HEAT-MASS TRANSFER IN LAYER OF BERRIES DURING FREEZING PROCESS

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Abstract. Qualitative changes of berries during freezing have been investigated with instrumental methods. In order to economize energy it is proposed to determine the freezing temperature of products. The objective characterisation of physical properties of products enabled to evaluate the quality, to incorporate it into the technological regimes of the treatment. Numerical results of process modelling are shown. The freezing regime is defined by several thermo-physical parameters of the production. Water stage turning into ice essentially affects the quality of the frozen product. In products ice crystal formation takes place at a relatively low temperature. This susceptibility of sugar containing products to temperature fluctuations possibly is due to their high concentrations of unfrozen water and lower melting temperature. It is possible to calculate the mass fraction of ice depending on the temperature and moisture content in product what is very important for predicting the product quality. Experimental investigation was carried out at the Institute of Horticulture, Latvia University of Agriculture.

Keywords: freezing, storage, berries, heat flow.

Introduction

Consumption of frozen foods has reached millions of tons per year in a number of countries [1]. Moreover, food manufacturers are using frozen ingredients to produce chilled products. Quality changes of some products during freezing and storage have been researched in the 21st century [2]. That is why there is a continuous interest in improving and simplifying methods of food freezing and thawing [3]. Primary aspect in the plan of the freezing process is to predict the freezing time correctly, since this parameter affects the quality of the final product. All factors that contribute significantly to the costs and benefits of the freezing process are connected with the choice of the freezing methods [4].

Unpackaged foods lose more water, initially by evaporation during the cooling stage – when surface temperature is still higher than the freezing point – but mainly by sublimation of ice from the frozen surface layer as freezing goes on. Freezing begins from the refrigerated surfaces, at the temperature (T_{if}) lower than that of pure water, due to the presence of dissolved materials, and continues along an equilibrium line, whose exact analytical shape is not known for most products. Besides, in most cases, not all of the liquid water is accessible to the freezing process, because part of it is linked to solutes and structural materials. Ice sublimation begins at the frozen surface and a dehydration part penetrates the material, the rate of advance of which is again determined by all the above mentioned characteristics of the material and environmental conditions. The production capacity of the equipment optimizes the energy consumption, all factors that contribute significantly to the costs and benefits of the freezing process. This rate is much lower than that of the freezing layer. [5].

Heat and mass transfer phenomena during freezing are related to the quality of frozen berries. Water evaporation or sublimation from the biological system during the lowering of the temperature changes the thermo-physical properties of the product. The stage when water turns into ice essentially affects the quality of the frozen product. The main transfer involved in freezing is heat transfer from the product to the cooling medium, in most cases it is air, because it is suitable for freezing berries. There are differences in water activity between the surface and the cooling medium. The highest surface temperature is in the beginning of the process and it decrease during freezing with lowering of the surface temperature [6]. Freezing is used to preserve and maintain the quality of many foods. During freezing, ice formation begins at the temperature T_f, characteristic to each type of foodstuff, and continues over a wide temperature range. Relatively low temperatures, the formation of ice as a separate phase, and the freeze concentration of dissolved substances contribute to conditions that limit the growth of microorganisms and preserve the quality factors such as flavour and colour. The water phase change brings about an important and continuous variation of the characteristic physical properties of the phenomenon (ρ, C_p, λ). Therefore, there are no general analytical solutions to predict the process time under usual freezing conditions. Several authors have proposed different numerical

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solutions (*via finite* differences or *finite* element schemes) that resolve the heat transfer problem adequately and calculate the freezing time in an accurate way. But, in spite of the fact that the use of computers is now common, it is more practical, in many instances, to employ simple and rapid prediction methods [4].

Delgado and Sun (2001) concluded that thermo-physical properties and heat and mass transfer coefficients greatly affect the accuracy of the prediction methods. Regimes of freezing and storage time were determined, taking into account their influence on the hydrophile and structure properties of the product. Different descriptive theoretical models of freezing and storage processes can be found in literature [7]. Because water and ice possess different thermo-physical properties, the main reason for the changes in the product is the transformation of the free water into ice. The aim of the research is to describe the heat transfer processes during freezing of berries grown in Latvia by numerical models.

Numerical methods are used to model heat transfer during food freezing processes. The advantage of numerical methods over simple equations is that effects of the phase change over a range of temperature. In general, fruits have a less fibrous structure than vegetables and often suffer more textural changes during freezing and storage. By changing the thermal properties and heterogeneity of plant products, fruit and berries can also be analysed. Numerical methods are generally considered to be the most accurate, reliable and versatile freezing and thawing time prediction methods [8].

Materials and methods

Research object: fresh and frozen red currants and black currants grown in Latvia. Black currants and red currants were harvested in the Institute of Horticulture, Latvia University of Agriculture. The berry samples of three black currant cultivars – "Selechenskaya", "Zagadka" and "Titania", red currant cultivars "Red Dutch" and "Vierlander" were submitted to experiments (currant-1, currant-2), and used in sorption experiments. Specific cultivars were chosen with already stated chemical content.

An actual berry freezing temperature was -20 ºC or -30 ºC, the layer thickness was 100 mm. For the determination of the layer density the weight-volume method was used. For experimental heat flow research, the equipment for heat flow measurement at the Department of Physics of the Latvia University of Agriculture was used. It consists of a horizontal freezing chamber with a steady temperature (-30 ºC) and a computerized wireless measuring system with heat flow sensors and thermocouples for temperature measurements.

During the project, the equipment was adjusted to measure the heat conductivity parameters of frozen berry samples. For this task, a sample holder of thermo-isolating material was made. The measurements were performed, placing frozen berries into a foam sample holder, which was placed inside the cold chamber. Under the sample of berries, there was a 0.3 mm metal plate placed for the insurance of the continuity of the temperature T_1. It was fixed by the thermocouple. Straight above the sample, another metal plate was placed for keeping and fixing the continuity of the higher temperature T_3. On the warmer metal plate, symmetrically to the sample, the heat flow q measuring sensor was placed. Above the "warmer" plate and the q sensor, an additional plate of thermo-isolating material was placed to supply negative temperature for the sample.

Results and discussion

The research shows that the influence of the temperature has to be differentiated – if one can ignore the influence of the temperature on the specific heat and heat conductivity of fresh fruit, then regarding the enthalpy of frozen products, the temperature is one of the main factors. After the placement of the sample, fast change of temperature and heat flow in time period can be observed. At the stationary temperature distribution the change takes place in one dimension. Heat flow through the sample is described by the Fourier equation.

The product temperature conductivity increases with ice crystals forming. So, simultaneously the specific heat reduces and the heat conductivity increases. The decreasing temperature of the products and growing of the temperature conductivity stops with ice forming finishing.

The mathematical model considers the third stage of freezing, which is freezing of products at temperatures below the freezing point. In the first approximation it could be described as freezing of infinite layer with a definite height (H) in the air (freezing from sides is not taken into account).

In the stage while the product is in a frozen condition, we will not consider mass transfer processes in this approximation. Heat exchange is considered to be unsteady-state process and unsteady-state thermal conductivity equation (1) for an infinite layer is taken as basis for further calculations:

$$\rho \cdot c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}), \quad (1)$$

where ρ – density, kg·m^{-3};
c – specific heat at constant pressure, J·(kg·K)$^{-1}$;
λ – thermal conductivity, W·(m·K)$^{-1}$;
T – temperature, K;
t – time, s;
x – co-ordinate axis where the process takes place.

We assume that the thermal conductivity of products is constant and equation (1) can be expressed in the form:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}, \quad (2)$$

where $a = \dfrac{\lambda}{\rho \cdot c}$.

For complete definition of the mathematical physics problem, the initial condition is necessary (Equation 3):

$$T\big|_{t=0} = T_0, \quad (3)$$

where T_0 – initial temperature of the currant layer.

The boundary conditions are (bottom and top of the layer):

$$T\big|_{x=0} = T_1, \quad (4)$$

$$T\big|_{x=H} = T_2, \quad (5)$$

To solve the problems (2)-(5) we use the variable separation method (by Fourier) and the solution is:

$$T(x,t) = T_1 + \frac{T_2 - T_1}{H} \cdot x + \frac{2}{\pi} \sum_{k=1}^{\infty} \frac{(T_2 \cdot (-1)^k - T_1)}{k} \cdot \sin \frac{\pi \cdot k \cdot x}{H} \cdot \exp(-a(\frac{\pi \cdot k}{H})^2 t) +$$

$$+ \frac{4T_0}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \cdot \sin \frac{\pi \cdot (2n-1) \cdot x}{H} \cdot \exp(-a\left(\frac{\pi \cdot (2n-1)}{H}\right)^2 t), \quad (6)$$

If the initial condition (3) is not a constant temperature but there is temperature distribution in the layer depending on the thickness of the layer, i.e.

$$T\big|_{t=0} = f(x), \quad (3')$$

Solution of (2), (3'), (4)-(5) is:

$$T(x,t) = T_1 + \frac{T_2 - T_1}{H} \cdot x + \frac{2}{\pi} \sum_{k=1}^{\infty} \frac{(T_2 \cdot (-1)^k - T_1)}{k} \cdot \sin \frac{\pi \cdot k \cdot x}{H} \cdot \exp(-a(\frac{\pi \cdot k}{H})^2 t) +$$

$$+ \frac{2}{H} \sum_{n=1}^{\infty} \sin \frac{\pi \cdot n \cdot x}{H} \cdot \exp(-a\left(\frac{\pi \cdot n}{H}\right)^2 t) \cdot \int_0^H f(\xi) \cdot \sin \frac{\pi \cdot n \cdot \xi}{H} d\xi, \quad (6')$$

We derived solution (6) from x and found the heat flux changes in a layer at freezing time t:

$$\frac{\partial T(x,t)}{\partial x} = \frac{T_2 - T_1}{H} + \frac{2}{H}\sum_{k=1}^{\infty}(T_2 \cdot (-1)^k - T_1) \cdot \cos\frac{\pi \cdot k \cdot x}{H} \cdot \exp(-a(\frac{\pi \cdot k}{H})^2 t) +$$

$$+ \frac{4T_0}{H}\sum_{n=1}^{\infty}\cos\frac{\pi \cdot (2n-1) \cdot x}{H} \cdot \exp\left(-a\left(\frac{\pi \cdot (2n-1)}{H}\right)^2 t\right), \quad (7)$$

Heat flow through the sample is described by the Fourier equation:

$$q = \lambda \frac{\partial T}{\partial x}, \quad (8)$$

where q – heat flow, W·m^{-2}

and at steady-state conditions ($t \to \infty$) $\lambda = \dfrac{q \cdot H}{T_2 - T_1}$.

From the experimental data we received the following values of heat conductivity coefficients for different cultivars of berries (Tab.1).

Table 1

Thermo-physical parameters of berries

No.	Sample type	ρ, kg·m^3	λ, W·(m·K)$^{-1}$
1	Currant-1	558	0.084
2	Currant-2	610	0.087
3	Black currant-1	438	0.072
4	Black currant-2	429	0.079
5	Black currant-3	458	0.084

By processing the experimental data the following thermo-physical parameters of frozen berries are obtained, which further help theoretically more precisely mathematically simulate both the process of storage and freezing frozen berries (see Tab.1). These parameters will allow determining processes more precisely taking place on boundary surface layer of frozen berries, as well as determine temperature conductivity coefficients for different kinds of frozen berries. Whole berries are used in the experiment, which according to the range of diameter and sugar content are similar. As the berry layer diameter ranges from 40-60 mm, but the sugar content is 7.3-8.2 %, these parameters are not considered for calculations.

The determination of the precise freezing temperature for each product type enables to create conditions for effective use of the technological process in temperature ranges, where the most unfavourable quality changes affecting the berries take place. By the temperatures below the freezing point, the influence on the berry heat physical indicators cannot be taken into consideration.

Using programme package COMSOL we received the following results of heat exchange during the period of 0.5; 3; 24; 48 hours with initial berries temperature -1 ºC and freezing air temperatures -20 ºC (Fig.1) and -32 ºC.

Ice formation in food products takes place at relatively low temperature and products stored at the temperature -18 ºC are not yet fully frozen. Products containing higher concentration of small molecular sugar at low temperature contain more unfrozen water because quick frozen carbohydrate solutions as well as most of biological products are characterised by non-equilibrium formation of ice crystals with its specific concentration of solution [9; 10].

During the research, evidence for the hypothesis on the ruling role of the temperature in the freezing processes was established. During the process of pre-treatment by washing berries an extra effect was reached, which was connected with simultaneous thawing of berries before freezing. Also discoveries and new information were gained on the freezing processes that are mutually interconnected. It provides scientifically practical evidence for some technological developments of qualitative improvement in berry freezing methods and their usage range.

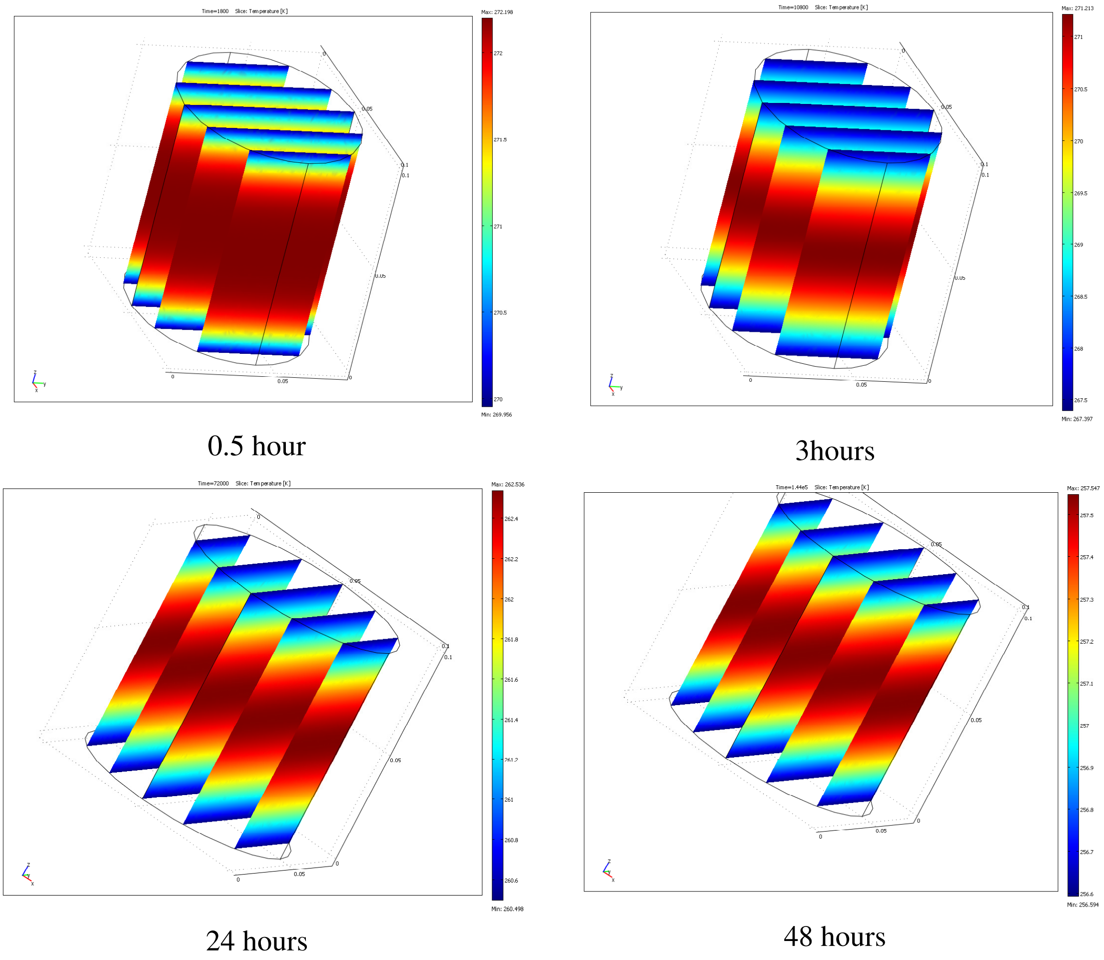

Fig. 1. **Temperature changes in black currant layer by changing storage conditions after 0.5, 3, 24 and 48 hours with freezing air temperature -20 ºC**

At the beginning of the freezing process sufficient temperature differences form along the layer (up to -6 ºC (Fig.1)), which level out during the freezing process. After 2 days freezing at -20 ºC temperature in the berry layer levels out, although the difference -1 ºC remains. Berry layer temperature is -16; -17 ºC. It cannot be adjustable to berry freezing because by formation of big ice crystals the product quality reduces.

If freezing is performed in the medium with the temperature -32 ºC, after 2 days stay in such a medium, the berry temperature decreases up to -24; -25 ºC (in the middle of the layer). In its turn, after 24 hours the berry temperature ranges from -16 ºC (in the middle) till -19 ºC on the surface. This means that it is not recommended to apply low temperatures continuously for freezing black currants, in case further storage is not going to be at lower temperature than the conventional one, which fully provides maintenance of the product quality. Our research shows that, when freezing grinded berries, on the tray in 10 cm thick layer the freezing temperature -32 ºC is not recommended longer than 24 hours. After that the freezing temperature should be increased up to the conventional storage temperature -18; -20 ºC.

Conclusions

1. On the basis of the carried out investigations technological processes and rules for frozen berries are worked out, indicating the consumption rates of raw materials and processing regimes.
2. The optimisation of the freezing temperature is essential for obtaining economically cheaper products though, without considering the quality changes, it is not possible to obtain good results. The possibility of freezing raw products as fruits and berries at the temperature of -20 ºC has not been determined.

3. The research shows that the influence of the temperature has to be differentiated – if one can ignore the influence of the temperature on the specific heat and heat conductivity of fresh fruit, then regarding the enthalpy of frozen products, the temperature is one of the main factors.
4. Modelling results show that freezing temperatures of berries should be observed. At the beginning stage it is recommended to apply lower temperature (-32 ºC), but it should be followed that over-freezing of the layer does not take place. After 24 hours of freezing it is recommended to increase the temperature up to the storage temperature.

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