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Thermal and physical properties and heat-mass transfer processes of drying pumpkin seeds

Abstract. *We have investigated pumpkin seed heat capacity influenced by the two factors of the heat agent temperature and the moisture content of the material. The difference between the heat of evaporation when drying pumpkin seeds in a differentiated microcalorimeter DMKI 01 from the tabular value is 6%. Increasing the temperature of the heat agent from 40 to 60°C reduces the drying process by 8 times, but the most appropriate is the drying mode at 40°C, under which the germination of pumpkin seeds is 98%. The study of heat and mass transfer during drying shows that active heat up process takes place at the beginning, then there is an intensive moisture evaporation from the material as evidenced by the value of the Rehbinder test, which is close to zero.*

Streszczenie. *Badano pojemność cieplną pestek dyni, na którą wpływają dwa czynniki: temperatura czynnika grzewczego oraz wilgotność materiału. Różnica pomiędzy ciepłem parowania podczas suszenia pestek dyni w zróżnicowanym mikrokalorymetrze DMKI 01 od wartości tabelarycznej wynosi 6%. Podwyższenie temperatury czynnika grzewczego z 40 do 60°C skraca proces suszenia 8-krotnie, ale najbardziej odpowiedni jest tryb suszenia w 40°C, w którym kiełkowanie pestek dyni wynosi 98%. Z badań wymiany ciepła i masy podczas suszenia wynika, że na początku zachodzi proces aktywne(go nagrzewania, następnie następuje intensywne odparowywanie wilgoci z materiału, o czym świadczy bliska zeru wartość testu Rehbindera.* (***Właściwości termiczne i fizyczne oraz procesy wymiany ciepła i masy suszenia nasion dyni***)

Keywords: pumpkin seed, heat capacity, evaporation, heat and mass transfer, destruction.
Słowa kluczowe: pestki dyni, pojemność cieplna, parowanie, wymiana ciepła i masy, niszczenie.

Introduction

Identifying thermal and physical properties of drying pumpkin seeds on the basis of the heat agent temperature and the material moisture allows to identify the properties and differences of pumpkin seeds from other seed crops [1, 2].

A lot of researchers studied the properties of pumpkin seeds, physical, mechanical and chemical properties in particular [3]. However, thermal and physical properties haven't been fully researched.

Analysis of literary sources and problem statement

A number of foreign authors looked at physical and mechanical properties of vegetable crops in their studies [2-7], where they emphasized a substantial difference between the properties of pumpkin seeds and those of other crops. The research on chemical properties of some pumpkin cultivars [8, 9] identified almost even redistribution of fats, proteins and carbohydrates depending on varietal characters. Thermal and physical properties of grain, oil and leguminous seeds [2, 10-13], as well as the seeds of other vegetable crops [4, 7] were analyzed.

In order to correctly describe heat-mass transfer processes during drying pumpkin seeds of the cultivar "Stofuntoviy" and calculate drying efficiency according to Rehbinder criterion, the following thermal and physical parameters have to be defined: heat capacity and the heat of moisture vaporization from the material.

Materials and methods

The differential microcalorimeter DMKI-01, which had been designed by the Thermometry department of the Institute of Engineering Thermophysics of NAS of Ukraine [14, 15], was used to determine the heat capacity and specific heat of evaporation of pumpkin seeds. The device consists of a thermal unit (Fig. 1a), analytical balance, compressor, electronic control unit and personal computer equipped with relevant software, that are all functionally interconnected.

In order to study rather big pumpkin seeds with high thermal resistance a calorimetric platform with cylindrical chambers of 36 mm deep was used. The heat flow converter is placed along the perimeter of the chamber walls (Fig. 1b).

Fig. 1. The schematics of the thermal unit DMKI-01 (a) and calorimetric platform with cylindrical chambers (b): 1, 2 – upper and lower temperature controlled units; 3 – working chamber; 4 – chamber with the material tested; 5 – chamber with sample; 6, 7 – heat flow converters; 8 – calorimetric platform body with the main electric heater; 9 – platform weight reduction cavity.

Finding evaporation heat by means of DMKI-01 is based on the simultaneous measurement of changes in the material mass and the amount of heat expended on evaporation during isothermal convective-conductive drying.

The current values of the moisture vaporization heat from the material tested during the experiment is determined after the experiment completion according to the formula:

$$r_i = \frac{\int_{\tau_i}^{\tau_{i+1}} Q(\tau)d\tau}{m(\tau_i) - m(\tau_{i+1})}, \tag{1}$$

where r_i – specific heat consumption for evaporation during drying from τ_i to τ_{i+1}, kJ/kg; τ_i and τ_{i+1} – current moments of time in the drying process, sec; $Q(\tau)$ – the heat flow inside the working chamber as function of time, kJ/sec; $m(\tau_i)$ and $m(\tau_{i+1})$ – the mass of the material tested in the time moments of τ_i and τ_{i+1}, kg.

Finding specific heat capacity by means of DMKI-01 was carried out according to a standardized step scan technique every 5°C [16, 17, 18]. On the basis of the findings we determined the specific heat capacity of seeds at the mid thermal stage temperature according to the formula:

$$c_i = \frac{\int_{\tau_{start}}^{\tau_{end}} Q(\tau)d\tau}{m(t_{end} - t_{start})}, \tag{2}$$

where c – specific heat capacity of the material at the mid temperature step, kJ/(kg·K); m – the mass of the material, kg; $t_{start.}$ and t_{end} – the starting and ending temperatures of the thermal step, K.

To calculate the drying kinetics of pumpkin seeds and determine the heat-mass transfer characteristics [3, 15, 19], the obtained values of experimental data of thermophysical characteristics of the material were used. The seeds were placed on a cage pallet of 100x50x4mm, which then was placed on a barbell of the balance in the drying chamber. Thermocouples were inserted into the seeds in order to measure the temperature change in the course of drying.

The choice of modes to study the kinetics of drying pumpkin seeds in the elementary layer in a convective drying stand, which is up to 8 hours at a heat agent temperature of 40… 60ºC, was made on the basis of the writings of foreign researchers [2, 3, 7, 8, 14]. Their data though do not refer to the kinetics of changing the speed of drying pumpkin seeds and do not analyze whether the seeds preserve their seedling vigor [20]. A personal computer with relevant software was used to collect information during the operation of the stand and to calculate the kinetics of the drying process, including building the graphs [6, 21, 22].

We calculated the kinetics of moisture exchange during pumpkin seeds drying on the basis of the obtained experimental data through formula (3):

$$\frac{dW}{d\tau} = f(W), \tag{3}$$

where W – is moisture content of the pumpkin seeds within certain period of time.

The integral characteristics of the heat-mass transfer process during pumpkin seeds drying were calculated according to the Rehbinder criterion, which is identified on the basis of findings on heat capacity and heat consumption for moisture evaporation from the material:

$$Rb = \frac{c}{r}\left(\frac{dt}{dW}\right). \tag{4}$$

The Rehbinder criterion determines the ratio of the amount of heat spent on heating the material during drying to the amount of heat spent on evaporation of moisture in an infinitesimal period of time.

Research results

Pumpkin seeds heat capacity with the initial moisture content 0 and 60% is identified at the drying agent temperature of 2995 - 3544 J/kg K (Fig. 2).

According to the obtained experimental data, we identified the formula for calculating heat capacity of pumpkin seeds during drying with an error within 3%.

The formula works best in the drying agent temperature range of 32.5 - 82.5° C and seed moisture from 0 to 60%:

$$c = 1632 + 1{,}78t + 23W, \text{ J/kg}\cdot\text{K}. \tag{5}$$

We used the microcalorimeter DMKI-01 to study moisture evaporation from the pumpkin seeds at convective-conductive drying temperature of 40, 50 and 60ºC. The results are presented as a correlation graph between specific heat consumption for evaporation (in reference values for pure water) and current seed moisture (Fig. 3).

The experimentally obtained (Fig. 3) specific heat of evaporation from pumpkin seeds exceeds the reference pure water evaporation heat values approximately by 6%.

This indicates that not just free, but also bound moisture is being removed from the seeds from the very start of drying.

However, it is traditionally believed that a significant increase in energy consumption for evaporation occurs at the final stage of drying and is due to the beginning of the removal of hygroscopic moisture of the material. The overall increase in the drying temperature from 40 to 60°C reduces the specific heat consumption for evaporation in accordance with the decrease in the specific heat of evaporation of pure water.

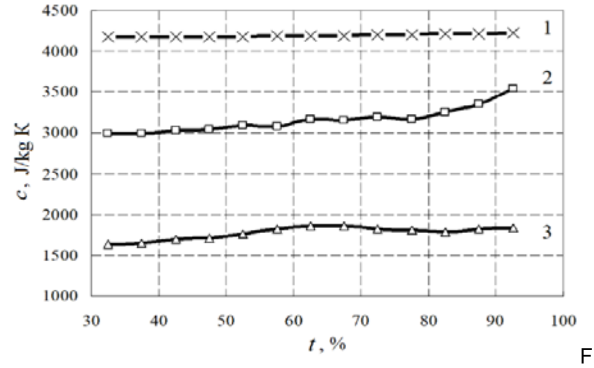

Fig. 2. Pumpkin seeds heat capacity: 1 – reference value of distilled water; 2 – pumpkin seed with 60% moisture content; 3 – pumpkin seed with oven-dry mass.

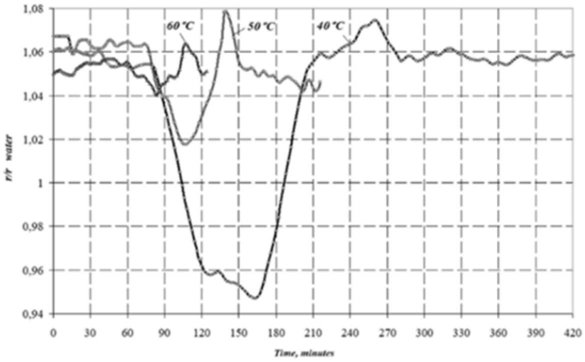

Fig. 3. The changes in the given specific heat consumption for evaporation during pumpkin seeds drying at different temperatures in DMKI-01.

We also obtained the peaks of reduction of heat consumption, the beginning of which is shifted. With the increase of drying temperature from 40 to 60ºC not just the peak is time shifted downwards, but also amplitude of the ratio r/r$_{water}$ decreases, which is shown on the experimental curves of changes in heat consumption for evaporation (Fig. 3)

Drying pumpkin seeds in a convective drying stand with the initial moisture content of 39% at the heat agent temperature of 40ºC took 4 hours, while the increase in temperature to 50ºC reduces the drying time by 2.28 times, and the increase to 60ºC does so by 4.14 times (Fig. 4).

The heat agent temperature doesn't change the nature of drying curves, which takes place during the phase of declining speed (Fig. 5).

The intensity of drying increases with increasing heat agent temperature. Thus, the drying rate reaches the maximum value at heat agent temperature of 60,8C -

0.8%/min, which is 2.85 times greater than the drying rate at a temperature of 40ºC.

As the heat agent temperature increases, the critical point Wk also shifts towards the decreased moisture content of the material, which also indicates higher intensity of the process.

The whole process takes place in the period of decreasing speed, which correlates with the data of Fig. 3, indicating the removal of bound moisture from the seeds from the very beginning of drying.

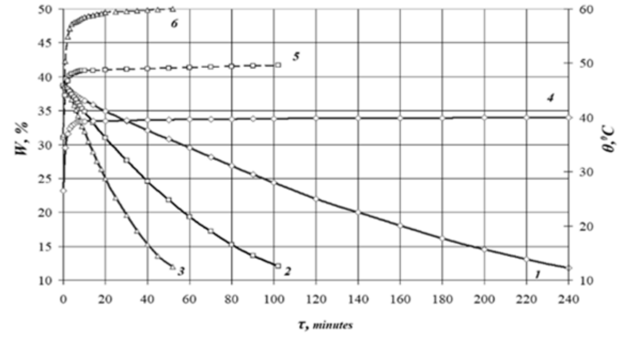

Fig. 4. The action of heat agent temperature on kinetics of pumpkin seed drying, the cultivar “Stofuntoviy” *Wп* = 39%, *V* = 1,5 m/s, *d* = 10 g/kg of d.p., *δ* = 2 mm: 1 – 40ºC, 2 – 50ºC, 3 – 60ºC.

We can also observe on the curves (Fig. 5) an unusual, as for the vegetable raw materials researched so far by many researchers, process of drying speed drop at the initial stage with the subsequent stabilizing at a lower drying speed. In terms of the achieved degree of dehydration at certain temperatures, a drying speed drop coincides with the beginning of reduction peak of heat consumption for moisture evaporation from the seeds (Fig. 3).

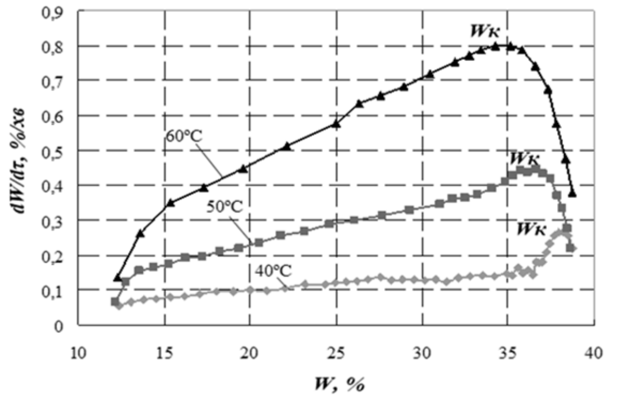

Fig. **5** The action of heat agent temperature on the speed of pumpkin seed drying, the cultivar “Stofuntoviy” *Wп* = 39%, *V* = 1,5 m/s, *d* = 10 g/kg of d.p., *δ* = 2 mm.

Additional visual observations of the current condition of the seeds during drying enabled us to identify this phenomenon as thermal and kinetic effect associated with the destruction of the outer thin shell of the seed, the end of evaporation of moisture from under this shell and the beginning of moisture removal through seed skin.

Thus, additional data obtained during the study of drying kinetics in a convective drying stand, as well as visual observations of the process enabled us to clarify the origin of the peak effect of reducing the heat consumption for moisture evaporation from the seeds (Fig. 3) and confirm that it is caused by heat release as a result of shell disruption. We shall note that, since the process of destruction is not equilibrium, it is not correct to draw any conclusions about the real value of the thermal effect of destruction on the basis of the obtained data.

According to the obtained experimental data, the process of heat and mass transfer during convective drying of pumpkin seeds was studied by calculating the heat flow change and the Rehbinder criterion (Fig. 6, Fig. 7).

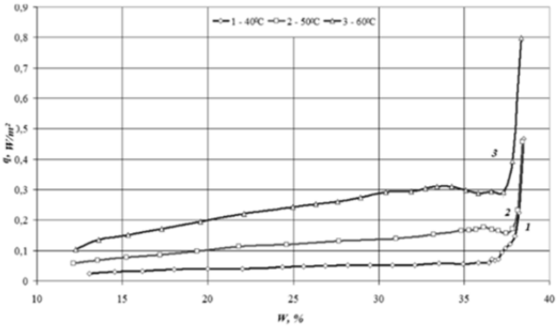

Fig. 6. Heat flow change during pumpkin seeds drying in a convective drying stand at different heat agent temperatures *Wп* = 39%, *V* = 1,5 m/s, *d* = 10 g/kg of d.p., *δ* = 2 mm: 1 – 40ºC, 2 – 50ºC, 3 – 60ºC.

At the beginning of the drying process, a high value of heat flow is observed during the heatup of the material, then during drying the material in the second phase the heat flow declines while moisture removal is increased. Although the amount of heat flow decreases in the second phase, it is still increased for a short term in the beginning, which explains the effect of rapid destruction of pumpkin seed shells and confirms the findings of the process study in the microcalorimeter DMKI-01.

We used Rehbinder criterion to study the heat and mass transfer intensity while drying pumpkin seeds. The criterion also describes the energy efficiency of the process (Fig. 7).

Drying phases: *I* – seeds heatup; *II₄₀* – the shell properties at the temperature of 40ºC, which requires a long term heatup; *II* – moisture evaporation from the shell; *III* – shell heatup; *IV* - shell destruction and moisture evaporation from the skin; *V* – skin warmup; *VI* – moisture evaporation from the skin; *VII* – warmup and simultaneous moisture evaporation from the core surface; *VIII* – activation of moisture evaporation from the inner layers.

To characterize the process of heat and mass transfer of pumpkin seeds, 2 drying modes of 40 and 60°C were considered (Fig. 7). The detailed examination of pumpkin seeds drying in terms of the Rehbinder criterion indicated the complexity of the process to be described.

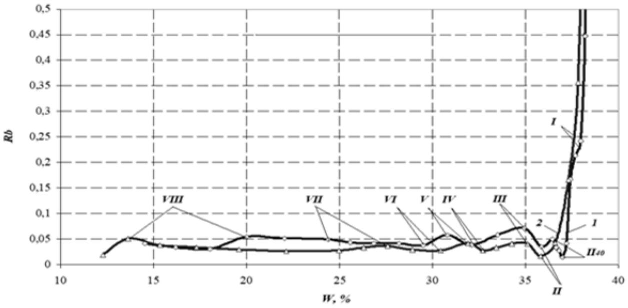

Fig. 7. Changing the Rehbinder criterion during pumpkin seeds drying in a convective drying stand at different heat agent temperatures *Wп* = 39%, *V* = 1,5 m/s, *d* = 10 g/kg of d.p., *δ* = 2 mm: 1 – 40ºC, 2 – 60ºC.

We propose to divide the drying process into 8 phases, such as: heating up the seeds, evaporation of moisture from the seed shell, heating up the shell, destruction of the shell and evaporation of moisture from the skin, heating up the skin, heating up and simultaneous evaporation of moisture from the core surface, activation of moisture evaporation from the inner layers.

For the drying mode of 40ºC after the initial heatup the moisture is not evaporated immediately but after some additional heating.

With the temperature increase the 8th phase of drying occurs later. Thus evaporation of moisture from the inner layers at a heat agent temperature of 40ºC occurs at a humidity of 20%, while at 60ºC the moisture content is 14%. The study of the pumpkin seeds' ability to germinate after the convective drying process showed that it decreases with increasing heat agent temperature and is 98% at 40°C, 96% at 50°C and 90% at 60°C. We shall note that after drying at the heat agent temperature of 80°C, the ability of pumpkin seeds to germinate dropped to 0%.

Conclusions

We have obtained pumpkin seed heat capacity influenced by the two factors of the heat agent temperature and the moisture content of the material.

2. The difference between the heat of evaporation when drying pumpkin seeds in a differentiated microcalorimeter DMKI-01 from the tabular value is 6%.

3. Increasing the temperature of the heat agent from 40 to 60°C reduces the drying process by 8 times, but the most appropriate is the drying mode at 40°C, under which the germination of pumpkin seeds is 98%.

4. The study of heat and mass transfer during drying shows that active heatup process takes place at the beginning, then there is an intensive moisture evaporation from the material as evidenced by the value of the Rehbinder test, which is close to zero.

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