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THE EFFECT OF TRAYS' SLOPE IN THE TUNNEL DRYER ON DRYING RATE OF CARROT CUBES

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Key words: carrot, convective drying, tunnel dryer, simulation, trays' slope.

Abstract

Drying of food is perhaps the oldest method of food preservation. The aim of this study was the analysis of the effect of changing the slope angle of trays in a tunnel dryer model on the drying rate. Real experiments were carried out for trays' slopes of 0, 5, 10 and 15°. Carrots' cubes were dried at a constant temperature of 60°C, with air flow velocity of 1.2 m/s. Also this process was simulated using the COMSOL Multiphysics 4.3 software. The research results showed that increasing slope angle of tray disrupted the laminar flow of the dried cubes layer through the drying air stream and forced the partial air flow through the layer. Thus, the contact surface of the heated air with the material particles and the drying rate have been increased and made it possible to shorten the duration of the drying.

Introduction

Convective drying of products with a high initial moisture content is a long-term and energy-consuming process as well as destructive in relation to biological products such as vegetables and fruits. However, this is the oldest, best known and therefore the most commonly used method of drying.

Many factors affect the convective drying process. One of them is the temperature of the drying agent. Higher temperature shortens the drying time

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(Skorupska 2005, Szarycz et al. 2011, Veleşcu et al. 2013, Garba et al. 2015, Naderinezhad et al. 2016, Maisnam et al. 2017). In addition, the temperature affects the colour change. An increase in temperature and a longer drying time means that the colour of the dried material is darker (Biller et al. 2005 Sharma, Prasad 2001, Sumnu et al. 2005). In the case of carrots, an increase in temperature causes a reduction in the content of β-carotene (Gawałek 2005). Disadvantages of drying include unfavourable changes in the plant tissue caused by chemical reactions such as: non-enzymatic browning, changes in vitamins or oxidation processes (Nowacka, Witrowa-Rajchert 2007), decrease in anthocyanin content (in strawberries, Morales-Delgado et al. 2014). During convective drying, the highest loss of volatile compounds was observed compared to other drying methods (Calín-Sánchez et al. 2012). Another important factor is the speed and direction of air flow relative to the material to be dried. Higher airflow speeds up the moisture removal process (Velić et al. 2004, Zlatanović et al. 2013, Veleşcu et al. 2013, Naderinezhad et al. 2016). Witrowa-Rajchert and Radecka's research (2005) showed that the air flow through the layer shortens the drying time compared to drying along the layer, while the shortest drying time was observed during fluidized bed drying.

The length of the convective drying time is also influenced by grinding degree of raw material (Głowacki et al. 2005, Fernando et al. 2011), geometric shape of the sample (Béttega et al. 2014, Naderinezhad et al. 2016) and physical properties dependent on the variety (Nowak et al. 2005). Ding et al. (2015) investigated the effect of different voltages on carrot drying rate. One of the basic physical changes taking place during drying is the drying shrinkage, which is manifested by the reduction of the volume of the dried material and, as a result, its density (Wang, Brennan 1995, Pabis, Jaros 2002). The disadvantage of this drying method at lower drying temperatures, although it results in a better quality of the final product and low flow of the drying medium, is a long drying time. Due to the above reasons, for many years various works have been undertaken to increase the efficiency of the drying process. The use of convection allows for both drying of large batches and getting a dried material of relatively good quality. Frequently, tunnel dryers are used in practice. The material to be dried is placed on trays filling the trolleys and placed in a drying tunnel. The drying air is forced into the tunnel generally co-currently or countercurrently manner with the direction of movement of the carriages. The range of flow velocity of the drying air stream causes that it flows over the layer laminar, possibly turbulent – in points of local flow disturbance due to various resistance. Thus, the air flows around the dried material, having contact with it mainly along the upper horizontal surface of the layer, while the local velocity of the drying air over this surface is greater than over the other surfaces of the particle.

Currently, it is possible to simulate such phenomena using specialized software, for example COMSOL Multiphysics. This tool is used, among others, to simulate phenomena related to fluid flow, including laminar flow, turbulent and coupled heat transfer (COMSOL Multiphysics… 2013). This software has been used, for example, to develop heat and mass transfer models during convective drying of fruits, depending on their shrinkage and temperature (KUMAR et al. 2012a) and variable material properties (KUMAR et al. 2012b). GERLICH et al. (2013) used COMSOL Multiphysics 4.3. for calculating the heat transfer in buildings and DZIAK et al. (2009) determined the values of heat and mass transfer coefficients during evaporation from a thin layer of a two-component liquid solution of high viscosity.

Increasing the active surface of heat exchange and mass of a moist material, dried convectively in a tunnel drier, i.e. with forced horizontal flow of the drying air stream, should result in a higher drying rate of this material. Therefore, a simple technical solution, increasing the efficiency of drying, would be to increase the active drying surface by sloping the trays. Therefore, the aim of the work was to examine how the inclination of the trays from the horizontal level by a certain angle will affect the drying rate of carrot cube in a tunnel dryer. In this study was analysing also how the flow of air flowing over the carrot inside the dryer changes. For this purpose, actual measurements and simulation tests were carried out using COMSOL Multiphysics 4.3 software.

Materials and methods

Carrot cubes of 0.01±0.001 m side were used as a research material. Carrot came from a single source. Cubes were prepared from carrot roots of even shape and mass. The initial mass of sample was 0.230±0.001 kg. The dry mass was determined according to PN-A-75101-03:1990 standard. Moisture content was determined according to the equation:

$$u(\tau) = \frac{m(\tau) - m_{ss}}{m_{ss}} \tag{1}$$

where:

τ – drying time [min],
$u(\tau)$ – moisture content at time τ [kg kg^{-1}],
$m(\tau)$ – mass at time τ [kg],
m_{ss} – mass of dry substance [kg].

Experiment

Carrots cubes were dried in a laboratory tunnel dryer equipped with trays of adjustable slope from 0 to 20° relative to the horizontal plane. The laboratory tunnel dryer used in real previous experiments had four sections, four trays with dimensions of 0.25 × 0.40 m, positioned from each other vertically at distance 0.10 m. However, placing trays in the dryer with the possibility of changing the slope angle forces the number of trays to be reduced to 12.

The experiments were carried out for trays' slopes of 0, 5, 10 and 15°. The measurements were carried out at a constant temperature of 60°C, flow rate of 1.2 m/s. Relative humidity and drying air pressure was the same as in the laboratory, i.e. 40% and about 1,000 (±15) hPa. The measurements of moisture content were made from initial to a final moisture content of 0.01 kg·kg^{-1}. To assess the influence of the trays' slope on drying time calculated the relative differences in moisture content samples after the same drying time were calculated relative to the moisture content in the 0 sample – dried on a horizontal tray, according to the equation:

$$\Delta u_{\%} = 100\frac{u(0^o, \tau_i) - u(S^o, \tau_i)}{u(0^o, \tau_i)} \tag{2}$$

where:

$\Delta u_{\%}$ – relative differences of moisture content [–],
$u(0°,\tau_i)$ – moisture content in sample on a horizontal tray [kg·kg^{-1}],
$u(S°,\tau_i)$ – moisture content in the sample on a tray inclined at angle of $S°$ [kg·kg^{-1}].

The effect of tray slope on the drying efficiency of the examined drying variants was also examined by determining the coefficients of: the initial drying rate and heat transfer. The carrot's cubes have a large initial moisture content, therefore in the relevant time range, the drying rate at the set temperature is determined by external mass exchange conditions. An indicator of this is the coefficient of heat transfer to the surface, depending on the speed of the drying air stream flowing over the boundary layer of the dried objects. The drying rate in this period is constant and is expressed by the equation (PABIS 1982):

$$\frac{du}{d\tau} = k_0 = \frac{\alpha A}{r\rho_s V_s}(t_p - t_M) \tag{3}$$

where:

α – coefficient of heat transfer [W·(m^{2}K)$^{-1}$],
A – material surface [m^2],
k_0 – coefficient of initial drying rate [min^{-1}],

r – heat of evaporation [$kJ \cdot kg^{-1}$],
ρ_s – density of dry material [$kg \cdot m^{-3}$],
V_s – volume of dry material [m^3],
t_p – temperature of the drying agent [°C],
t_M – temperature of the wet thermometer [°C].

Equation (3) is the basis for the formulation of theoretical models of the first drying period. The structure of the theoretical model taking into account the shrinkage (PABIS, JAROS 2002) is a third degree polynomial with the form:

$$u(\tau) = u_0 - k_0\tau + C_2\tau^2 + C_3\tau^3 \tag{4}$$

where:
u_0 – initial moisture content [$kg \cdot kg^{-1}$],
C_2, C_3 – model coefficients [–].

The k_0 values of the drying rate coefficient, in the tested tray settings, were taken from the trend function – third degree polynomials, matched for moisture content measurements. Then the values of aA were calculated from the equation (3).

Comparison of these values gives the premise to formulate the conclusion about the impact of the angle of tray settings in the tunnel dryer on the drying rate of the tested carrot cubes.

Simulation

For the purpose of simulating the drying process COMSOL Multiphysics 4.3 application was used. First a tunnel dryer model with trays and material in the form of cubes was created. The model also included tray holders and a grid placed at the end of one diffuser because these elements significantly affect the airflow inside the dryer. Next, the model was covered with a computational mesh consisting of approximately 130,000 irregular triangles (Fig. 1). The compaction degree at the trays, holders and diffuser inlet is higher since those are elements which affect the most an air flow.

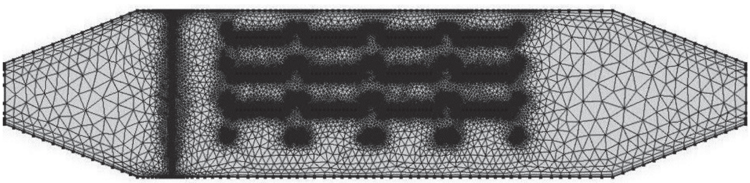

Fig 1. Model of a laboratory tunnel dryer with a mesh

In COMSOL Multiphysics 4.3 was used the Navier-Stokes equation in the form:

$$\rho(u \cdot \nabla)u = \nabla \cdot [-p + \eta(\nabla u + (\nabla u)^T) - \frac{2}{3}\eta(\nabla \cdot u)] + F$$

$$\nabla(\rho u) = 0 \tag{5}$$

where:

ρ – air density [kg·m^{-3}],
u – air velocity [m·s^{-1}],
p – the pressure [Pa],
η – dynamic viscosity [Pa·s],
T – temperature [K],
F – volume force [N·m^{-3}].

Boundary conditions used in the model were: no slip, stationary and laminar flow, geometry 2D. As the initial condition for the simulation was assumed the air velocity of 1.2 m/s and pressure 1000 hPa at the inlet to the dryer chamber. Density and viscosity of air were calculated by the program for the assumed temperature.

Results and discussion

Drying kinetics

The results of measurements of moisture content of carrot cubes, dried in a tunnel dryer for different slopes of trays, depending on time, are presented in Figure 2.

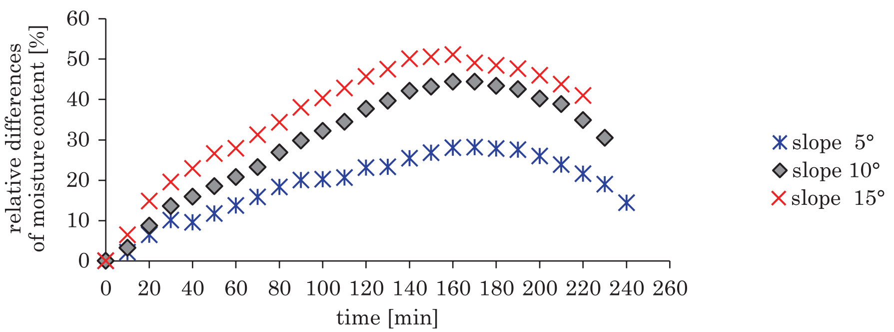

Fig. 2. Graph of changes in moisture content of dried carrot cubes at various slope angles of tray

Analysing the effect of different slopes of trays on moisture content of carrot cubes it was observed that for the largest trays' slope the drying process ran the fastest. It can be supposed that increasing the slope of trays increased the active surface of drying, which caused that the heat and mass exchange runs faster, so the drying process is shorter. For example, without slope of tray, the moisture content of 1 kg/kg was achieved after 160 minutes of drying, for slope 5° after time 140 minutes, for 10° after 130 minutes and for the largest angle 15° after 120 minutes. Analysing the results of moisture content measurements, it was found that increasing the slope of trays by another 5° resulted in shortening the drying time by 10 next minutes. Then the percentage changes in the moisture content were analysed.

Figure 3 presents percentage differences in moisture content in dried samples relative to drying time determined for 0 sample – dried on a horizontal tray (equation 2).

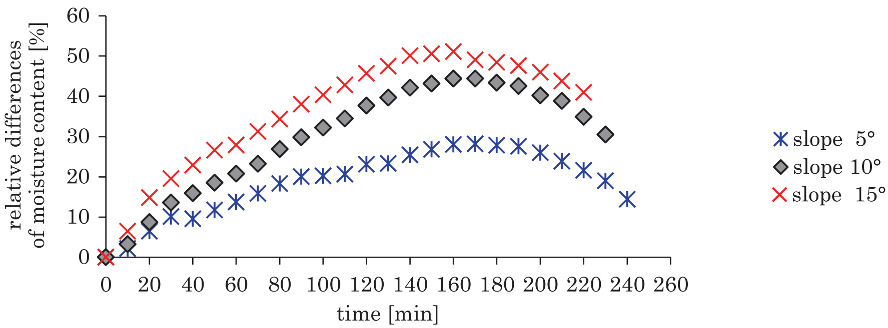

Fig. 3. Differences in the moisture content in the samples relative to the drying time in the 0 sample – dried on a horizontal tray

The highest percentage differences in moisture content in dried samples relative to drying time determined for 0 sample – dried on a horizontal tray were observed after a drying time of 160 min, it was: 28, 44, 51% respectively for slope of trays of 5, 10, 15°.

The effect of the slope of tray on a dried sample of carrot cubes can be concluded on the basis of the coefficients determined from the model (3) and (4), whose values are summarized in Table 1.

It can be noticed that the drying rate of the same carrot cubes mass increases with the increase of tray's slope – the coefficient of the initial drying rate k_0 increases. Its value has increased by about 60% for a slope of 15° compared to without slope of tray.

Similarly, the product of the heat transfer coefficient and the αA surface increases for the higher slope of tray. The largest values of k_0 and αA were obtained for slope of 15°.

Table 1

Parameters of the drying model

Slope of tray [°]	Coefficient of initial drying rate k_0 [min^{-1}]	Mass of dry substance m_{ss} [kg]	Product of heat transfer coefficient and surface [W/K]
0	0.096	0.00243	0.2117
5	0.121	0.00244	0.2657
10	0.134	0.00244	0.2962
15	0.158	0.00244	0.3478

Computer simulation

The next stage of the research was a computer simulation of air flow in a dryer with 12 trays in COMSOL Multiphysics 4.3 software. It can illustrate the way and parameters of air flow at various slope of the trays and at any

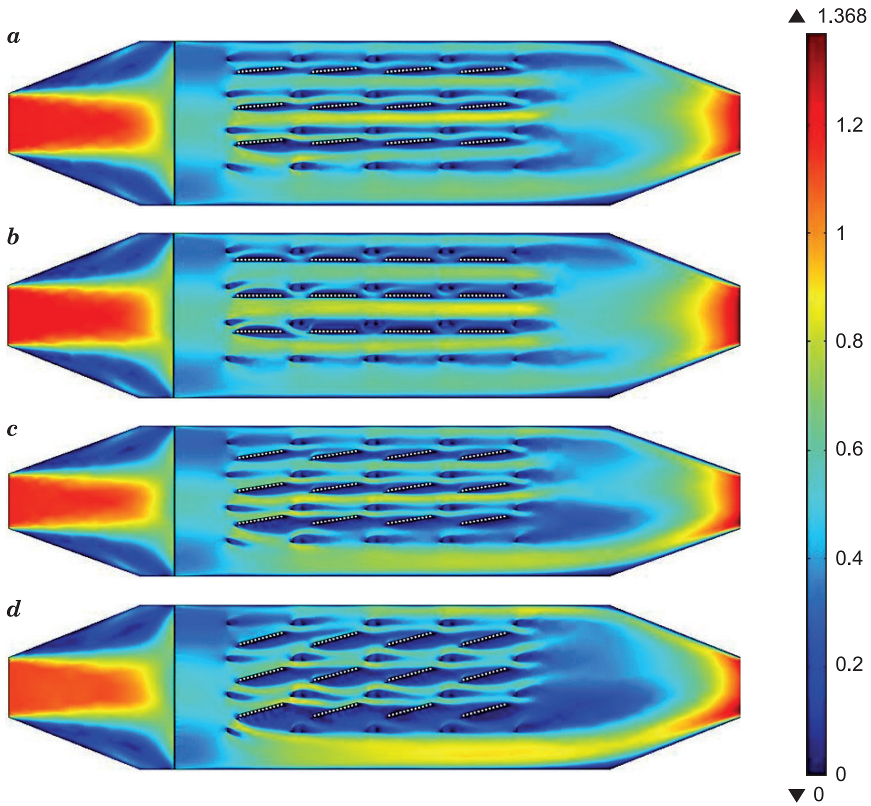

Fig. 4. Simulation of air flow: *a* – trays in horizontal position, *b* – trays' slopes of 5°, *c* – trays' slopes of 10°, *d* – trays' slopes of 15°

places of the drying chamber, in which measurement is practically impossible (KUBIASZCZYK 2017). Figure 4 shows the result of air flow simulation for selected slopes of trays.

Analysing Figure 4 it can be noticed that for trays in horizontal position the air flew only along the material placed on the trays. Values of airflow velocities indicate laminar flow or laminar but disturbed in the central part of the drying chamber. The air stream was lifted up during contact with material particles, which caused that the airflow velocity near above the layer decreased. In this case, an increase of air velocity along the layer allows for shorten the drying time and thus increase the efficiency of the process. Increasing a slope of trays forced the airflow through the layer thus the active drying surface also increased. Changing the slope of trays to the value of 15° caused an expansion of the active drying surface. The airflow velocity at the bottom of the chamber also increased. In general, the increase of the trays' slope caused a decreasing the surface of the high velocity air stream that occurred between the trays.

Table 2 presents the minimum and maximum values of air flow velocities along and through the material placed on trays of different slopes, obtained from simulation.

Analysing the data in Table 2, it can be noticed that the highest air flow velocities along and through the material layer were observed for slope of 15°.

Table 2

Simulated values of air flow velocity along and through the layer

Slope of tray [°]	The velocity of the air flow along the layer [m/s]		The velocity of air flow through the layer [m/s]	
	min.	max.	min.	max.
0	0.03	0.12	–	–
1	0.03	0.40	–	–
2	0.03	0.53	–	–
3	0.06	0.64	0.06	0.18
4	0.07	0.69	0.06	0.20
5	0.07	0.73	0.06	0.21
6	0.07	0.75	0.06	0.21
7	0.07	0.77	0.07	0.25
8	0.07	0.79	0.08	0.29
9	0.07	0.82	0.08	0.33
10	0.07	0.85	0.08	0.35
11	0.07	0.88	0.09	0.40
12	0.08	0.88	0.09	0.43
13	0.09	0.88	0.09	0.46
14	0.11	0.88	0.10	0.50
15	0.12	0.88	0.10	0.55

On the other hand, the smallest values occurred during traditional drying method, without sloping the trays. For minimum airflow velocities, the first change occurred at an angle of 3°, then above 11°. At maximum airflow velocities a sudden increase was observed already at the first change of slope. Subsequent trays' slope changes allowed gradual change of the airflow velocity along the layer.

The air flow through the material layer was forced already at the trays' slope of 3°. It can be noticed that airflow velocity increase is not directly proportional to the change of slope. When changing the trays' slope, a change in the heat exchange surface took place. As the slope increased, the active drying surface also increased. At the slope of 15°, the air flow through the layer did not cover the entire surface of the dried material. This phenomenon shows that it is possible to further optimize the process, but it must be remembered that too large slope may result in sliding material from the trays.

Conclusions

Drying carrot cubes in the same conditions in the drying tunnel, on inclined tray by 5, 10 and 15°, shortened the drying time and allowed to reduce the moisture content by 30–50% at the moisture content around 1 $kg \cdot kg^{-1}$.

The coefficient of the initial drying rate increased with the increase of the slope angle of the tray. This was caused by the increase of the air flow velocity along the layer, the occurrence of the flow through the layer and the increase of the contact surface of the material particles with the drying agent.

The computer simulation illustrated that increasing the slope angle of trays increases the flow velocity of the drying agent along the dried material and forces the flow of air through the layer of raw material laid on the tray. Another phenomenon, which was caused by the flow of the drying agent between the raw material particles, is the increase of contact surface of the stream of heated air of higher velocity with particles of the dried material, which results in a shorter drying time.

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