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THE INFLUENCE OF DRYING CONDITIONS ON THE EFFECTIVE MOISTURE DIFFUSIVITY AND ENERGY OF ACTIVATION DURING THE HOT AIR DRYING OF RED BEETROOT

CECLU LILIANA,
Associate professor, PhD in Technical Sciences,
Cahul State University "Bogdan Petriceicu Hasdeu"
E-mail: ceclu.liliana@gmail.com

Abstract. *The main goals of the present work are the influence of drying characteristics on red beetroot, effective moisture diffusivity determination and the activation energy. The drying characteristics of red beetroot were investigated theoretically and experimentally by convection drying at different air temperatures, ranging 50 – 80ºC and relative humidity 30,6 – 53,8%. Red beetroot samples were dried from moisture content of 88,84±0,35% until 9.88±0.5%. The results have shown that, increasing the drying air temperature causes shorter drying times from 450 min to 240 min. Moisture transfer from red beetroot samples was described by applying the Fick's diffusion model. The effective diffusivity coefficient of moisture transfer varied from 1,471x10*$^{-8}$ *to ,.8145 x10*$^{-8}$ *m*^{2}*/s in first stage and 6,0094 x10*$^{-8}$ *to 1,19x10*$^{-7}$*m*^{2}*/s in second stage of drying process, over the temperature range analised. The temperature dependence of the diffusivity coefficients was described by Arrhenius type relationship and was found to be 22,33 kJ/mol in first stage and 19,85kJ/mol in second stage of drying process.*

The research aimed to establish the kinetics of the drying process of red beetroot, in order to investigate the optimal drying parameters for this vegetable.

Keywords: *red beetroot, convection, drying kinetics, moisture content.*
UDC: 338.45

1. Introduction

The fruits and the vegetables are the fundamental items of a balanced diet. This group of products is considered as the main source of bioactive compounds and minerals, carbohydrates such as simple sugars (glucose, fructose, sucrose), polysaccharides, cellulose (such as hemicellulose), gums and pectic substances, in varying proportions, fibers, micro and macronutrients, but also a high water content, up to 94%.

Due to the seasonal character of food products it requires their preservation. Drying is intended to preservation of food products, which can be used as a primary operation or a intermediate storage process.

Dried fruits are one of the healthiest alternatives to refined sugar and great way to satisfy the sweet appetite. Chips from dried fruits and vegetables can be a quick and tasty snack during a busy day. However, dried fruits should be eaten in moderation because of high sugar content and high intake of kilocalories.

Dried fruits and vegetables besides being consumed as raw products, represents a feedstock for a wide range of food products, medicines and pharmaceuticals.

Drying represents one of the most used methods for preserving food [1]. This process is based on the biological principle of xeroanabiosis, which is characterized by partial removal of humidity from the product, or to a level that results in disruption, reduction or cessation of the microorganisms' vital functions. Low moisture content at which the bacteria grow is between 25-30%, while for yeasts is 10-15% [2].

The using of drying as a preservation method offers the possibility of obtaining a wide range of new products while extending their shelf life. Dried food products have the advantage that occupies a low volume and weight compared to the raw materials. This aspect has a direct impact significantly reducing the storage and transportation of dry products [3].

Drying is one of the most complex processes in food industry and one of the most commonly subjects studied in food engineering field. Optimizing this process can reduce production costs and improve product quality [4].

Beetroot (*Beta vulgaris*) is rich in valuable, active compounds such as carotenoids, glycine betaine, saponins, betacyanines, folates, betanin, polyphenols and flavonoids [5, 6]. However, fresh beetroots are exposed to spoilage due to the high moisture content. One of the preservation methods which is ensuring the microbial safety of biological products is drying. Dried beetroot can be consumed directly in the form of chips as a substitute of traditional snacks, that are rich in trans fatty acids, or after easy preparation as a component of instant food.

Convective drying in hot air is still the most popular method applied to reduce the moisture content of fruits and vegetables. The main objective in drying food products is the removal of water content up to a certain level, at which microbial spoilage and deterioration chemical reactions are greatly minimized [7]. Other important objectives of food dehydration are weight and volume reduction, intended to decrease transportation and storage costs.

This study has the aim to establish the kinetics of the drying process of red beetroot, in order to investigate the optimal drying parameters for this vegetable.

Abbreviations:
MR, moisture ratio, dimensionless;
DR, drying rate, (g water/g dry matter)/min;
M, moisture content, g water/g dry matter;
M_0, initial moisture content, g water/g dry matter;
M_e, equilibrium moisture content, g water/g dry matter;
RH, relative humidity, %; t, drying time, min.

2. The degree of investigation of the problem currently, and purpose of research

Drying is a commonly used technique for improving the product stability of biotherapeutics or nutraceuticals properties of foods. Most plant products contain high water content (typically ≥80%, w/w). Removal of water through drying provides numerous benefits, including ease of handling and storage, reduction in transportation costs, and improved stability [8].

Drying process involves the application of heat to remove moisture and some means of carrying-off water vapor after its separation from the tissue plant products. Therefore, the drying process is a complex unit operation that is carried out with simultaneous heat and mass transfer with the energy supply.

Although all drying techniques share a common objective, conceptually they are different and require modification/adaptation based on the properties of the compound. Control of process parameters of drying is essential to both the quality of the product and the economics of the process. Chemical reaction kinetics, microbial activity and physical structure in foods all depend on moisture content, or the corresponding water activity. Hence, is most immportant to predict the variation moisture content in food, during processing.

The choice of drying method depends on several factors including the physical properties of the product, application of the product, type of energy source available, container closure system, and scalability of the equipment. Drying process may be performed by convection (direct dryers), by conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. In addition, forced air or vacuum may be applied to enhance the rate of dehydration. Over 85 percent of industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium. Over 99 percent of the applications involve removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundaries of the drying object so that the heat diffuses into the solid primarily by conduction. The liquid must travel to the boundary of the material before it is transported away by the carrier gas (or by application of vacuum for non-convective dryers) [9].

Several models are found in the literature, representing mass and energy transfer which take place during food drying. Usually, approximate solutions are obtained with these models by fixing geometric characteristics (slab, sphere or cylinder) and considering constant transport properties.

Currently most of the dried fruits and vegetables are produced by the technique of convective drying, which is the simplest and most economical among the various methods. Air is generally used as the drying medium because it is plentiful, convenient, and overheating of food can be controlled.

3. Methods and materials applied

3.1. Raw material

Red beetroot *(Beta vulgaris L. var. Cylindra)* was purchased from a local market.The initial water content of the fresh material varied between 0,84-0,85 kg/kg. The red beetroots were washed, peeled and cut into parallelepipedic slices 20 mm in length, 20 mm in width, and 5 mm in thickness.

3.2. Drying process

The drying studies were conducted in the laboratory of unit operations at the Food Science and Engineering Faculty of Galati. The beetroot drying process was performed in a convection dryer at 50, 60, 70 and 80°C temperature and 30.6 – 53.8% RH values. All drying experiments were triplicated, and average values regarded.

4. Results obtained and discussions

The drying curves of red beet obtained from experiments, $M=f(t)$, where M is the moisture content of red beets in dry basis and t is the elapsed drying time in min, were converted into dimensionless moisture content MR (moisture ratio) using the following equation (1):

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

where M_0 is the initial moisture content (g water/g dry matter), M_t is the moisture content at any time (g water/g dry matter) and M_e is the equilibrium moisture content (g water/g dry matter). The value of M_e was determined as the moisture content at the end of drying when the samples stopped to lose weight [10].

Moisture ratio (MR) represents the amount of moisture remaining in the red beetroot samples reported to the initial moisture content.

The effect of drying temperature on the moisture ratio is shown in Picture1. The curves reveal that the decrease of moisture content with time is in a non-linear fashion, indicating that the moisture movement is controlled by diffusion and that diffusion is dependent on the moisture content of the samples.

From graph shown in Picture 1, can be observed the influence of temperature during drying on the moisture content of red beetroot samples. Increasing the drying temperature reduces the drying time. The time needed to reach equilibrium moisture content decreased with increase in temperature.

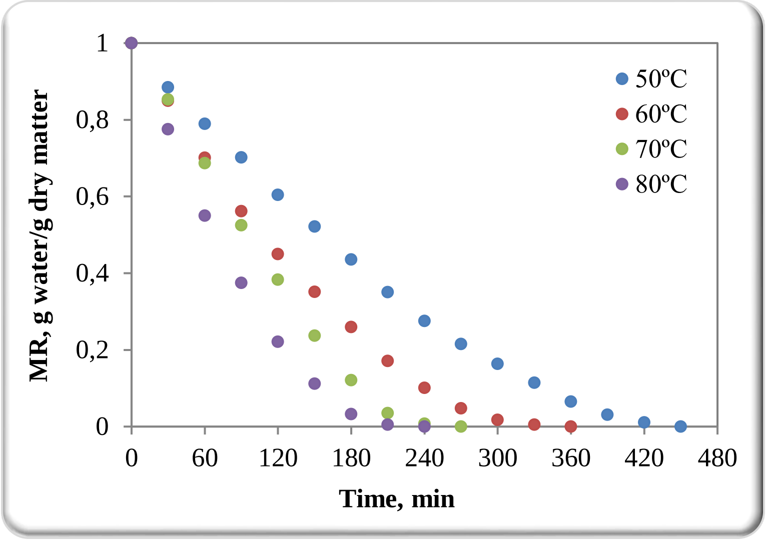
It is obvious from Pictures 1 and 2 that increasing the drying temperature caused an important increase in the drying rate, thus the drying time is decreased.

Drying rate were calculated as quantity of moisture removed per unit drying time per unit dry solids.

The drying rate (DR) of red beetroot samples can be determined using the following equation (2):

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (2)$$

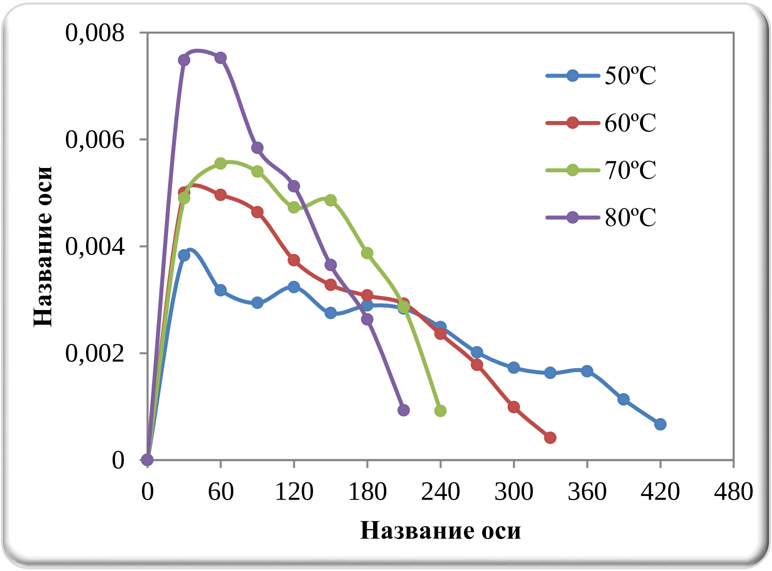
where M_{t+dt} is moisture content at time $t + dt$ (g water/g dry mater), t is the time (min) [10].



Picture 1. Effect of drying air temperature and drying time on the moisture ratio of red beetroot samples.

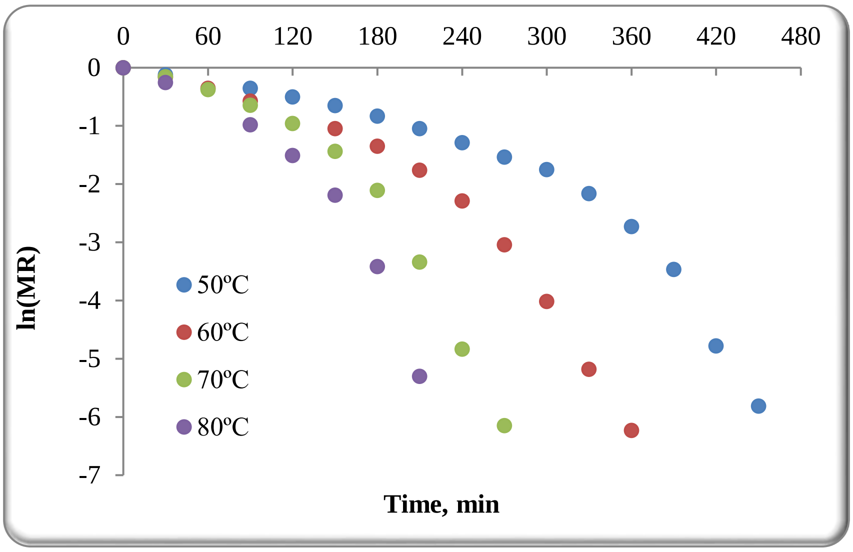
In Picture 2 is shown drying rate curves of red beetroot samples. It can be observed that the drying rate intensify with increasing temperature and decreases with increase in drying time of irrespective of drying temeperature.

Theoretical studies of drying indicate that the drying process can be divided into a constant drying rate period and one or two falling drying rate periods. This constant drying rate period is missing from most products with capillary-porous structure such as fruits and vegetables.



Picture 2. Drying rate of red beetroot samples changes with drying time.

In the case of red beet samples, the constant drying rate is too short (insignificant) or missing totally. This stage being followed by a falling drying rate period. As the samples dries, water becomes less available on the surface and diffuses from the centre. A moisture gradient between the centre and the surface is installed and drying rate will progressively fall until equilibrium with the drying air is reached. During this period the mechanism of internal moisture flow dominates the rate of drying.



Picture 3. Logarithmic drying curves at various temperatures for red beetroot samples.

The effective moisture diffusivity is an important transport property in modeling of food drying process, being a function of temperature and material moisture content.

In drying process, liquid diffusion is generally accepted to be the main mechanism during the transport of moisture to the surface in order to be evaporated. This important phenomenon was described analytically by Fick in 1855 [11].

When liquid diffusion controls the internal movement of moisture and it occurs only in one dimension Fick's equation can be written as

$$\frac{\partial C}{\partial t} = -D_{eff}\frac{\partial^2 C}{\partial x^2} \qquad (3)$$

where

C is the concntration of the diffusing substance (g/m^3) at distance *x* (m) along the diffusion path, and

D_{eff} is the diffusion coefficient (m^2/s).

Crank using Fick's second law proposed Eq. (4) for the effective moisture diffusivity for an infinite slab [12].

$$\frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^{2}} exp\left(\frac{(2n+1)^2\pi^2 D_{eff}t}{L^2}\right) \qquad (4)$$

where

D_{eff} is the effective diffusivity (m^2/s),

and

L is the thickness of samples (m), n is a positive integer.

For longer drying periods is necessary to make some simplifying assumptions. It is assumed that moisture transfer is unidirectional, the initial moisture is uniformly distributed and the diffusion coefficient of moisture is constant and negligible shrinkage

$$MR = \frac{M-M_e}{M_0-M_e} = \frac{8}{\pi^2}\exp\left(-\pi^2 D_{eff}\frac{t}{L^2}\right) \qquad (5)$$

The diffusion coefficients are typically determined by plotting experimental drying data in terms of ln(MR) versus drying time (t), [13].according to Eq. (6):

$$slope \quad k = \frac{\pi^2 D_u \tau}{L^2} \qquad (6)$$

The non-linear shape of drying curves (Picture 3.) indicates variable moisture diffusivity. Each curve consist of two falling rate periods (linear shape) for drying.

The linear regression analysis was employed to calculate the diffusion coefficients from the slopes of the straight lines. The diffusion coefficients were calculated for the first falling rate at each temperature. The diffusion coefficients for second falling rate periods were calculated without shrinkage for each temperature.

In Table 1 are shown the diffusion coefficients for each temperature in both falling rate periods, and regression coefficient

Table 1. Effective moisture diffusivity and correlation coefficient at different temperatures for first and second falling rate periods

t (°C)	R^2	D_{eff1} x10^{-8} (m^2/s)	R^2	D_{eff2} x10^{-8} (m^2/s)
50	0,9771	1,4706	0,9891	6,0094
60	0,9834	2,0792	0,9841	7,7336
70	0,9849	2,3835	0,9849	10,2692
80	0,9934	2,8145	0,9867	11,9935

It can be seen that the values of D_{eff1} and D_{eff2} increased greatly with increasing temperature. Drying at 80°C gave the highest D_{eff} values in both stages.

The dependence of the diffusivity coefficient on temperature is often given by an Arrhenius type equation [14]

$$D_{eff} = D_0 exp\left(-\frac{E_a}{RT}\right) \qquad (7)$$

where

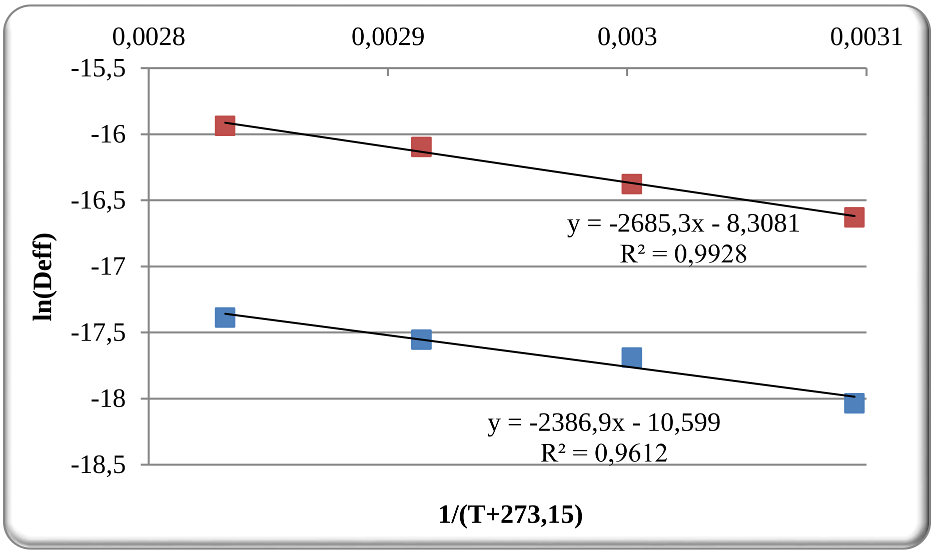
E_a is the activation energy of the moisture diffusion in kJ/mol;

D_0 is the pre-exponential factor of Arrhenius equation m^2/s; D_{eff} is the moisture diffusivity m^2/s;

R represents the universal gas constant kJ/mol·K

and

T_a is the absolute drying air temperature in K.



Picture 4. The relationship between $\ln(D_{eff})$ and 1/(T+273,15)

The activation energy can be determined from the slope of the Arrhenius plot, $\ln(D_{eff})$ versus $1/T_a$. [15]

The activation energy calculated from the slope of the straight line in Picture 4. It was found to be 22,33 kJ/mol in first stage and 19,85 kJ/mol in second stage. The activation energy for water diffusion in first stage is higher than activation energy in second stage.

5. Conclusions

Drying behavior of red beetroot slices was investigated in a hot air dryer at 50, 60, 70 and 80˚C. The obtained results showed that total time of drying was reduced substantially with the hot air temperature increasing from 450 min at 50˚C to 240 min at 80˚C. The highest effective diffusion was found to be from 6,0094 $x10^{-8}$ up to $1,19x10^{-7} m^2/s$ in second stage. The lowest effective diffusion was from $1,471x10^{-8}$ to 2,8145 $x10^{-8}$ m^2/s in first stage of drying process. The temperature dependence of the diffusivity coefficients was described by Arrhenius type relationship and was found to be 22,33 kJ/mol in first stage and 19,85 kJ/mol in second stage. It can be seen that temperature significantly affected the drying process.

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