined by the equation

$$\min J_E = \int_0^{t_d} \dot{m}_a \left(c_{p,a} + c_{p,v} Y_a\right)\left(T - T_a\right) dt \quad (3)$$

where $\dot{m}_a$ is the mass air-flow rate, $c_{p,a}$ is the specific thermal capacity of dry air, $c_{p,v}$ is the specific thermal capacity of water vapor, Y_a is the ambient air moisture content, T_a is the ambient air temperature, T is the drying agent temperature, t_d is the duration of drying.

The mass air flow rate $\dot{m}_a$ is determined as

$\dot{m}_a = Sv\rho$,

where S is the area of layers, v is the drying agent velocity, ρ is the humid air density.

It is obvious that (3) determines the dependence of the energy consumption of the drying agent's temperature T and velocity v.

Determining the minimum duration of the process

The availability of drying kinetic curve allows to determine the parameters of the drying agent so that a minimum duration of the process can be achieved.

From the kinetic curve of drying (2) we determine

$$t_d = -\frac{\left(\ln \dfrac{u - u_e}{u_o - u_e}\right)^{\frac{1}{n}}}{k}$$

Consequently, the temperature and the velocity of the drying agent can be determined so that we have a minimum duration $\min t_d$ to reach a pre-set final moisture content value $u = u_{end}$.

Determining the final product quality

We considered the impact of the drying agent's parameters on the colour change ΔE, β-carotene and vitamin C content above. The issue of optimization consisted of determining the optimal values of the air parameters, for which the analyzed changes in the quality characteristics of the dried product reach a minimum. The criterion of the optimization is

$minQ(T, v) = w_1\Delta E(T, v) + w_2\beta(T, v) + w_3C(T, v)$ (4)

where w_1, w_2 and w_3 are weight values;

$$\Delta E(T,v) = \frac{\Delta E_{dm}}{\Delta E_{\max}} \to \min$$

$$\beta(T,v) = \frac{\beta_f - \beta_{dm}}{\beta_f} \to \min$$

$$C(T,v) = \frac{C_f - C_{dm}}{C_f} \to \min$$

f - fresh material; dm – dry material.

Optimization of the drying process by genetic algorithm

The lowest specific energy value E=1.44kWh/kg necessary to implement the drying process is obtained at parameters of the drying agent T=50°C and v=0.5m/s. The process duration is t_d =889.52min.

The minimum duration of the drying process t_d =402min is obtained at parameters of the drying agent T=80°C and v=2m/s. The energy necessary to implement the process is E=6kWh/kg.

The optimal values of the drying agent's temperature and velocity for processes ensuring pre-set quality of the final product according to criterion (4) at different values of the weight coefficients are shown in Table 2.

The highest value of the duration and the lowest value of the energy necessary to implement the process is obtained at a greater weight of the component of the criterion (4) for vitamin C content.

The shortest duration and the highest value of the energy necessary to implement the process are obtained at a higher weight of the component of the criterion (4) for β-carotene content. Close optimal values of the drying agent's parameters were obtained according equal weight values and at highest weight values of the component minimum loss of colour of the criterion (4). Figure 1. shows the criterion $Q(T, v)$.

Table 2. The optimal values of the drying agent's temperature and velocity

w_1	w_2	w_3	T,°C	v,m/s	t_d ,min	E, kWh/kg
0.25	0.25	0.5	55.2	2	456.72	3.56
0.25	0.5	0.25	67.8	2	426.32	4.86
0.5	0.25	0.25	61.8	2	439.32	4.26
0.333	0.333	0.333	60	2	444.34	4.07

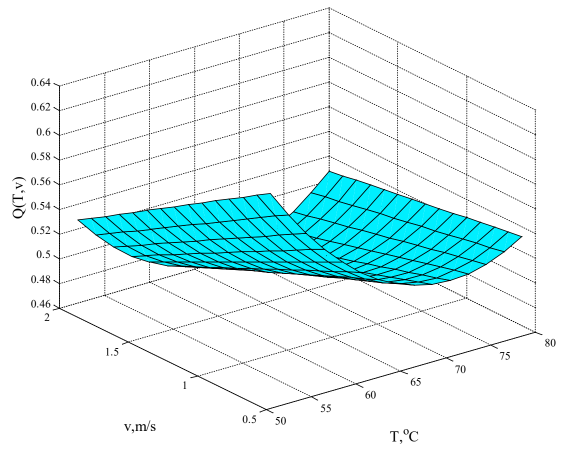

Figure 1. Dependence of the criterion Q of the drying agent's parameters

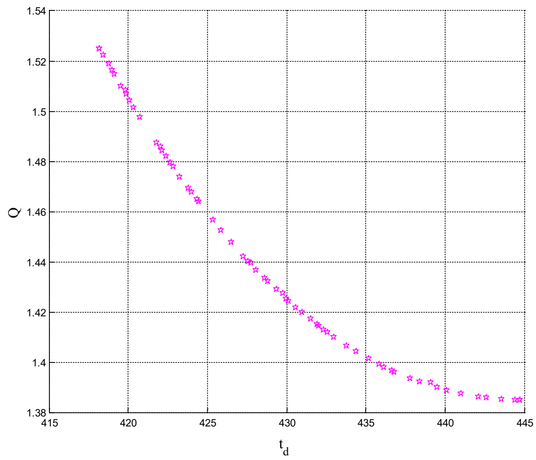

Figure 2. Pareto line for criteria $\min t_d$ *and* $\min Q$

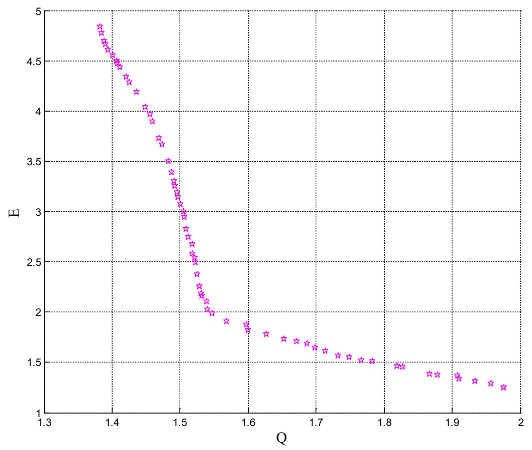

Figure 3. Pareto line for criteria $\min Q$ *and* $\min E$

The optimal values of the drying agent's parameters according the criteria for the quality of the final product and minimum process duration are T=67.5°C and v=2m/s. The process duration is t_d =426.97min and the energy necessary to implement it is E=4.84kWh/kg. The Pareto line is shown in Figure 2.

The optimal values of the drying agent's parameters according criteria for the quality of the final product and minimal energy for implementation of the process are T=71.8°C and v=0.5m/s. The process duration is t_d =664.89min and the energy necessary for its implementation is E=2.09kWh/kg. The Pareto line is shown in Figure 3.

The optimal values of the drying agent temperature and velocity according criteria for the quality of the final product, duration of the process and minimum value of the energy are T=63.5°C and v=0.5m/s. The process duration is t_d =700min and the energy necessary for its implementation is E=1.834kWh/kg.

4. Conclusions

A mathematical model of the drying kinetics of apricots was obtained, which was used to determine the process duration.

The impact of the drying agent's parameters on the quality indicators loss of colour, β-carotene and vitamin C content was studied. With the increase in the drying agent's temperature to 65°C, the loss of colour of the dried apricots decreases.

The increase in the drying agent's temperature is connected to the increase in the β-carotene content and with the decrease in the vitamin C content.

A regression dependence of the quality indicators was derived from the temperature and the velocity of the drying agent. The obtained optimal values of the drying agent parameters according to different criteria are: for the criterion quality of the final product accounting for the loss of colour, β-carotene and vitamin C content - T=60°C and v=2m/s; the quality of the final product and process duration - T=67.5°C and v=2m/s; the quality of the final product and the energy consumption - T=71.8°C and v=0.5m/s.

The optimal values of the drying agent's temperature and velocity, according to the criteria for quality of the final product, the process duration and the minimum energy consumption are T=63.5°C and v=0.5m/s.

The approach for the optimization of the drying process of apricots, presented hereinabove, can be applied in the drying of various fruits and vegetables.

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