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STUDY ON THE KINETICS, HYDRODYNAMICS AND MASS TRANSFER OF THE PROCESS OF ZUCCHINI FRUITS SATURATION WITH SUCRSE FROM AN AQUEOUS SOLUTION

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Abstract. Processes of sucrose diffusion inside plant fruits and their generalization require special attention, namely theoretical generalization of experimental data and organization of energy-saving production of candied fruits while preserving the quality of the finished product. This work deals with the experimental and theoretical studies of the kinetics, hydrodynamics and mass transfer of the process of zucchini fruits saturation with sucrose from an aqueous solution. Experimental studies were conducted in static and dynamic modes. In static mode, fruit saturation occurs from an aqueous solution of sucrose in a stationary state of the solution. Dynamic mode occurs under conditions of air bubbling of an aqueous sucrose solution. Specific heat consumption of the studied modes of saturation of zucchini fruits in sugar syrup was theoretically calculated. The kinetic process of changes in the sucrose concentration in zucchini fruits at different rates of air supply for bubbling was studied in detail. It was found that the process kinetics occur in the regions of external and internal diffusion. Based on Fick's law, a generalization of the saturation processes of the particles of zucchini fruits with sucrose in the external diffusion region was carried out using the similarity theory. The existence of three hydrodynamic regimes during fruit saturation in dynamic mode was proved. Criterion equations were derived allowing us to theoretically calculate the mass transfer coefficient under the conditions of three hydrodynamic regimes. From technological and economic points of view, the most expedient process of zucchini fruit particles saturation with sucrose occurs at a syrup temperature of 70°C and a rate of air flow for bubbling from 6 to 8 m/s. The derived criterion equation allows to establish the numerical value of the air pressure for bubbling depending on the air supply rate.

Key words: fruits, sucrose saturation, dynamic mode, static mode, heat consumption, mass transfer coefficient, criterion equations.

Introduction. Formulation of the problem

The production of candied fruits is a complex energy-intensive process, both from a technological point of view and from the standpoint of preserving the quality of the finished product. The main stages of candied fruit production are the process of saturating fruits and vegetables with sucrose followed by their drying to the final moisture content. Such processes are heat and mass exchange in the system "solid body - liquid", "solid body - gas", the study of which is widely described in the scientific literature using the example of adsorption [1,2], dissolution [3,4], extraction [5], and drying [6-8].

An important task in the production of candied fruits is the calculation of the process of saturation of fruits with sucrose based on the generalization of experimental data and the creation of criterial mass transfer equations. This, in turn, will make it possible to design energy-saving equipment for the production of candied fruits.

Analysis of recent research and publications

For example, the dynamics of copper ions adsorption in a stationary layer of the adsorbent and the mathematical interpretation of the process first stage are presented by Gumnitsky et al. [1]. The first stage of adsorption is mathematically formulated by the differential equation of molecular diffusion with the boundary condition of the first kind. The kinetics of albumin adsorption by natural zeolite is studied by Hyvlud et al. [2]. The mass transfer coefficient for external diffusion and the molecular diffusion coefficient for the interdiffusion region were determined.

The mass transfer coefficient is determined using criterion equations for the dissolution processes of potassium chloride particles [3] and a polydispersed mixture of benzene acid [4]. For the processes of extracting the target component from straight capillaries, the mass transfer coefficients for the convective zone were determined [5].

A mathematical model of the dynamics of

temperature changes during the drying of a hot monodispersed layer of candied fruits was derived [6], and the dynamics of the drying process of candied fruits in the period of decreasing rate was investigated [7]. Borin et al. studied the kinetics of candied pumpkin drying and determined the diffusion coefficients based on Fick’s law [8]. The drying kinetics of cotton stalks [9] and sunflower stalks [10] were examined and kinetic coefficients were established by several authors. Giovanni et al. [11] investigated the osmotic dehydration of liquid waste from candied sugar production and determined mass transfer coefficients. On the basis of Fick's law, analytical equations for generalizing the kinetics and determining the diffusion coefficients of water in the peel and pulp of cherry fruits were derived by Maldonado et al. [12].

As can be seen from the review of literature sources, a number of heat and mass transfer processes can be generalized on the basis of the fundamental laws of mass transfer. However, the processes of sucrose diffusion in the middle of the plant fruits and generalization of such processes require special attention, namely theoretical generalization of experimental data and organization of the energy-saving process of production of candied fruits while preserving the quality of the finished product. Moreover, each process will depend significantly on the nature and structure of the fruit, from which candy is made.

The purpose and objectives of the research

The aim of this work is an study on the kinetics, hydrodynamics and mass transfer of the process of zucchini fruits saturation with sucrose.

To achieve the goal, the following tasks must be solved:

1. Experimental study of the kinetics of zucchini fruits saturation with sucrose in static and dynamic mode.
2. Determination of the specific heat consumption.
3. Generalization of the results, and derivation of criterion equations, which allow theoretically determining the mass transfer coefficient.
4. Derivation of criterion equations, which makes it possible to theoretically calculate the air pressure for bubbling and determine the energy costs for the implementation of the bubbling saturation mode.

Research materials and methods

The object of research was zucchini Albarello. The samples were prepared as follows: the zucchini fruits were separated from the skin and the samples of the same size (18x10x8 mm) in the form of parallelepiped were formed. All samples were blanched for 7 minutes and then divided into two parts to carry out the experiments in static (without air supply for bubbling) and dynamic (with air supply) modes. For both modes, the samples were saturated with sugar in sugar syrup with a concentration of 65 wt.%. The experimental temperatures were 40°C, 70°C, and 100°C to avoid syrup boiling.

The schematic experimental setup is shown in Fig. 1. For static mode: sugar syrup is poured into the cylindrical enameled body 1 through fitting 2. The syrup is heated by water vapor through the shell 11. When device 7 fixes the set temperature by means of a thermocouple, samples of blanched zucchini fruits are loaded into the enameled body 1 through fitting 2. The samples are removed one by one from the syrup every 2 minutes. After that, the samples are cut into two identical halves, the juice is squeezed out of them, and the concentration of zucchini juice is determined according to the Brix scale using a HT118 refractometer (0–80% Brix) [13]. The experiment continues until the moment when the juice concentration of the last 3 samples becomes unchanged.

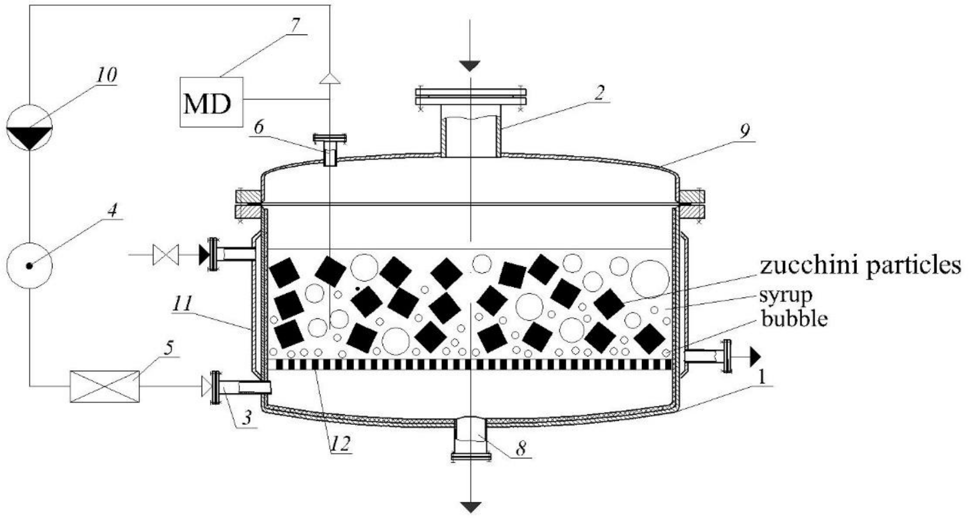

Fig. 1 The schematic experimental setup for the saturation of zucchini particles with sugar

1 – cylinder body; 2 – fitting for supplying sugar syrup and zucchini particles; 3 – compressed air supply nozzle; 4 – fan; 5 – heater; 6 – nozzle for air outlet; 7 – device for measuring temperature; 8 – fitting for draining syrup; 9 – cover; 10 – entrainment separator; 11 – shell; 12 – grid

Dynamic mode: sugar syrup is poured into the cylindrical enameled body 1 through fitting 2. The syrup is heated by water vapor through the shell 11. When device 7 fixes the set temperature by means of a thermocouple, samples of blanched zucchini fruits are loaded into the enameled body 1 through fitting 2. At the same time, compressed air with a temperature equal to the temperature of the syrup is supplied to the cylinder through nozzle 3. The air is supplied and its flow is regulated by fan 4; the air is heated by heater 5. The air flows out of the device through fitting 6 and is recirculated through the entrainment separator 10. In this way, intensive pneumatic mixing of the zucchini particles with sugar syrup takes place in the cylinder. Further, the experiment is carried out similarly to static mode. Experiments in dynamic mode were carried out at the following air flow rates: 2, 5, 8, and 9.5 l/min; the air velocities in nozzle 3 are 1.5, 4, 6.6, and 8 m/s, respectively. The selected air flow rates ensure intensive mixing of the zucchini fruits and prevent the intensive removal of syrup drops from the apparatus.

At the end of the experiments, the air supply is turned off, and the syrup is drained through connector 8. The temperature is fixed by an eight-channel PT-108 thermoelectric converter. The diameter (d) of the cylinder body 1 is 200 mm.

Statistical processing of data occurs by means of cluster and regression analysis.

Results of the research and their discussion

Fig. 2. shows the kinetic curves of changes in the sucrose concentration in zucchini fruits under two modes of saturation: static and dynamic. Static mode (steady state) is represented by curves 3, 4, and 6 (Fig. 2). Dynamic mode (bubble state) is represented by curves 1, 2, and 5 under conditions of an air supply rate of 6.6 m/s.

As can be seen from the graphs (Fig. 2), each kinetic curve (1 – 6) has a section of both external and internal diffusion regions. From the beginning of the saturation to the moment when the kinetic curves reach equilibrium, the process of matter transfer is carried out by external diffusion. The intensity of this process will depend on the medium temperature and the rate of air supply. The increase in temperature, as well as air supply (Fig. 2) contribute to the process intensification. While the interdiffusion region is much less dependent on medium parameters (Fig. 2), it will be affected primarily by the internal structure of the zucchini fruits. The inner region starts from that point in time when the parts of the kinetic curves, which asymptotically approach equilibrium, can be approximated by a straight line.

The total time of zucchini fruits saturation to equilibrium concentrations is 1920 s (curve 1), 2000 s (curve 2), 2330 s (curve 3), 2400 s (curve 4), 3120 s (curve 5), and 3450 s (curve 6). Based on the obtained results it is concluded that saturation at 400°C in both static and dynamic modes is inefficient due to the significant saturation time. Analyzing curves 2 and 3 (Fig. 2), we observe that in dynamic mode the saturation occurs at a temperature of 70°C (curve 2) in a shorter period of time than in static mode at a temperature of 100°C (curve 3).

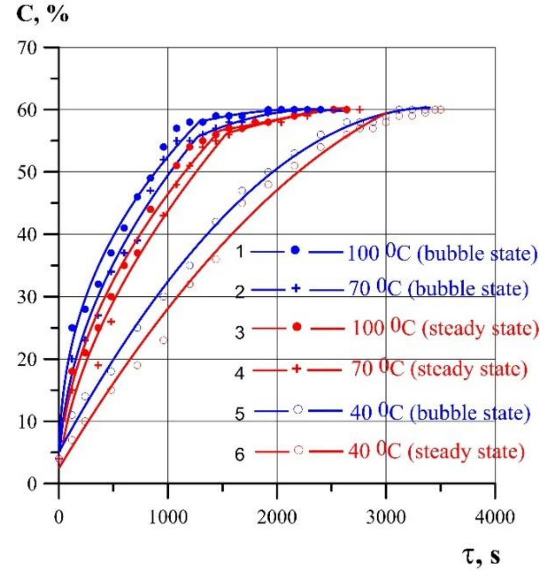

Fig. 2 Kinetic curves of changes in sucrose concentration in zucchini fruits over time

1 – kinetic curve of saturation in dynamic mode at a temperature of 100°C;
2 – kinetic curve of saturation in dynamic mode at a temperature of 70°C;
3 – kinetic curve of saturation in static mode at a temperature of 100°C;
4 – kinetic curve of saturation in static mode at a temperature of 70°C;
5 – kinetic curve of saturation in dynamic mode at a temperature of 40°C;

Thus, in order to establish the most effective mode of saturation, it is necessary to calculate the specific heat consumption (MJ/kg of syrup) for the process. Heat consumption for heating the syrup to the defined temperature and for the reaching equilibrium of the saturation process (Q), is calculated according to Eq. (1). The heat consumption of the fan for supplying air (Q_{fan}) is calculated according to Eq. (2). Heat consumption for air heating (Q_{heater}) is calculated according to Eq. (3). Total heat consumption (ΣQ) is calculated according to Eq. (4):

$$Q = c_s \cdot (t_2 - t_1) \cdot \frac{\tau_2}{\tau_1} \cdot 10^{-6} \tag{1}$$

$$Q_{fan} = V_{air} \cdot \Delta p \cdot \tau_2 \cdot 10^{-6} / m_s \tag{2}$$

$$Q_{heater} = V_{air} \cdot c_{air} \cdot (t_2 - t_1) \tau_2 \cdot 10^{-6} \tag{3}$$

$$\sum Q = Q + Q_{fan} + Q_{heater} \tag{4}$$

where

t_2 is the saturation temperature, °C;

t_1 is the initial temperature of the syrup, 20°C;

τ_2 is the time of zucchini fruits saturation to the equilibrium concentration, s;

τ_1 is the time of syrup heating to saturation temperature, s;

V_{air} is a volumetric flow rate of air for bubbling, m^3/s;

c_{air} is a specific heat capacity of air, J/kg·degree;

Δp is a pressure of air for bubbling, Pa;

m_s is a syrup weight, kg;

c_s is a specific heat capacity of syrup, J/kg·degree.

The obtained numerical values of the specific heat consumption for all studied modes are shown in Table 1.

Table 1 – Specific heat consumption of the studied modes of saturation of zucchini fruits in sugar syrup

Mode	**t_2,°C**	**τ_1, s**	**τ_2, s**	**Q, MJ/kg**	**Q_{fan}, MJ/kg**	**Q_{heater}, MJ/kg**	**Σ Q, MJ/kg**
Static	100	480	2330	1.113	0	0	1.138
Dynamic	100	480	1920	0.938	0.128	0.020	1.085
Static	70	300	2400	1.172	0	0	1.172
Dynamic	70	300	2000	0.977	0.133	0.013	1.123
Static	40	75	3450	2.532	0	0	2.696
Dynamic	40	75	3120	2.438	0.207	0.008	2.653

As can be seen from Table 1, the total heat consumption is lower in dynamic mode compared to the static one, at the same medium temperatures. Moreover, the heat consumption in dynamic mode at 70°C (1.123 MJ/kg) is lower than the heat consumption in static mode at 100°C (1.138 MJ/kg).

The highest heat consumption is observed at a temperature of 40°C in both static and dynamic modes. Therefore, such a temperature regime is inappropriate for the saturation of candied fruits.

Based on the experimental results, it is recommended to produce candied fruits in dynamic mode at temperatures of 70-100°C. Under such conditions, the lowest heat consumption is observed (Table 1). At 100°C, a slight concentration of the syrup is observed with simultaneous evaporation of the solvent, which can lead to a deterioration in the quality of the finished product. Therefore, dynamic mode and a temperature of 70°C were chosen for further studies of external diffusion processes.

Fig. 3 shows the kinetic curves of changes in sucrose concentration in zucchini fruits at different rates of air supply to the bubbler.

It is obvious that each kinetic curve (1 – 4, Fig. 3) has a section of the external and internal diffusion region, similar to the kinetic curves shown in Fig. 2. One can see from Fig. 3 that the intensity of sucrose molecules transfer to the zucchini fruits depends on the rate of air supply. An increase in the rate of air supply to the bubbler contributes to the intensification of the saturation process.

Let's analyze the nature of kinetic curves 1-4 (Fig. 3). The interdiffusion region is the section of kinetic curves 1–4 (Fig. 3), which asymptotically approaches the equilibrium values. Such a section can be approximated by a straight line that summarizes the experimental points with an error of 3%. The approximation is carried out using the Grapher 10 graphic editor. A moment of time, at which the generalization of experimental values with a straight line is impossible due to the rapid growth of the generalization error, will correspond to the moment of termination of the external diffusion and the beginning of the internal diffusion. Thus, it is possible to graphically determine the time of the saturation process in the external diffusion region.

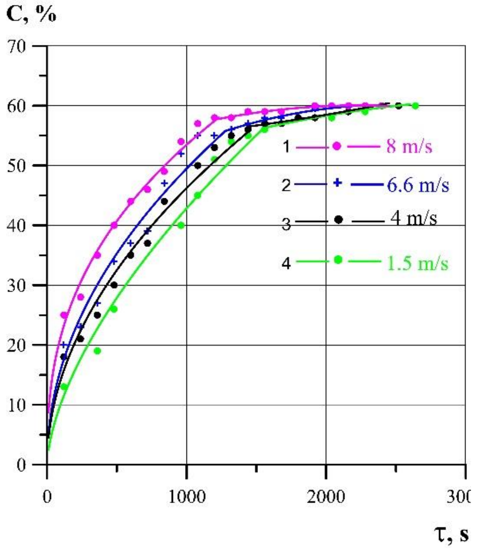

Fig. 3 Kinetic curves of changes in the sucrose concentration in zucchini fruits at different rates of air supply to the bubbler at a temperature of 70°C

1 – kinetic curve of saturation at an air rate of 8 m/s;
2 – kinetic curve of saturation at an air rate of 6.6 m/s;
3 – kinetic curve of saturation at an air rate of 4 m/s;
4 – kinetic curve of saturation at an air rate of 1.5 m/s.

Diffusion of sucrose molecules into zucchini fruits occurs more intensively in the external diffusion region. For example, at an air rate of 1.5 m/s (curve 4, Fig. 3), the saturation time in the external diffusion region is 1560 s, and at the rate of 8 m/s (curve 1, Fig. 3), the saturation time is 1200 s, i.e., saturation is more intense by 1.3 times. The internal diffusion region lasts 840 s at an air rate of 1.5 m/s (curve 4, Fig. 3) and 600 s at an air supply rate of 8 m/s (curve 1, Fig. 3). It means that an increase in the rate of air supply for bubbling contributes to the decrease in saturation time in both diffusion regions.

The fact that the mass transfer resistance is usually concentrated in the external boundary layer contributes to the reduction of the saturation time in the internal diffusion region. Therefore, the hydrodynamics around the particle is of great importance. It is known [13] that mass transfer around a particle occurs both by molecular diffusion (the process depends on the medium nature) and by mass transfer (the process depends on the thickness of the boundary layer around the particle). The decrease in the thickness of the boundary layer and the reduction of the saturation time will be facilitated by the increase in the rate of air supply, which is confirmed by the experimental results (Fig. 3).

The kinetics of diffusion processes is described by Fick's law [14]:

$$\frac{\partial c}{\partial \tau}+\omega_x\frac{\partial c}{\partial x}+\omega_y\frac{\partial c}{\partial y}+\omega_z\frac{\partial c}{\partial z}=D\cdot\left(\frac{\partial^2 c}{\partial x^2}+\frac{\partial^2 c}{\partial y^2}+\frac{\partial^2 c}{\partial z^2}\right) \quad (5)$$

In the differential Eq. (5) of mass transfer in a moving medium, the concentration of the diffusing substance (c) is variable in time (τ), and depends on the medium rate (ω) and medium properties, in particular, on the molecular diffusion coefficient (D).

To generalize the results regarding the saturation process of zucchini fruit particles with sucrose, the authors transform the differential Eq. (5) using the methods of the similarity theory.

Let us consider the external diffusive region of saturation and the processes occurring at the phase interface, i.e., in the external boundary layer around the particle.

Mass transfer and molecular diffusion processes occur simultaneously at the phase interface [15]:

$$\beta\cdot\left(c-c_{\lim}\right)=-\mathrm{D}\cdot\frac{\mathrm{dc}}{\mathrm{dn}} \quad (6)$$

The mass transfer coefficient is calculated according to Eq. (7) [15]:

$$\beta=\frac{V_{sug}}{F\cdot\left(c-c_{\lim}\right)} \quad (7)$$

where c is the current sucrose concentration in zucchini fruit, kg/kg;

$c_{\lim}$ is the sucrose concentration in the zucchini fruit, which is reached at the time of fruit saturation in the external diffusion region, kg/kg;

V_{sug} is the volume of dissolved sucrose absorbed by the zucchini fruit during the saturation time in the external diffusion region, m^3/c;

F is the external surface of a zucchini fruit particle, m^2.

According to the similarity theory [15], the Sherwood criterion is derived from Eq. (6) specifically for the saturation process of zucchini fruits particles with sucrose:

$$Sh=\frac{\beta\cdot d_e}{D} \quad (8)$$

where

β is the mass transfer coefficient from the medium of sugar syrup to the phase interface "syrup - zucchini fruit particle", m/s;

de is the equivalent diameter of a zucchini fruit particle (de = 4F/P), m;

F is the area of the external surface of the particle, m^2;

P is the wettable perimeter of the particle surface, m;

D is the molecular diffusion coefficient of sucrose molecules in water, m^2/s.

Equation (8) includes the mass transfer coefficient β, which is an averaged value for an entire external particle of a parallelepiped-shaped zucchini fruit. In the process of saturation in the apparatus shown in Fig. 1, there are many variables that will affect the mass transfer coefficient β: the shape and size of the apparatus, the physical and chemical properties of sugar syrup, and the hydrodynamics of the process that takes place under the conditions of air bubbling.

It is known from the similarity theory that compliance with hydrodynamic and geometric similarity is a necessary factor for the generalization of mass transfer processes. That is why the Sherwood criterion will depend on the Reynolds criterion ($Re = \omega\cdot de\cdot\rho/\mu$), the Schmidt criterion ($Sc = \mu/(\rho\cdot D)$) and the geometric simplex (H/d),

where ρ, μ are the density and viscosity of sugar syrup, respectively, under the experimental conditions; H is the height of the syrup level in the apparatus (Fig. 1); d is the diameter of the apparatus (Fig. 1).

The results obtained at the experimental setup (Fig. 1) show that the geometric simplex within the range of $0.25 < H/d < 0.75$ has no effect on the process of zucchini fruits saturation with sucrose under the conditions of air supply for bubbling (experimentally proved and theoretically confirmed below).

Since the Schmidt criterion (Sc) for the saturation processes shown in Fig. 3, is constant, for generalization we introduce the Péclet diffusion criterion ($Pe_d=Re\cdot Sc$).

The results of experimental studies, which are shown in Fig. 3, are summarized in Fig. 4, where the criterion dependence $Sh=f(Pe_d)$ is given.

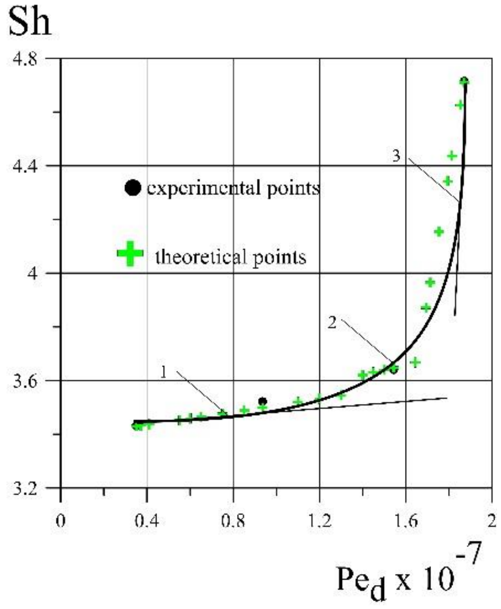

Fig. 4. Generalization of the saturation process of the zucchini fruit particles with sucrose at a temperature of 70°C with a change in the air supply rate.

1 – laminar mode; 2 – transition mode; 3 – turbulent mode

As can be seen from Fig. 4, the generalizing curve can be described by three modes. The first mode is the laminar one (section 1) under the conditions of slight flow turbulence. At values of $Re < 5500$ and $Pe_d <$

$1.1\cdot10^7$, the section of the curve (Fig. 4) is well described by the ratio:

$$Sh = 1.68\cdot10^{-9}\cdot Pe^{1.18}\cdot\left(\frac{H}{d}\right)+3.4 \qquad (9)$$

As can be seen from the curve (Fig. 4) and from Eq. (9), the increase in flow turbulence under laminar conditions has a slight effect on the mass transfer coefficient, resulting in an increase in saturation time.

The second regime is the transitional one (section 2) under the conditions of increased flow turbulence. At values of $5500 < Re < 10000$ and $1.1\cdot10^7 < Pe_d < 1.75\cdot10^7$, the section of the curve (Fig. 4) is well described by the ratio:

$$Sh = 1.68\cdot10^{-9}\cdot Pe^{1.2}\cdot\left(\frac{H}{d}\right)+3.4 \qquad (10)$$

As can be seen from the curve (Fig. 4) and Eq. (10), under the conditions of the transition regime, the effect of the increase in flow turbulence on the mass transfer coefficient is initially insignificant, and then rapidly increases. The rapid growth begins at an air supply rate of approximately 6 m/s. Thus, it is advisable to carry out saturation at the rates of air supply, at which the mass transfer coefficient rapidly increases.

The third mode is the turbulent one (section 3) under conditions of maximum flow turbulence. At values of $Re > 10000$ and $Pe_d > 1.75\cdot10^7$, the section of the curve (Fig. 4) is well described by the ratio:

$$Sh = 32.82\cdot10^{-8}\cdot Pe^{1.08}\cdot\left(\frac{H}{d}\right)-3.5 \qquad (11)$$

As can be seen from the curve (Fig. 4) and from Eq. (11), under the conditions of the turbulent regime, the effect of the mass transfer coefficient increases rapidly, even with a slight increase in rate. It is advisable to carry out saturation in the turbulent mode as well. However, at the rate of air supply $\omega \geq 8$ m/s, a significant droplet removal of syrup from the saturation zone is observed (Fig. 1), which can lead to excessive energy consumption and deterioration of the quality of the finished product.

The generalized criterion Eq. (9-11) derived by the authors make it possible to calculate the mass transfer coefficient of the saturation process of zucchini fruit particles with sucrose in dynamic mode within the range of air supply rates from 1.5 to 8 m/s.

Based on the experimental results and generalized Eq. (9–11), it can be concluded that from a technological and economic point of view, the most expedient is the process of zucchini fruit particles saturation with sucrose under the conditions of a syrup temperature of 70°C and a rate of air supply for bubbling from 6 to 8 m/s.

To theoretically calculate a more accurate rate and corresponding air pressure for bubbling, the experimental data were generalized based on the theory of hydrodynamic similarity [16]. This theory is used to derive the criterion equations by transforming the Navier-Stokes differential equation of motion [17,18]. In the criterion form, the equation for describing hydrodynamics is as follows:

$$Eu = A\cdot \mathrm{Re}^{n}\cdot\left(\frac{H}{d}\right)^{m} \qquad (12)$$

Eq. (12) shows that the Euler criterion is a function of the Reynolds criterion and the geometric simplex. The dependence of the Euler number on the Reynolds number for different heights of the syrup level in the apparatus (Fig. 1) is shown in Fig. 5. It is obvious that all experimental points can be generalized by a single power function.

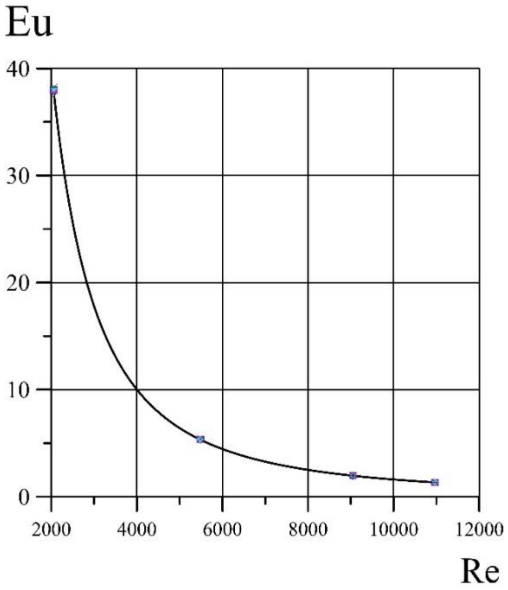

Fig. 5. Dependence of the Euler criterion on the Reynolds criterion for geometric simplexes (H/d): 0.25; 0.35; 0.5; 0.6; 0.75.

The experimental results shown in Fig. 5 prove that the geometric simplex within the $0.25 < H/d < 0.75$ limits has no effect on the hydrodynamics of zucchini fruits saturation with sucrose under the conditions of air supply for bubbling. Generalization of the experimental data allows us to obtain eq. (13).

$$Eu = 1.6\cdot10^{8}\cdot \mathrm{Re}^{-2} \qquad (13)$$

The maximum error between the experimental data and the calculated values according to eq. (13) does not exceed 0.5%. Eq. (13) makes it possible to calculate the air pressure for bubbling depending on the air supply rate, or to perform the inverse problem. Also, eq. (13) makes it possible to determine the energy costs for the implementation of the bubbling mode within the $0.25 < H/d < 0.75$ geometric simplex.

Conclusion

Fig The kinetic process of changes in sucrose concentration in zucchini fruits was studied in static and dynamic modes of saturation. The specific heat consumption of the studied modes was determined. It is proved that the lowest heat consumption (Σ Q = 1.123

MJ/kg syrup) is for the saturation process conducted under dynamic conditions at a syrup temperature of 70°C.

The kinetic process of changes in the sucrose concentration in zucchini fruits was studied at different rates of air supply for bubbling at a temperature of 70°C. The generalization of the process was carried out using the similarity theory. The existence of three hydrodynamic regimes during fruits saturation in dynamic mode was proved. Criterion Eq. (9 – 11) were derived, which make it possible to theoretically calculate the mass transfer coefficient under the conditions of three hydrodynamic regimes.

From a technological and economic point of view, the most expedient is the process of zucchini fruit particles saturation with sucrose under the conditions of a syrup temperature of 70°C and a rate of air supply from 6 to 8 m/s.

The criterion eq. (13) was derived, which makes it possible to theoretically calculate the air pressure for bubbling and determine the energy costs for the implementation of the bubbling saturation mode.

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ДОСЛІДЖЕННЯ КІНЕТИКИ, ГІДРОДИНАМІКИ ТА МАСООБМІНУ ПРОЦЕСУ НАСИЧЕННЯ ПЛОДІВ КАБАЧКА ЦУКРОЗОЮ З ВОДНОГО РОЗЧИНУ

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Анотація. Процеси дифузії цукрози в середину плодів рослинних речовин та їх узагальнення потребують окремої уваги, а саме: теоретичного узагальнення експериментальних даних, організації енергоощадного процесу виробництва цукатів із збереженням якості готового продукту. В роботі проведені експериментальні та теоретичні дослідження кінетики, гідродинаміки та масообміну процесу насичення плодів кабачка цукрозою з водного розчину. Експериментальні дослідження проведені в двох режимах: статичному та динамічному. При статичному режимі насичення плодів відбувається з водного розчину цукрози в нерухомому стані розчину. Динамічний режим відбувається в умовах барботажу повітрям водного розчину цукрози. Теоретично розраховані питомі теплові затрати досліджуваних режимів насичення плодів кабачка в цукровому сиропі. Детально досліджено кінетичний процес зміни концентрації цукрози в плодах кабачка за різних швидкостей подачі повітря на барботаж. Встановлено, що кінетика процесу відбувається в зовнішньо дифузійній та внутрішньо дифузійній області. На основі закону Фіка проведене узагальнення процесів насичення частинок плодів кабачка цукрозою у зовнішньо дифузійній області з використанням теорії подібності. Доведено існування трьох гідродинамічних режимів під час насичення плодів в динамічному режимі. Виведені критеріальні рівняння, які дають змогу теоретично розрахувати коефіцієнт масовіддачі за умов трьох гідродинамічних режимів. Встановлено, що найбільш доцільним з технологічної та економічної точки зору є процес насичення цукрозою частинок плодів кабачка за умов температури сиропу 70°С та швидкості подачі повітря на барботаж від 6 до 8 м/с. Виведене критеріальне рівняння, яке дає змогу встановити числове значення тиску повітря на барботаж в залежності від швидкості подачі повітря.

Ключові слова: плоди, насичення цукрозою, динамічний режим, статичний режим, теплові затрати, коефіцієнт масовіддачі, критеріальні рівняння.