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Analysis of the geometrical changes of celery in a test piece during convection drying

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Abstract. The study has been devoted to change analysis of linear dimensions, surfaces and drying shrinkage rate, in the course of the convector drying of celery. It has been found that drying resulted in most significant changes of cube edges in their central parts. The shape of lateral surfaces of celery cubes changed from the originally square to irregular, resembling sandglass. In spite of this, the analysed characteristic linear dimensions altered in a nearly identical way. In the course of drying and the progressive reduction of water content, the characteristic linear dimensions and the surface of celery samples declined, while the drying shrinkage rate increased. The change rate of studied values depended on the appearance of the first and the second drying periods. No significant dependency was found between the temperature of drying medium (in the analysed measurement period) and the dynamics of surface change, linear dimensions alteration and shrinkage rate. Next, the studied values were used in the empirical verification of adopted theoretical models of celery drying kinetics, in the first and the second period of drying. Empirical verification confirmed the correctness of adopted mathematical models. The relative local error was no higher than 15%, while the global error did not exceed 2.5 %.

Keywords: shrinkage, dimensions, surface, drying, celery

INTRODUCTION

Vegetables belong to the group of materials with high initial water content. Because of this and as the result of transportation of water out of the material, significant changes take place in their linear dimensions during the drying process. It is obviously accompanied by shrinkage of outside area and volume. The stated parameters are very important in the mathematical description of heat and mass transportation in drying. That is why it is essential to make the analysis of geometric changes of the specimen through empirical tests and on this basis to verify existing models or formulate new mathematical models of the process.

Discussing the mathematical description of drying kinetics, particularly the model of the initial period of drying (predominating surface mass exchange), it should be concluded that the size of the exchange area and its change over time is a crucial factor determining the course of the entire process. In the existing models of mass transport, describing this period of drying, both the body and linear shrinkage processes are taken into consideration (Balaban and Pigott, 1988; Wang and Brennang, 1995; Pabis, 1999; Yang *et al*., 2001; May and Perre, 2002; Pabis and Jaros, 2002). Moreover in the case of the transport of mass from inside the material by diffusion (the second drying period) the characteristic dimension of the drying specimen (Pabis, 1982) is one of parameters influencing the process. It additionally enhances the importance of geometric changes of material during drying.

Because of this, the aim of the present study was the analysis of the changes of characteristic geometric dimensions such as the outside surface area and the volume of the celery specimen during the process of convection drying. The Feret diameter has been taken as the element characterising the linear dimensions of specimen. The results obtained have been used in the empirical verification of the mathematical models of the first and second periods of drying.

METHOD

Research was undertaken on the ‘President’ variety of celery. The celery, cut in the form of cubes 10x10x10 mm, was force-dried in a convector drier, at temperatures of 50, 60, and 75°C. Every ten minutes, the specimens were removed from the drier in order to measure their volume, outside area and linear dimensions, additionally, on the basis of registered mass reduction; water content was calculated according to the generally known formula (Pabis 1982).

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The volume of the samples was determined in a measurement cylinder filled with toluene following the methodology proposed by other authors (Lozano *et al.*, 1983). The data obtained was used to calculate the drying shrinkage quantity.

The characteristic linear dimensions and outside surface of celery specimens were described by means of the computer image analysis technique. Diagram of it is shown at Fig. 1.

An image of celery specimens, shot by a Panasonic camera VC-X10 (Hi 8) was transferred to the computer using the Shaw Time Plus card (Fig. 1A). After the initial preparation, consisting of cutting out a fragment of the image containing an area of the specimen analysed, the picture was processed using Multi Scan software. To remove unwanted electronic noise, special morphology transformation was applied first, as a result of which all existing cavities and dilatations were filled up. The entire process was completed by binarisation. Measurements of the chosen dimensions were effected on the image prepared in the above way. The size of the outside area was described by calculating the percentage participation of grey area, in total surface and then by multiplying the result by the value (taking magnification into account). In the case of the characteristic linear dimension of a specimen, in the absence of any advice concerning selection of the element, measurements of Feret diameters were taken. Based on the data obtained, one was chosen for which the least error was received during the fitting of the model to the real conditions. In accordance with the purpose of study in the final stage of the work, the results of the tests received and the measurements of the changes in the water content in the testing material were used to verify the models of the first and second period of drying.

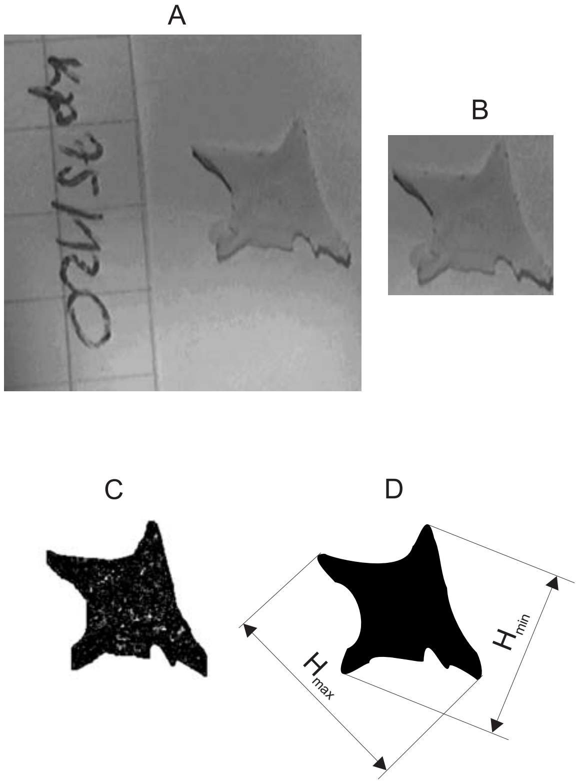

Fig. 1. The computer image analysis. A – initial image, B – the cut out fragment, C – the image after morphological processing, D – image after binarisation with indicated measured linear dimensions, adopted as characteristic.

The following models were chosen to describe the particular drying periods:

– mathematical model of the first drying period:

$$u = u_o\left[\frac{1}{1-b}\left(1-\frac{1-b}{Nu_o}k_o\tau\right)^N - \frac{b}{1-b}\right] \quad \text{for } u \in \langle u_o, u_{kr}\rangle, \tag{1}$$

where: b – coefficient of maximum shrinkage (min^{-1}), k_o – constant drying rate (kg kg^{-1} min^{-1}), u – moisture content (kg kg^{-1}), u_{kr} – critical moisture content (kg kg^{-1}), u_o – initial moisture content (kg kg^{-1}), τ – time (min), N – parameter:

$$N = \frac{3n}{3n-2} \tag{2}$$

n – parameter in relationship between the area of the shrinking body $A(u)$ and its water content; this can be calculated from the equation below:

$$A(u) = A_o\left[(1-b)\frac{u}{u_o}+b\right]^{\frac{2}{3n}}, \tag{3}$$

where: $A(u)$ – the area of the drying body at a given moment of time (m^2), A_o – the initial area of the drying body (m^2).

Constant n and N should be determined experimentally on the basis of the measurement of changes of the outside area and the drying shrinkage calculated from the equation:

$$s = 1 - b(\tau); \tag{4}$$

– the second drying period, obtained through solution of the equation reflecting Fick's 'Second Law of the Cube', considering initial and boundary conditions (Jaros, 1999):

$$\text{if } \tau = \tau_{kr} \text{ then } u(\tau) = u_{kr} \text{ and if } \tau > \tau_{kr} \text{ then } u(\tau) = u_r,$$

$$\frac{u(\tau)-u_r}{u_o-u_r} = \frac{512}{\pi^6}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{\pi^2}{4}(2n+1)^2\frac{3a_m\tau}{d^2}\right)$$

$$\text{for } u \in (u_{kr}, u_k), \tag{5}$$

where: a_m – the coefficient of mass diffusion (m^2 min^{-1}), d – the characteristic dimension (m), u_{kr} – critical moisture content (kg kg^{-1}), u_r – the equilibrium moisture content (kg kg^{-1}), τ – time (min), τ_{kr} – critical time (min).

RESULTS

The typical image of changes in celery specimens during drying at 50°C has been shown in Fig. 2. The biggest edge deformation of the cubes occurred in their central part. The shape of the side surface of the cubes changed from square to irregular, similar to sandglass. In spite of this, Ferret diameters changed in a nearly identical way (Figs 3 and 4). This fact may be the evidence of the relatively uniform exchange of mass on all side surfaces. The developed deformations of the edges are probably the result of stresses which appeared in the material under the influence of temperature gradient and pressure inside leeks. Simultaneously with the change of linear dimensions, the size of the lateral area of the celery cube also changed. The course of these changes is presented in Fig. 5. In the first phase of drying (to the water content level approx. 7 kg kg^{-1} a rapid decline of the area size occurred. In a further stage of the process, the value discussed tended to stabilise and it was only when the water content reached a level of approx. 2 kg kg^{-1} that it started to fall again. The phenomenon corroborates the existence of the two drying periods mentioned earlier.

The division of celery drying kinetics indicated above can be observed also in relation to drying shrinkage but far less clearly. The curves presented the trend of change of the shrinkage, at various temperature levels of the drying medium and have an inflexion point, which probably correspond with the transition from one drying period to another

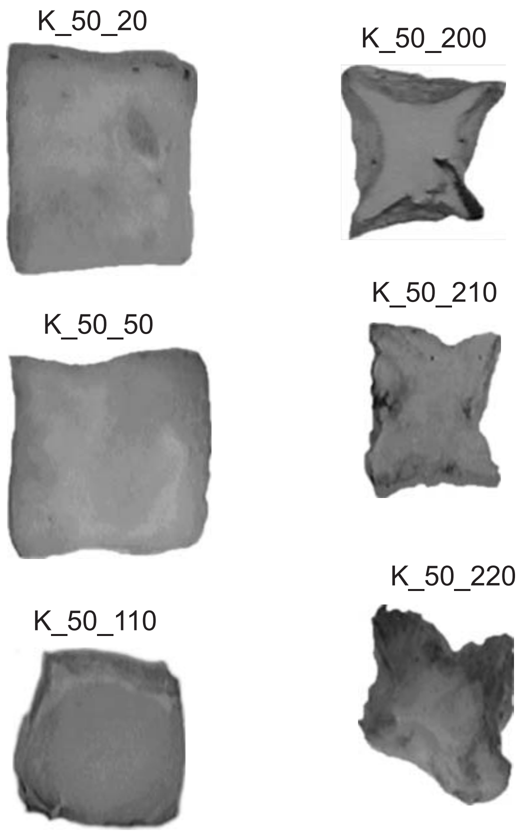

Fig. 2. The shape changes of celery samples in the course of drying at 50°C – trend line.

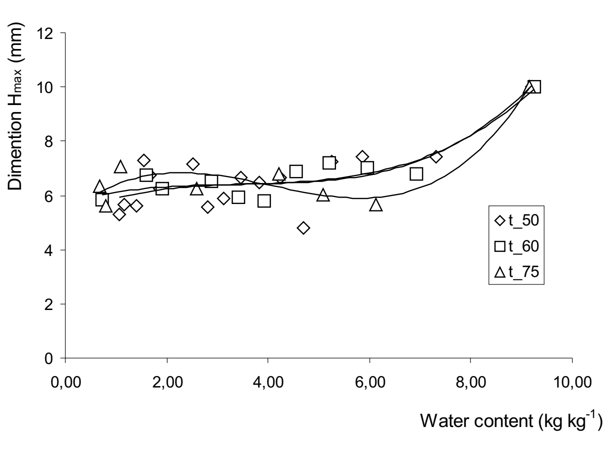

Fig. 3. Changes in $H_{\max}$ depending on water content.

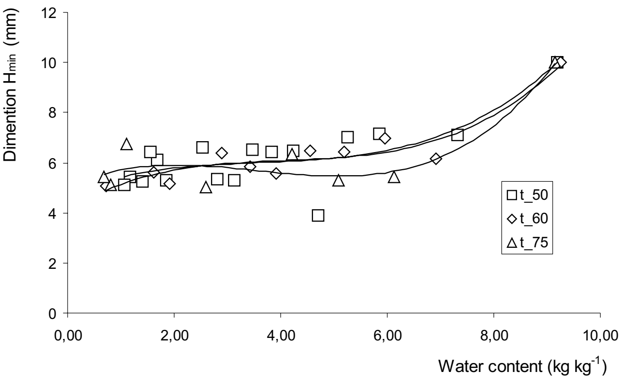

Fig. 4. Changes in H_{min} depending on water content.

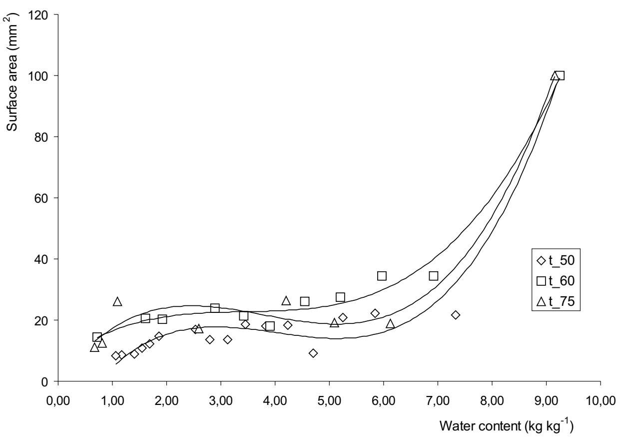

Fig. 5. Changes in the size of celery cube lateral surface, in the course of drying.

(Fig. 6). It seems that the chemical composition and morphological structure of plant tissue are the main factors determining the course of changes mentioned and values discussed. This is because during drying, not only water diffusion occurs, but also diffusion of dissolved nutrients (e.g., carbohydrates), which leads to the stiffening of tissue after a certain heating time. On the basis of the results obtained, the adopted mathematical models were verified. The following values had been taken to verify the calculations: $u_o = 9.19$ kg kg^{-1}, $u_r = 0.09$ kg kg^{-1}, $u_{kr} = 2$ kg kg^{-1}, $k_o = 0.11$ min^{-1}, τ_{kr} =100 min, $a_m = 1.25 \cdot 10^{-8}$ m^2 min^{-1}. A smaller Feret diameter described the characteristic dimension.

The exemplery changes in the water content calculated on the basis of models and obtained by measurement are shown in the Fig. 7. The accuracy of the models in the projection of celery drying kinetics was described by means of errors calculated from following equations:

The local relative:

$$\delta_1 f(x_i) = \left| \frac{f_{emp}(x_i) - f_{\mathrm{mod}}(x_i)}{f_{emp}(x_i)} \right| 100\% . \qquad (6)$$

The global relative:

$$\delta_g f(x_i) = \sqrt{\frac{\sum\limits_{i=1}^{n} \left| f_{emp}(x_i) - f_{\mathrm{mod}}(x_i) \right|}{\sum\limits_{i=1}^{n} f^2{}_{emp}(x_i)}}\ 100\% , \qquad (7)$$

where: $f_{emp}(x_i)$ – measured value, $f_{mod}(x_i)$ – model calculated value, i – number of measurement.

The local error changed within the range from 0.6 to 15.5%. But the global relative value between the calculated

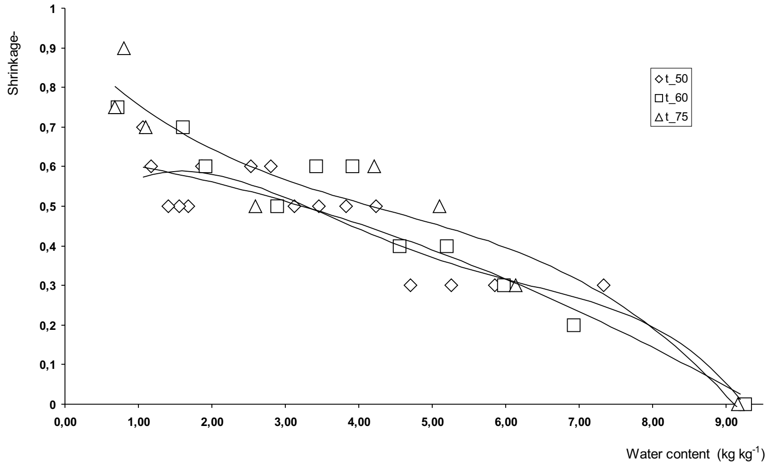

Fig. 6. Changes in drying shrinkage rate of celery samples.

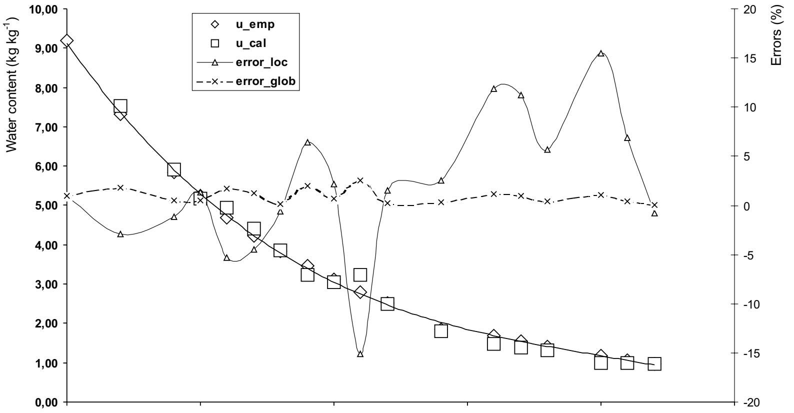

Fig. 7. Changes in water content in the course of drying. The theoretical curve and empirical values.

and measured values did not exceed 6%. The result confirms the correctness of the models used for the description of the first and second celery drying periods and the usefulness of the applied measuring methods.

CONCLUSIONS

1. The characteristic linear dimensions and the area of test pieces of the drying process and the simultaneous reduction of water content decrease with time, while drying shrinkage increases.

2. The change rate of the values studied depends on the drying period.

3. In the analysed drying period, no significant influence of the temperature of the drying medium was found on the dynamics of changes of area, linear dimensions, and the value of shrinkage.

4. Empirical verification confirmed the correctness of the mathematical models adopted. The local relative error did not exceed 15%, and the global error 6%.

5. The analysis was completed and thanks to it the characteristic linear dimension was determined, which occurs in the model of the second drying period. This is a smaller Feret diameter.

6. The research work undertaken makes it possible to identify more accurately and with the wider parameters essential for the computer simulation of the drying process, based on accepted models, to optimise it.

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