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Investigation of the Energy-Saving Method during Candied Fruits Filtration Drying

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Abstract

The drying process, which is the limiting and power-consuming stage of candied fruits production, has been considered. The heat-transfer processes during the filtration drying of pumpkin candied fruit have been investigated. The filtration drying of finished candied fruits (80 °C) is the filtration of a hot heat agent (100 °C) in the direction of "candied layers – grate". As a result of experimental studies, the kinetic curves of candied fruits drying, as well as the dependence of temperature on the height of the candied fruit layer, were obtained. The experimental data confirm the zonal mechanism of the filtration drying.

It was found that during the filtration drying, the upper layers, which reached their final moisture content, overheat and accumulate a considerable amount of unused energy. It was proved that the accumulated energy can be used for drying the lower layers with simultaneous cooling the upper ones. On the basis of the equation of non-stationary heat-mass transfer, the amount of heat is calculated, which will be sufficient to dry the bottom layer. The stoppage time of hot heat agent supply and start of cold heat agent supply were determined. Filtration of cold heat agent through a layer of candied fruits makes it possible to cool the layer, reduce drying time and energy costs for the process.

Dried candied fruits have sufficient shelf life, good taste and organoleptic properties.

Keywords

candied fruits, drying, cooling, heat energy

1 Introduction

Drying is the most limiting and power-consuming stage in many industries. In particular, in the food industry, 90 % of all products are subjected to drying [1]. Food drying is the most energy-intensive and time-consuming process owing to the necessity of sufficient shelf life, good taste and organoleptic properties of the finished dried product. The most common method of food drying is a convective drying with a hot heat agent in a stationary layer. To reduce the drying time, other methods are used: microwave drying [2], sublimation vacuum drying [3], fluidized bed and pneumatic transport drying [4], combined methods such as convective and microwave ones [5]. However, all mentioned methods are expensive. Filtration drying is less expensive and more efficient than convective drying [6]. The method of heat agent filtration gives both an economic effect and certain reduction of drying time due to mechanical displacement of moisture and a large surface of heat transfer [7]. The disadvantages of filtration drying are the considerable height of the material layer [8] and the considerable drying time for materials containing mainly bound moisture [9, 10]. The elimination of these disadvantages is an urgent task. The problem may be solved during adsorbent regeneration [11]. However, adsorbents have a short regeneration time due to their free moisture content [12].

Such healthy product as candied fruits, after saturation with sucrose, is subjected to long-term drying in a stationary layer due to the available bound moisture. To intensify the process a method of the heat agent filtration through a layer of moist candied fruits is used [13]. However, the reduction of drying time and energy costs during candied fruits drying remains an urgent task.

2 Materials and methods

The objects of the study are pumpkin fruits, purified from skin and seeds and formed into 20x10x10 mm rectangular particles.

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For saturation of fruits with sucrose a sugar syrup (70 wt.%) was used at 80 °C.

The production of candied fruits was carried out according to the following procedure: the formed particles were blanched (processed with hot steam) for 10 minutes and kept in sugar syrup (stirring conditions) for 3 hours. The weight ratio of pumpkin particles to the syrup was 1:5.

After 3 hours the syrup was poured out and finished candied fruits with the temperature of 80 °C were directed for drying [14]. The process was carried out via a filtration method in a container, the scheme of which is shown in Fig. 1.

The container body 1 (Fig. 1) with a diameter of 0.1 m consists of four parts with grates 3. The container walls and the grates are manufactured of fluoroplast in order to eliminate the conductive heating of candied fruits during drying and to preserve the taste and nutritional value of the finished product. Thermocouples 4 and 5 are connected to the inlet and outlet of container, respectively. Every four parts of the container are connected with corresponding thermocouples I–IV.

Candied fruits were placed in one layer (in 16 pieces) over each of four grates 3. Such method of placing provides uniform distribution of the heat agent and minimizes the hydraulic resistance of the layer. Thermocouples were installed above each layer. The distances between the container top edge and thermocouples were 10 mm, 40 mm, 70 mm and 100 mm for thermocouple I, II, II and IV, respectively (Fig. 1). The thermocouple 4 on the top of container measured a temperature of the heat agent for drying; the thermocouple 5 at the bottom of container – the temperature of the heat agent at the container outlet. The filtration drying setup is shown in Fig. 2.

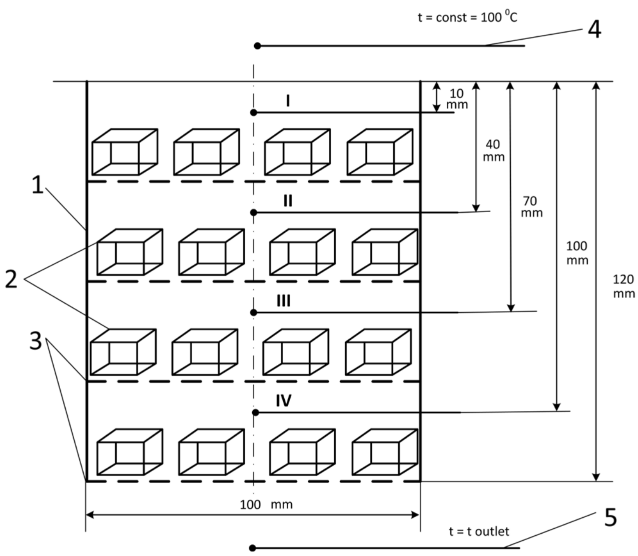

Fig. 1 Scheme of a container for filtration drying of candied fruits: 1 - body, 2 - candied fruits layers, 3 - grates, 4 – thermocouple at the container inlet, 5 – thermocouple at the container outlet; I – thermocouple above first layer of candied fruits, II – thermocouple above second layer of candied fruits, III – thermocouple above third layer of candied fruits, IV – thermocouple above forth layer of candied fruits.

It consists of container 1 (scheme is shown in Fig. 1) installed on the receiver 2, which is connected with a water-packed vacuum pump 6 through the pipeline system and rotameter 3, the shutoff valve 4 and the regulating valve 5. A diffuser of electro-calorifier 7 connected to the fan 8 is installed over container 1. To measure the temperature of the heat agent over a layer of dispersed material the thermocouple 9 is set. The thermocouple 10 measures the temperature the heat agent temperature at the outlet. The thermocouples, shown in Fig. 1, are placed inside the container. All thermocouples are connected by a thermoelectric converter 11. Vacuum-gauge 12 measures the vacuum under the material layer [15].

The experimental procedure was as following: container 1 was installed on the receiver 2. The vacuum pump 6 was switched on and the flow rate of heat agent was specified by the control valve 5. A heat agent with a constant temperature of 100 °C and flow rate of 0.015 m^3/s was filtered through four layers of candied fruits. The flow rate value was chosen on the basis of literature data [8, 10, 15]. Higher values of flow rate do not intensify the drying because the process proceeds in the range of decreasing rates. Lower flow rates do not provide the moisture carrying-out from the drying zone. The flow rate was measured by rotameter 3, and the pressure loss – by vacuum meter 12. The drying process

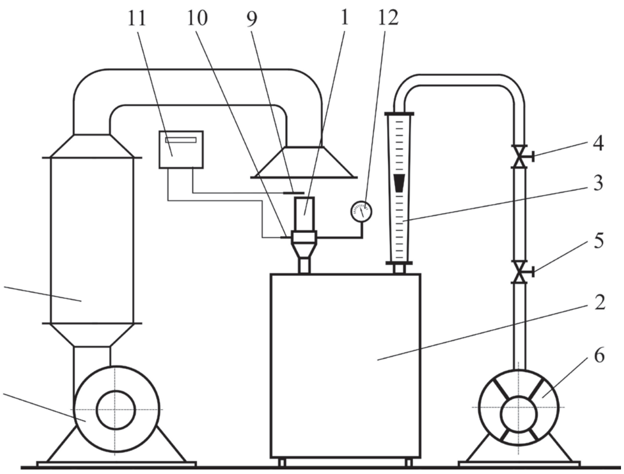

Fig. 2 Experimental setup:
1 - container, 2 - receiver, 3 - rotameter, 4, 5 - shutoff and regulating valves, 6 - water-packed vacuum pump, 7 - heater, 8 - fan, 9, 10 - thermocouples, 11 – measuring device, 12 - vacuum meter.

was carried out until the moisture content of 20 wt.% was reached. Pumpkin candies with such moisture content were well preserved, tasty and had a nutritional value. The temperatures along the entire height of the layer, as well as at the inlet and outlet of container were fixed by an eight-channel PT-108 thermoelectric converter with a personal computer in 1.8 s. The weight of container during filtration drying was measured using an electronic weighing scale AXIS-3000 with an accuracy of 0.01 g.

3 Results and discussion

The kinetic curve of drying for candied fruits layer with a total height of 110 mm and weight of 400 g at the temperature of the heat agent t = 100 °C is shown in Fig. 3.

It is obvious from Fig. 3 that the drying takes place during the period of decreasing drying rate, i.e., the bound moisture is removed from the middle and surface of candied fruits. To achieve the final moisture of 20 wt.% the drying continues for 1500 s. The weight of evaporated moisture is 160.5 g. The results of temperature changes of the heat agent at the outlet of the pumpkin layer are shown in Fig. 4.

As can be seen from Fig. 4, at the initial moment of time, the temperature of the heat agent at the layer outlet is slightly higher (48 °C) than the wet-bulb temperature. The increase in time increases the temperature at the layer outlet due to the low intensity of the pumpkin slices heating and moisture evaporation. After 1500 s the temperature of the heat agent at the outlet is actually unchanged and is close to that at the inlet. The temperature change of the heat agent during filtration drying versus time along the height of the candied fruits layer is shown in Fig. 5.

It is known that filtration drying has a zonal nature [16]. This is confirmed by the experimental data presented in Fig. 5. Let us consider layer I (Fig. 5), which is the first in contact with the heat agent. At the initial moment of time the temperature of the heat agent decreases to 70 °C. This value is slightly higher than the wet-bulb temperature. This phenomenon is explained by the fact that the process of candied fruits drying occurs during a period of decreasing rate, i.e. during partial saturation of the heat agent with moisture. In the next period of time (up to 135 s), the temperature of the heat agent increases. The reason is less intense evaporation of moisture and less saturation of the heat agent with moisture at each interval of time. At some moment (135 s for layer I) the temperature of the heat agent is not changed and becomes equal to the temperature at the layer inlet. After 135 s the layer I reaches its final moisture content. Its temperature is equal to the temperature of the heat agent and this layer does not participate in the following mass transfer process.

Similar processes occur with the lower layers. The layer II reaches its final moisture content after 300 s, the layer

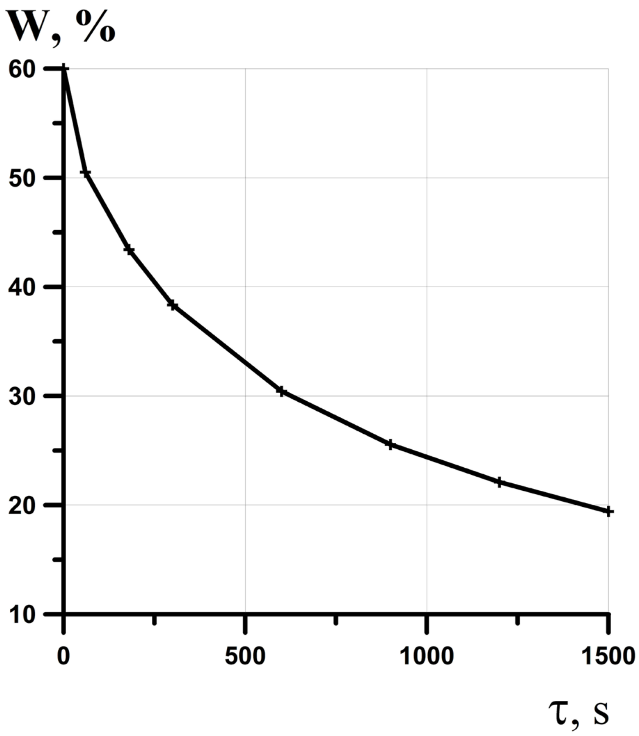

Fig. 3 Kinetic curve of candied fruits drying.

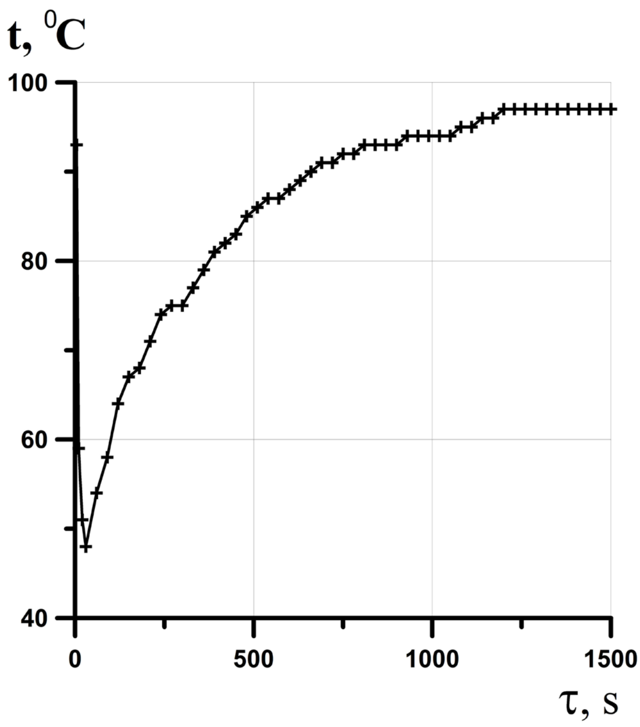

Fig. 4 Temperature dependence of the heat agent at the layer outlet on time.

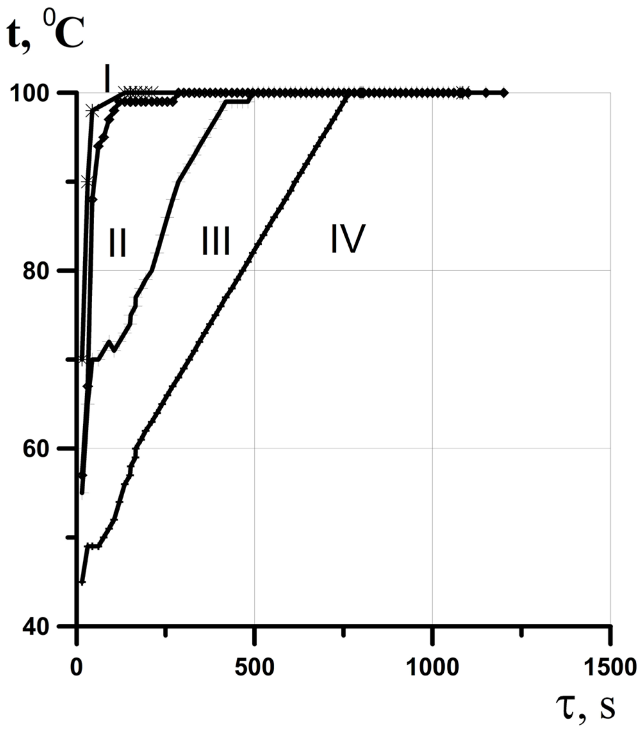

Fig. 5 Temperature dependence of the heat agent during filtration drying on time along different heights of the candied fruits layer: I - 10 mm, II - 40 mm, III - 70 mm, IV - 100 mm.

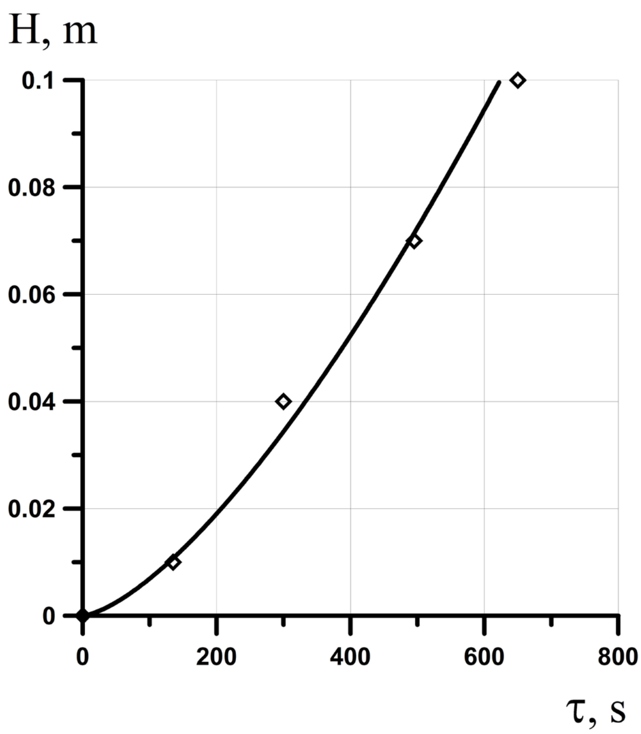

Fig. 6 Layer height versus time of reaching equilibrium moisture.

III – after 495 s, the layer IV – after 660 s. Then the layers do not participate in the mass transfer process.

As a result of such mechanism of candied fruits filtering drying, the layer simultaneously contains a dry layer of material with the temperature of 100 °C, which accumulates the thermal energy and a wet layer with the temperature below 100 °C. With a certain heights ratio of the dry and wet layers, when the accumulated energy of the dry layers is sufficient to dry the wet layers, it is advisable to apply a cold heat agent that cools the upper layers of the material and dries the wet material. Taking into account that candied fruits have a low coefficient of thermal conductivity, it is possible to use the accumulated energy of the upper dried layers to dry the wet material due to which the upper candied layers are cooled. As a result, the power consumption, drying and cooling time are reduced.

It was necessary to determine the amount of accumulated energy in the upper layers necessary to evaporate the moisture from the lower layers without heating the heat agent that is filtered through the candied layer. Using experimental data (Fig. 5), we plotted the height-time graph (Fig. 6).

As a result of the experimental data approximation by a power function (Fig. 6), the dependence (Eq. (1)) was obtained:

$$H = 8.9 \times 10^{-6} \cdot \tau^{1.45}. \quad (1)$$

The approximation was conducted using the Grapher 10 complex. The experimental points and the curve of power function are consistent with each other, and the maximum relative error does not exceed 1.5 %, so the calculated dependence (Eq. (1)) is recommended for practical calculations of drying equipment with the height up to 120 mm, which operates within the temperature range of 20 – 100 °C.

Equation (1) gives the possibility to calculate the height of the dried candied fruits layer at any time, and the time of reaching equilibrium moisture of any section within the investigated layer heights.

As can be seen from the experimental results (Figs. 3-6), the filtration drying is a complex non-stationary heat-mass transfer process in which the parameters are periodically changed in coordinates and time [17, 18].

The equation of thermal balance (Eq. (2)) at the elementary section *dH* in the form of differential equation of the periodic process (Eq. (2)) of filtration drying in a fixed layer of candied fruits is:

$$\begin{aligned} & S \cdot dH \cdot \rho_{cand} \cdot \frac{\partial W}{\partial \tau} \cdot r \cdot d\tau = \\ & = S \cdot dH \cdot \rho_{cand} \cdot \frac{\partial t_{cand}}{\partial \tau} \cdot c_{cand} \cdot d\tau \\ & + S \cdot dH \cdot \rho_{t.a.} \cdot \frac{\partial t_{t.a.}}{\partial \tau} \cdot c_{t.a.} \cdot d\tau, \end{aligned} \quad (2)$$

where S is a cross-sectional area of the layer, m^2; dH is a height of the layer elementary section, m; ρ_{cand} is a candied fruits density, kg/m^3; $\frac{\partial W}{\partial \tau}$ is the change in moisture content of the heat agent for time $d\tau$; r is a specific heat of vaporization J/kg; $\frac{\partial t_{cand}}{\partial \tau}$ is the change in temperature of wet candied fruits for time $d\tau$; c_{cand} is a heat capacity of can died fruits, J/(kg·K); $\rho_{t.a.}$ is a heat agent density, kg/m^3; $\frac{\partial t_{t.a.}}{\partial \tau}$ is the change of heat agent temperature for time $d\tau$; $c_{t.a.}$ is a heat capacity of the heat agent J/(kg·K).

Using Eq. (2), we calculate the amount of heat required to evaporate the moisture (Q_{evap}) for time $d\tau$ at the elementary section dH. Generalized results are represented in Table 1.

The heat required for evaporation is accumulated by dry hot layers of candied fruits. It can be used for drying wet layers. The results given in Table 1 show that the heat accumulated by upper three layers of candied fruits (Q_{evap}= 70.14+46.16+50.7 = 167 kJ) will be sufficient for drying the bottom layer (Q_{evap}= 73 kJ) (Fig. 1). That is why, at time τ = 495 s, it is possible to switch off the heater 7 (Fig. 2) and apply a 20 °C heat agent for drying, which will save energy.

Using Eq. (2), we calculated the energy consumed by the heat agent at 100 °C, which is spent on drying the all layer of candied fruits with a total height of 110 mm and weight of 400 g for 1500 s, which corresponds to the time of reaching the final moisture of 20 %:

$$Q^{I}_{t.a.} = 295.9 \text{ kJ}. \tag{3}$$

The energy consumed by the thermal agent at 100 °C, which is consumed over a period of 495 s was calculated as:

$$Q^{II}_{t.a.} = 205.28 \text{ kJ}. \tag{4}$$

160.5 g of moisture were evaporated during drying.

The amount of energy per unit of evaporated moisture mass, which is saved by the proposed energy-saving method of filtration drying is:

$$q = \frac{Q^{I}_{t.a.} - Q^{II}_{t.a.}}{m_{water}} = \frac{295.9 - 205.28}{0.1605} = 564.61 \text{ kJ/kg}_{\text{water}}. \tag{5}$$

Thus, stopping the supply of hot heat agent at a certain point in time, cooling the top layers of candied fruits with a cold heat agent and simultaneous drying the lower layers of candied fruit, will reduce the energy costs of the process by 564.61 kJ/kg$_{\text{water}}$.

Table 1 The amount of heat required for evaporation of moisture (Q_{evap}) and water weight (m_{water}) on the elementary section dH for time $d\tau$

dH, mm	$d\tau$, s	Q_{evap}, kJ	m_{water}, g
10	135	70.14	28.06
40	300	46.16	20.03
70	495	50.7	19.29
100	660	73	13.61

For the mathematical description of the temperature field in the whole layer of dispersed material, it is necessary to introduce a mathematical description of the "short-length" layer. Such a layer is described by an exponential dependence.

It was mentioned above that filtration drying has a zonal nature. The "short-length" layer is a layer which is the first in contact with a heat agent during filtration drying. When this layer reaches the equilibrium moisture, the bottom layers begin to be dried.

In the process of heat transfer, the upper layers are a source of heat with a constant power q_V (hot layer of dried candied fruits).

Dimensionless temperature θ for upper layers:

$$\theta_{I\_II} = \frac{t - t_{w.t.}}{T - t_{w.t.}}, \tag{6}$$

for lower layers:

$$\theta_{III\_IV} = \frac{t - t_{w.t.}}{T - t_{w.t.}} - \frac{t - t_{w.t.}}{q_V \cdot H^2 / (2\lambda)}, \tag{7}$$

Dimensionless height (ω):

$$\omega_I = \frac{h_I}{H};\ \omega_{II} = \frac{h_{II}}{H};\ \omega_{III} = \frac{h_{III}}{H};\ \omega_{IV} = \frac{h_{IV}}{H}, \tag{8}$$

for dimensionless heights ω_I, ω_{II}, function $\theta_I(Fo)$ is an exponential dependence:

$$\theta_{I\_II}(Fo) = 1 - e^{-Fo}. \tag{9}$$

A transformation theorem for dimensionless heights ω_{III}, ω_{IV} was used to calculate.

For double length, the exponential dependence will have the form:

$$\theta_{III\_IV}(Fo) = (1 - e^{-Fo}) \cdot (1 + Fo), \tag{10}$$

where T is the temperature of the candied fruits layer, °C; t is a temperature of the heat agent, °C; $t_{w.t.}$ is a wet thermometer temperature, °C; Fo is the Fourier criterion; H is the height of the candied fruits layer, m; h_I is the height of the "short-length" layer (0.03 m); h_{II}, h_{III}, h_{IV} are two, three, four heights of the layers, respectively, m; q_V is the specific thermal power of the dried candied fruits layer, W/m^3; λ is the thermal conductivity coefficient of candied fruits, $W/(m \cdot K)$, Eq. (9) is for calculating dimensionless heights, ω_I, ω_{II}. Equation (10) is for calculating dimensionless heights ω_{III}, ω_{IV}. Results of calculations of dimensionless temperature along the layer height are shown in Fig. 7. Curves I and II show the results calculated according to Eq. (9), and curves III and IV - according to Eq. (10).

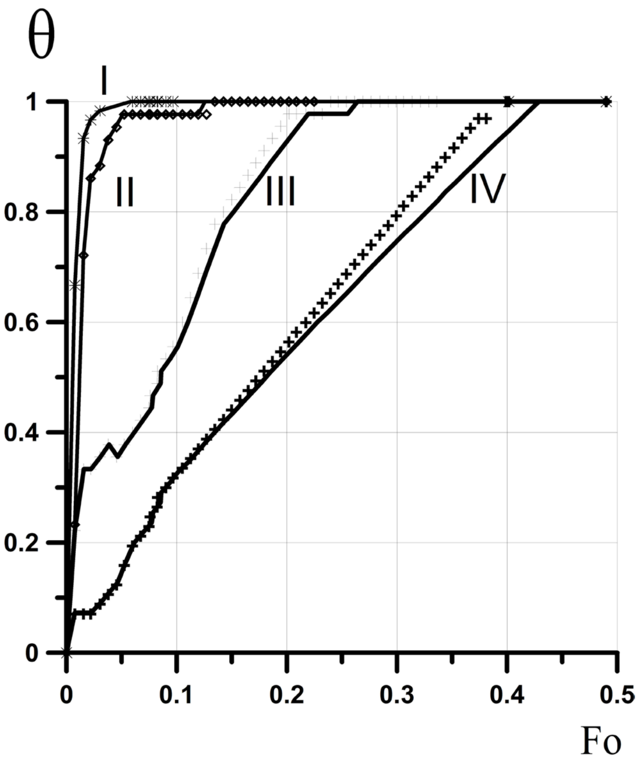

Fig. 7 Comparison of experimental data and data calculated by Eq. (9) (curves I – II) and Eq. (10) (curves III – IV).

3.1 Points indicate experimental data

The calculation model is adequate, the error between the experimental and theoretical data does not exceed 7 %. Good agreement between the calculated and experimental results allows us to determine the temperature distribution along the height of the monodispersed layer, using various ratios ω.

The mathematical model, which describes the filtration drying process of dispersion material and allows to predict the energy costs during design calculations of new drying equipment was developed.

4 Conclusions

In order to intensify the drying process of the candied fruits from pumpkin, it is suggested to filter the hot heat agent through the hot (after the saturation process) layer of candied fruits. The kinetic curve shows the presence of bound moisture in the candied fruits and, as a consequence, the long drying time. Curves of temperature change along the layer height indicate the zonal mechanism of filtration drying. It is proposed to dry a portion of the candied fruits layer to the final moisture content, the accumulated heat of which is sufficient to finish the drying of the whole layer. On the basis of the equation of non-stationary heat-mass transfer, the amount of heat accumulated by three upper layers was calculated (Q_{evap} = 167 kJ), which is sufficient to dry the bottom layer. In accordance to the proposed method it is possible to stop filtration of the hot heat agent through the candied fruits layer after 495 s and start filtering with the heat agent at 20 °C. Thus the energy costs of the process will be reduced by 564.61 kJ/kg_{water}.

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