POLISH JOURNAL OF FOOD AND NUTRITION SCIENCES

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Pol. J. Food Nutr. Sci.
2007, Vol. 57, No. 2(A), pp. 211-214

THEORETICAL MODEL FOR FLUID BED DRYING OF CUT CELERY

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Key words: fluidisation, theoretical model, cut of celery, drying

Researches on process of drying of cut celery by means of fluidising were a result of seeking for new methods of drying, which allowed achieving dry vegetables of the best quality. At the same time use was made of a theoretical model of drying of cut vegetables in the first period and simplified model in the second period. Verifying those models and setting their area of use researches showed that interior exchange of mass and heat is the most important in the exchange of water in this process. Their dynamics depend on initial drying rate in the first period. New model of fluidised-bed drying was proposed and it was positively verified for cut of celery.

NOTATIONS

b – coefficient of drying shrinkage (−), K – coefficient of drying rate in the second period (L/min); k_0 – coefficient of drying rate for initial period (kg/(kg min)), N – coefficient indicated the kind of shrinkage (-), u – mean water content in the drying particles (kg/kg), u_0 – initial, mean water content (kg/kg), u_{cr} – critical water content (kg/kg), u_e – water content equilibrium (kg/kg), τ – drying time (min).

INTRODUCTION

The tests of sliced celery drying using fluidization method resulted from research on new methods of drying which can assure obtaining high quality dry mass. During fluidizing drying the material in the form of solid particles is dried in a convective manner, by means of swirling in the streamline. Such state assures large development of the surface of the dried product, which in turn facilitates the exchange of warmth and mass between this product and the drying factor. Drying in the stream of hot air provides much more advantageous conditions of warmth and mass exchange than in a stable bed [Lewicki *et al*., 1990]. Fluidizing drying method is an important method among modern drying methods, since its competitiveness in relation to the others consists in the best relation of the obtained intensity of drying to the costs of gas pumping [Strumiłło, 1983]. It is used mainly for drying materials of fine particles, such as paper, leather, pastes, suspensions and solutions sprayed on fluidal inert bed [Strumiłło, 1983]. However, few papers have been published considering drying materials of big particles such as sliced vegetables, in particular sliced celery and there are no models for this process.

Very large value of the surface velocity of the drying airflow is a characteristic parameter of fluidizing drying. It is from tens to a few hundred times larger from the flow velocity through stable bed and for example, for particles of 10 mm it is from 1 to 6 m/sec [Grace, 1982]. Such an intensive airflow causes a rapid and considerable decrease in water steam concentration in the bed and as an effect we can consider that only humid and drying air have an influence upon warmth and mass exchange in the bed. Temperature measurements for the fluidizing air leaving the bed show a decrease of only few degrees, which means that the particles are dried almost at the same temperature of the drying factor. Therefore, it can be logically considered that the process of fluidizing drying of particles takes place in the same manner as convective drying of solid particles in a thin layer, and in the consequence, mathematical models of fluidizing drying of single solid bodies, swirling freely in the stream of the drying gas, such as kinetics equations of thin layer drying can be applied.

PROCESS MODELLING

It was empirically concluded that sliced celery, constituting material of high initial water content, when dried by fluidization dries several times quicker then in a solid bed, at the same temperature of the drying air. It can be concluded that essential and even dominating conditions of water particle transport from the surface of dried mass through the border air layer at the beginning of this process take place. At the end of drying only internal diffusion of water particles (steam) to the solid surface decides about the process. In reality, however, both processes coexist and do not exclude each other and it is difficult to show them empirically. If we assume that the indicated processes dominate as

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alternative processes, it is easy to build a model of kinetic equations of so called first or second period of drying, with preservation of model continuity for glued function.

Pabis [1999a, b] made an assumption that at the beginning of drying the kinetic model of convective drying of solid masses during the first step of drying, including drying contraction, can be used as a model for water content changes of very wet particles such as vegetable cutting in a portion fluidizing drying machine.

$$u_I(\tau) = u_0\left[\frac{1}{1-b}\left(1-\frac{1-b}{Nu_0}k_0\tau\right)^N - \frac{b}{1-b}\right] \tag{1}$$

Equation coefficients b, k_0 and N can be empirically determined on the basis of suitable theoretical dependences.

Equation (1) was checked on the base of measurements of fluidizing drying of celery cutting [Pabis & Jaros, 2002] for which N was 2.93. Consistency of calculations was obtained for measurements within the range of water content not smaller than 3 kg/kg, with the relative mistake not exceeding 10%. Violent growth of relative mistake for model (1) shows that different rules begin to decide about the process beyond the indicated range – the internal diffusion of water begins to predominate in the solid state.

Beginning from the critical time τ_{cr}, for which $u(\tau>\tau_{cr})<u_{cr}$, the process can be modeled using differential equation of diffusion, at the given initial-border conditions or, in well-founded cases, from its simplified solution. The equation of the average water content in the dried product is most often used, which means:

$$u_{II}(\tau) = u_e + (u_{cr} - u_e)exp(-K\tau) \tag{2}$$

Using model (2) helps to create a model for further drying, according to the theory. However, it demands introduction of a corrected drying time $(\tau - \tau_{cr})$. Equation (2) is then as follows:

$$u_{II}(\tau - \tau_{cr}) = u_e + (u_{cr} - u_e)\exp\left[K(\tau - \tau_{cr})\right] \tag{3}$$

The course of drying demands that its model is shown by a continuous and differential function. This condition for a glued model means that in point, $(\tau = \tau_{cr})$, transition from model structure (1) to model structure (2) there must be an equal amount of water content and drying speed, defined from these models, which means:

$$k_0\left(1-\frac{1-b}{Nu_0}k_0\tau_{cr}\right)^{N-1} = K(u_{cr} - u_e) \tag{4}$$

Equation (4) allows calculating coefficient value K, after transition using (1), from the following:

$$K = \frac{k_0}{u_{cr} - u_e}\left((1-b)\frac{u_{cr}}{u_0} + b\right)^{\frac{N-1}{N}} \tag{5}$$

Analysis of measurements of water content and drying product temperature measurements allows showing a range, within which a critical water content u_{cr} can be found. It can be said that u_{cr} value is found in a diffused set of water content, relating to transitional time period.

Mathematical model of fluidizing vegetable cutting drying is composed from an equation system (1) and (3). This system allows for computer simulation of vegetable cutting drying before the experiment, if only numeric values of thermo-physical and geometrical coefficients in this model are known and if the critical water content is known.

MODEL VERIFICATION RESULTS

Verification of the proposed model was carried out based on the experiments done in the laboratory fluidizing dryer by Zaremba & Jaros [2002], Zaremba [2004]. Measurements of fluidizing drying were carried out for celery tubes cutting in a form of cubicles of 10 mm and of equal water content. Changes of cutting mass, depending on the time and temperature of the drying air, within the range of initial water content to a close to equilibrium were registered. Measurements were carried out for beds of initial heights 4, 8, 12, 16 and 20 cm, dried with air of 40, 50, 60, 70, 80°C temperatures at the flow velocity of 4 ÷ 4.5 m/s. The mass of the dried substance was calculated for each sample using the drying machine method. The value of coefficient b was determined empirically for drying contraction (b = 0.08) as well as the empirical relation of initial drying velocity k_0 for initial water content (in the dried product) was determined $u_0 \cong 8$ kg/kg, $k_0(t_p, h) = (0.0085$-

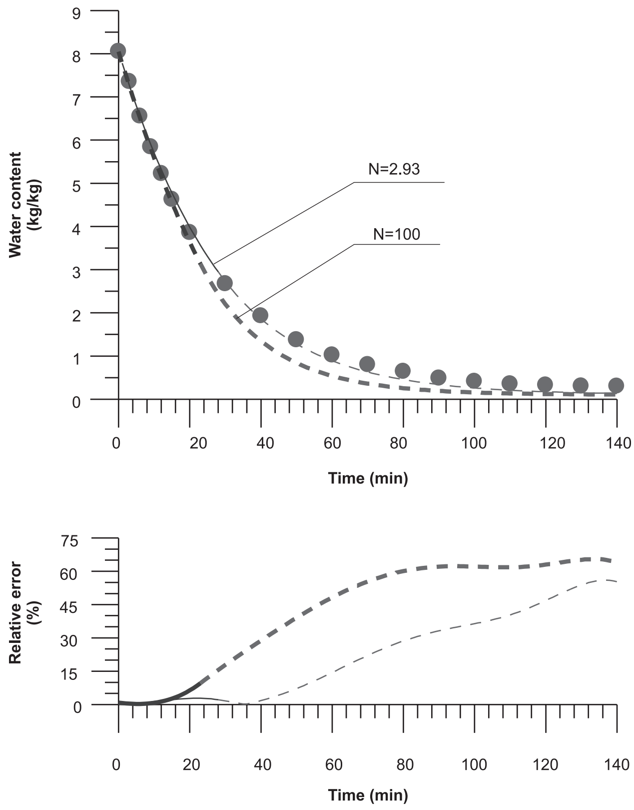

FIGURE 1. Comparison of measurements and calculations for model (1) and (3) of water content in celery cubicles, dried at 60°C, if $u_{cr} \cong 3$ kg/kg, at different values of N. Legend: • measurements, —— charts for model (1), – – charts for model (3).

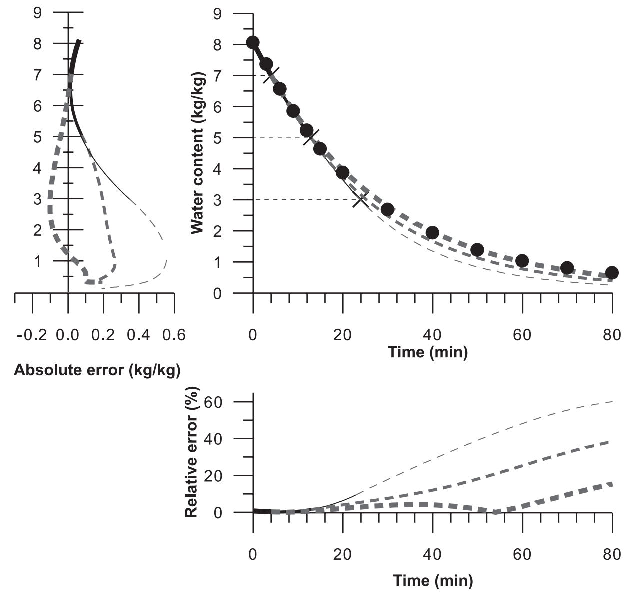

FIGURE 2. Comparison of measurements and calculations for model (1) and (3) of water content in celery cubicles, 60°C, if N=3 and $u_{cr} \cong 3$ – thin lines, $u_{cr} \cong 5$ – moderate lines, $u_{cr} \cong 7$ – thick lines.

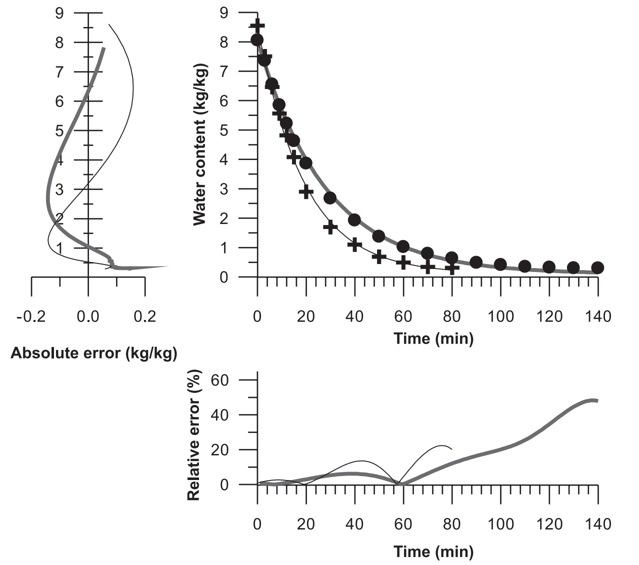

FIGURE 3. Measurements and calculations for model (6) and model's mistakes of fluidizing drying of celery cutting bed of the resting height of 12 cm, with the air of 60°C and 80°C.

0.0016 ln h)t + (0.0395-0.0098ln h), within the range of $t_p \in (40 \div 80°C)$ and $h \in (4 \div 20$ cm).

The set of equations (1) and (3), due to using formula (5) in the second period as a coefficient K for drying velocity constitutes a model for the whole process, in a form of glued, but continuous and differential within the whole range, function.

The closeness of calculations in this model depends very much on *a priori* assessed critical value of water content. If we assume that the critical water content is approximately 3 kg/kg, then the exactness of the drying process modeling is not satisfactory, which is shown by the values of relative and absolute mistakes for both models based on approximation formula (Figure 1). The higher is coefficient N, the higher is closeness of the model. Increasing its value above 100 decreases the mistakes in a smaller degree and at the same time, when N > 3 it is difficult to interpret it physically. If N>3, then cubical particles must be characterised with a smaller surface change than the isotropic particles (retaining smooth surface). Therefore, the range of water content, in which the model for first drying period is assumed as verified, is limited to N equal to at highest 3.

Figure 2 shows results of model verification, with the assumption that the critical water content u_{cr} is approximately 3, 5 and 7 kg/kg and N=3.

Analysis of performed calculations, as shown in Figure 2, allows to conclude that model (1) is verified for water content changes to a lesser degree than is was assumed earlier. It means that internal diffusion decides about mass exchange much faster than in natural or forced convection (at smaller values of air flow than during fluidization). Increasing the values of critical water content it is possible to obtain smaller values of mistakes for both models. The end of this is the initial water content. If it is assumed that $u_{cr} \cong u_0$ and $\tau_{cr} \cong 0$, then the equation (3) is as follows:

$$u(\tau) = u_r + (u_0 - u_r)\exp\left(-\frac{k_0}{u_0 - u_r} \cdot \tau\right) \qquad (6)$$

Coefficient K for drying velocity in the second period can be defined based on coefficient k_0 for initial drying velocity in the first period, and coefficient N is then insignificant.

Figure 3 shows a comparison of measurements and calculations for model (6) of drying at 60°C and 80°C of a bed with a resting height of 12 cm.

Results similar to the ones shown in Figure 3 were obtained for the tested temperature range and resting heights of celery cutting bed. Absolute mistakes do not exceed ± 0.3 of the value within the whole range of water content changes u, while the relative mistake is smaller than 10% for water content u higher than 1 kg/kg. The analysis carried out above allows concluding that the model of the second period of drying, in a form of equation (6), was positively verified for fluidizing drying of celery cutting.

CONCLUSIONS

1. Empirical and logical verification of the second period of drying shows that during fluidizing drying of celery cutting, internal water diffusion has an essential influence upon water content.

2. External drying resistance, which can have a significant influence upon mass exchange in celery cutting only at the initial stage of this fuidized process, has a significant influence on drying velocity coefficient in the model of the second period. Coefficient K of the drying velocity in the second period is directly proportional to coefficient k_0 for initial drying velocity and inversely proportional to the difference between the initial and equilibrium water content.

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TEORETYCZNY MODEL FLUIDYZACYJNEGO SUSZENIA KRAJANKI WARZYW

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Do modelowania procesu suszenia krajanki selera metodą fluidyzacji wykorzystano teoretyczny model suszenia krajanki warzyw w pierwszym okresie oraz model uproszczony drugiego okresu. Prowadząc empiryczną weryfikację tych modeli, wykazano, że o wymianie wody w tym procesie istotnie decydują warunki wewnętrznej wymiany ciepła i masy, ale ich dynamika zależy od początkowej szybkości suszenia. Nowy model fluidyzacyjnego suszenia krajanki selera zweryfikowano empirycznie.