



THEORETICAL AND EXPERIMENTAL STUDY OF THE PROCESS OF WET CLEANING OF WAX RAW MATERIALS FROM ORGANIC IMPURITIES

N.V. Byshov, I.A. Uspenskiy, D.E. Kashirin, D.N. Byshov, V.V. Pavlov, A.V. Protasov, S.S. Morozov, A.M. Afanasyev, S.N. Gobelev, V.V. Kochenov and A.V. Kupriyanov
Ryazan State Agrotechnological University Named after P.A. Kostychev, Ryazan, Russian Federation
E-Mail: fsd_58@mail.ru

ABSTRACT

The aim of this study is the scientific substantiation of the parameters of the process of wet cleaning of wax raw materials from impurities, bee bread, in particular, and the development of a theoretical model of water dispersion of impurities and verification of the model obtained in the laboratory experiment. The basis for constructing a mathematical model is the idea based on the assumption that a boundary layer exists on the surface of a solid that dissolves in a liquid medium, through which the transfer of particles of the solid phase into the bulk of a liquid takes place. In this case, the rate of mass transfer is directly proportional to the energy expended on the forced mixing of the system under consideration. The model includes three variables: the intensity of mixing, the time of the process and the residual concentration at any time. In the model obtained, the nonlinear effect of the dependence of the residual concentration on the time and intensity of the dispersion process is clearly manifested. It is theoretically established that with an increase in intensity, the time for complete dissolution is significantly reduced. The article presents the description and results of a multi-factor experiment that establishes the effect of mixing intensity, mixing time and particle size distribution of the material under study on the degree of dispersion in water, which is estimated by the percentage of undissolved material from the initial mass, calculated on the dry matter. Comparison of dependences obtained theoretically and experimentally show sufficient convergence of the results. The results obtained can serve as a basis for designing specialized means of mechanization to calculate productivity, energy intensity and other parameters of the cleaning process.

Keywords: wax raw materials, wax, bee bread, cleaning, mixing, dispersing, dissolving.

INTRODUCTION

The production technology of bee wax in beekeeping or factory conditions implies compulsory heat treatment of wax raw materials, which is carried out dry or wet, while the raw material is heated above the melting point of wax [1-4]. The presence of bee bread, propolis and other inclusions in the comb not only pollutes the wax that has been heated, significantly reducing its quality, but also reduces its quantitative yield, as free-flowing wax absorbs impurities and becomes a bound state [5, 6]. All currently known methods of cleaning wax from impurities are based mainly on processing of the finished wax after it is received. This includes, for example, settling the melted wax over the surface of hot water for a long time. Wax bleaching is also used, but bleached wax is non-grade, technical wax [4]. Pressed wax obtained by pressing the boiled secondary wax raw materials - slumgum and waste product, as a rule, is heavily polluted and is also substandard, low-quality wax [4-6]. It is possible to improve the quality and yield of marketable wax by cleaning the wax raw materials before its thermal processing, that is, it is necessary to remove spoiled bee bread and other contaminants from the combs before remelting. In connection with the foregoing, the aim of this study is to substantiate the parameters of wet cleaning of wax raw materials from bee bread [7-15]. At the initial stage of investigations, it is necessary to develop a mathematical apparatus that allows, taking into account the accepted limitations and assumptions, to estimate the time required for dispersion of solid organic pollutants of a

given particle size distribution in water under mechanical agitation in the turbulent mode. The second stage of investigations consists in experimental verification of the developed mathematical model.

The process of dissolution of solids in a liquid medium is accompanied by rather complex phenomena occurring at the interface between the phases [16-19]. The complexity of their analytical description is due to the influence of many latent factors, such as the surface roughness of dissolving particles, the dynamic effect of fluid flow on the surface of dissolution, etc. Probably, all these factors contribute to the so-called submicron decay of dissolving bodies, in which microscopic particles are split off from a solid particle. The bee bread elementary structural component - pollen grains, the size of which can be from a few to several tens of microns are viewed as micro particles that are separated from the bee bread particle.

When studying phenomena occurring during dissolution in the liquid - solid phase system, many researchers have concluded that there is a so-called boundary layer through which mass transfer from the core of the solid phase to the core of the liquid occurs [18-23]. The boundary layer is understood to be a region of flow, which is thin in the transverse direction to the flow, characterized by sharp changes in the flow velocity and concentration of the dissolved solid component [18, 19]. Accordingly, within the boundary layer, a high-speed (or convection) layer and a diffusion (or concentration) layer are distinguished. At high Reynolds numbers, convection



prevails over diffusion, and the thickness of the convection layer is comparable with the thickness of the diffusion layer. For low flow rates, the thickness of the convection layer exceeds the thickness of the diffusion layer, and the role of diffusion in the dissolution process becomes predominant.

The aim of the study is the theoretical and experimental substantiation of the parameters of wet cleaning of wax materials from impurities contained in it, mainly bee bread. To achieve this aim, it is necessary to solve the following research objectives: 1) to develop a theoretical model of water dispersion of impurities of wax materials; 2) to conduct a laboratory experiment that establishes the influence of the factors under study on the optimization criterion; 3) to compare the results of theoretical and experimental investigations.

MATERIALS AND METHODS

Let us formulate the main provisions on which the mathematical model of dispersion should be based (the one-dimensional diffusion model) and describe the process of pollen grains transition from the bound state to the free one.

a) The transfer of pollen grains into the liquid core occurs from the mass transfer surface along the normal to this surface, while the mutual influence of neighboring grains on the transition process is negligible.

b) In the absence of the medium (liquid) movement, pollen grains under the action of gravity or convection sink to the bottom near the particle of bee bread. The pollen is clustered around the particle, not spreading from its borders.

c) Pollen extraction process is described by the following diffusion equation:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}, \quad (1)$$

Where

C is the concentration; D is the diffusion coefficient; t is time; x is the coordinate.

d) The movement of pollen in a liquid is similar to the Brownian motion. In this regard, diffusion coefficient D can be selected based on the Einstein formula [1, 6]:

$$D_A = \frac{k_b \cdot T}{3 \cdot \pi \cdot \eta \cdot d_r}, \quad (2)$$

Where

k_b is Boltzmann constant, J / K; T is water temperature, K; η is dynamic viscosity, Pa · s; d_r is characteristic particle size of the diffusing component, m.

e) If a particle is washed by a fluid flow, in particular, caused by a forced mechanical action, then the neighborhood of the particle is considered as a layer separating the particle from the fluid flow. On the inner

border, the liquid “sticks” to the particle and is stationary relative to it. On the outer boundary, the speed of movement coincides with the speed of the external flow. Thus, the concept of a “boundary layer” is introduced, the thickness of which is determined by the velocity of the external flow around the particle. The value of the thickness of the boundary layer can be estimated, for example, by the following formula:

$$\delta = \sqrt{\frac{\eta \cdot L}{\rho \cdot V}}$$

As it follows from this expression, the layer thickness depends on the geometrical sizes of particles (L), the density of the liquid (ρ) and its viscosity (η), and the most basic is the dependence on the velocity (V) of the incoming flow. An increase in the flow velocity leads to a decrease in the thickness of the boundary layer. All pollen grains on the outer boundary are carried away by an external stream. The smaller the layer thickness is; the more pollen grains are removed.

f) The flow rate is directly related to the energy for mixing the fluid in the vessel. The more power expended in mixing, the greater the speed is, the thinner the boundary layer is, and thus the more intense the dispersion process is.

Before formulating the task, we proceed from concentration C , which is expressed either in mass (kg / m³) or in volume units, to relative (dimensionless) concentration:

$$U = \frac{C - C_1}{C_m - C_1}, \quad (3)$$

Where

C is residual concentration (unknown quantity); C_1 is the concentration of pollen grains in the core of the liquid (given that the mass of the liquid is much greater than the mass of pollen in the solution, we will consider this value constant and equal to zero); C_m is the maximum concentration of pollen grains in a particle of bee bread (saturation concentration).

Such an approach is all the more appropriate, since in this study, it is not the absolute values of the change in concentration that are of interest, but their relative ratios. Then the following boundary value problem for the one-dimensional diffusion model is obtained:

$$\begin{cases} \frac{\partial U}{\partial t} = D \frac{\partial^2 U}{\partial x^2}, & 0 < x < l, \quad t > 0 \\ \frac{\partial U}{\partial x} \Big|_{x=0} = 0, & t > 0, \\ -D \frac{\partial U}{\partial x} \Big|_{x=l} = k U \Big|_{x=l}, & t > 0 \\ U \Big|_{t=0} = U_0(x), & 0 < x < l \end{cases} \quad (4)$$



Where

l is the length over which diffusion is observed, more precisely, where diffusion prevails over convection.

The first line is the differential diffusion equation. Since we are interested in the detachment of pollen grains from the bee bread particle, that is, a sufficiently large distance from it, one spatial variable is enough. The process of dispersion itself (it is irreversible) takes place within the limits of the bee bread particle, or directly on its surface, where there is no influence of the washing fluid movement. The second line is the boundary condition on the left border. This is either the "bottom" of the particle, or the axis of symmetry. In any case, there is no flow of pollen grains in this direction. The third line is the boundary condition on the right border. This is the outer boundary of the dissolved bee bread particle. This is where the liquid contacts the pollen. The last, fourth line in the system (4) is the initial condition that determines the distribution of pollen grains on the surface of the bee bread particle.

Suppose that the unknown solution of boundary value problem (4) is representable as a product of $U(x, t) = X(x) \cdot T(t)$, each factor of which depends only on one variable. Substituting this product in the first equation of the system, one gets:

$$\frac{\partial}{\partial t}(X(x) \cdot T(t)) = D \cdot \frac{\partial^2}{\partial x^2}(X(x) \cdot T(t)) \quad (5)$$

Having performed differentiation and divided into independent variables one can get:

$$\frac{1}{D \cdot T(t)} \cdot \frac{dT(t)}{dt} = \frac{1}{X(x)} \cdot \frac{d^2X(x)}{dx^2} = -\lambda^2 \quad (6)$$

Since each part of this equality depends only on one independent variable, this equality will be fulfilled only in the case when each of the fractions is a constant value. Therefore, the following two equations are obtained (arguments are omitted by tradition)

$$X'' + \lambda^2 X = 0 \quad (7)$$

$$T' + \lambda^2 DT = 0 \quad (8)$$

Having substituted the proposed type of solution in the left boundary condition one gets:

$$T \cdot \left. \frac{dX}{dx} \right|_{x=0} = 0 \quad (9)$$

Since we are only interested in nontrivial solutions, we obtain the solution for the coordinate component:

$$X'(0) = 0 \quad (10)$$

Having performed a similar action with the right boundary condition, one gets:

$$-D \left. \frac{dX}{dx} \right|_{x=l} \cdot T = k \cdot X|_{x=l} \cdot T \quad (11)$$

The need of non-trivial solution leads to another equation:

$$X'(l) + h \cdot X(l) = 0, \quad h = \frac{k}{D} \quad (12)$$

Thus, the problem reduces to successive finding the unknown function $X(x)$ and unknown number λ from the following boundary value problem (the Sturm-Liouville problem):

$$\begin{cases} X'' + \lambda^2 X = 0, & 0 < x < l, \\ X'(0) = 0, \\ X'(l) + h \cdot X(l) = 0 \end{cases} \quad (13)$$

The unknown time function $T(t)$ is found from equation (8):

Let's start solving the formulated problems. Let's start with spatial function $X(x)$. The general solution of the equation looks like:

$$X(x) = A \cdot \cos \lambda x + B \cdot \sin \lambda x \quad (14)$$

Where

A, B are arbitrary constants.

To determine arbitrary constants A and B , we substitute the general solution into the left boundary condition:

$$(A \cdot \cos \lambda x + B \cdot \sin \lambda x)' \Big|_{x=0} = 0$$

or

$$B \cdot \lambda \cdot \cos \lambda 0 = B \cdot \lambda = 0$$

Since we are interested in nontrivial solutions, we should set $B = 0$. The general solution now takes the following form:

$$X(x) = A \cdot \cos \lambda x \quad (15)$$

Having repeated the method with the right boundary condition, one gets:

$$A \cdot (-\lambda) \cdot \sin \lambda l + h \cdot A \cdot \cos \lambda l = 0$$

Now one can't put $A = 0$, because the solution will be trivial. Therefore, the equality should be:

$$\lambda \cdot \sin \lambda l - h \cdot \cos \lambda l = 0, \quad (16)$$



which is the equation for finding magnitude λ .

This (secular or characteristic) equation is transcendental, whose sequence of roots (eigenvalues) is denoted by λ_k . As a result, we obtain a sequence of particular solutions for each eigenvalue λ_k :

$$X_k(x) = \cos \lambda_k x \quad (17)$$

The resulting sequence has the following properties:

- each of its elements is a solution to the Sturm-Liouville problem;
- the elements of the sequence are pairwise orthogonal on the segment $[0, l]$:

$$(X_k, X_m) = \int_0^l \cos \lambda_k x \cdot \cos \lambda_m x \, dx = 0 \quad (18)$$

- the square of the norm of the sequence element is:

$$\|X_k\|^2 = (X_k, X_k) = \int_0^l \cos^2 \lambda_k x \, dx = \frac{l \cdot (\lambda_k^2 + h^2) + h}{2 \cdot (\lambda_k^2 + h^2)} \quad (19)$$

The solution for the time component is obtained from (8) taking into account the found value of parameter λ by simple integration for each value:

$$T_k(t) = e^{-\lambda_k^2 D t} \quad (20)$$

It now remains to multiply the spatial and temporal components:

$$u_k(x, t) = X_k(x) \cdot T_k(t) = \cos \lambda_k x \cdot e^{-\lambda_k^2 D t}. \quad (21)$$

Taking into account that the initial boundary value problem is linear, the general solution of this boundary value problem can be represented as a series:

$$U(x, t) = \sum_{k=1}^{\infty} A_k \cdot e^{-\lambda_k^2 D t} \cdot \cos \lambda_k x \quad (22)$$

Arbitrary constants A_k , ($k = 1, 2, \dots$) are determined by the initial conditions. Substitute the resulting solution $t = 0$ and equate the initial concentration distribution:

$$U(x, 0) = \sum_{k=1}^{\infty} A_k \cdot e^{-\lambda_k^2 D \cdot 0} \cdot \cos \lambda_k x = \sum_{k=1}^{\infty} A_k \cdot \cos \lambda_k x = C_0(x) \quad (23)$$

Considering the left side of the resulting expression as a Fourier series expansion of the initial density, one gets expressions for coefficients:

$$A_k = \frac{1}{\|X_k\|^2} \cdot (C_0, X_k) = \frac{1}{\|X_k\|^2} \cdot \int_0^l C_0(\xi) \cdot \cos \lambda_k \xi \, d\xi \quad (24)$$

Having substituted the obtained expressions into a series, one can get the final concentration value at an arbitrary point and at an arbitrary point in time:

$$U(x, t) = \sum_{k=1}^{\infty} \left(\frac{1}{\|X_k\|^2} \cdot \int_0^l C_0(\xi) \cdot \cos \lambda_k \xi \, d\xi \right) \cdot e^{-\lambda_k^2 D t} \cdot \cos \lambda_k x \quad (25)$$

While it is not interesting to know the concentration value at an arbitrary point, rather it is more important to know the average concentration of the remaining pollen in the bee bread particle as a function of time, that is, to perform averaging over the coordinate. To do this, it is enough to perform integration over a spatial variable:

$$\bar{C}(t) = \int_0^l U(x, t) \, dx = \sum_{k=1}^{\infty} \left(\frac{\sin^2 \lambda_k l}{l \lambda_k^2 \|X_k\|^2} \cdot \int_0^l C_0(\xi) \cdot \cos \lambda_k \xi \, d\xi \right) \cdot e^{-\lambda_k^2 D t} \quad (26)$$

So, the resulting expression for the average concentration is as follows:

$$\bar{C}(t) = \sum_{k=1}^{\infty} B_k \cdot e^{-\lambda_k^2 D t}, \quad (27)$$

Where

$$B_k = \frac{\sin^2 \lambda_k l}{l \lambda_k^2 \|X_k\|^2} \cdot \int_0^l C_0(\xi) \cdot \cos \lambda_k \xi \, d\xi$$

The resulting equation allows us to find the rest of the concentration of pollen grains in a bee bread particle at an arbitrary time. This value should be interpreted as the relative value of the amount (volume or mass) of undissolved bee bread after a certain time of mixing.

To use the obtained model, it is necessary to estimate the thickness of the boundary layer and the mass transfer coefficient.

As noted at the outset, it is possible to control the dispersion process by changing the supplied useful power, that is, the power expended in mixing. Thus, at different values of Re , mass transfer will not be the same. The mass transfer coefficient k , m/s is expressed in terms of the boundary layer in the following form [1]:



$$k = \frac{D}{\delta}, \quad (28)$$

Where

D is the diffusion coefficient, m^2 / s ; δ is the boundary layer thickness, m .

This expression was used by many researchers to calculate the thickness of the diffusion layer δ from the experimentally determined value of the mass transfer coefficient k . Since δ depends significantly on the intensity of mixing, according to some data, its value varies from 5 to 100 μm at various flow rates of the fluid (Axelrud, Brunner and Tollochko).

An analytical evaluation of δ becomes possible, if the Nusselt diffusion criterion is introduced:

$$Nu = \frac{l_n}{\delta}, \quad (29)$$

Where

l_n is characteristic particle size of the dissolved solid component, m .

The definition of Nu , proposed by Axelrud, Planovskiy and Svinarev [1, 8, 9] is used:

$$Nu = A \cdot \sqrt[3]{Pr} \cdot \sqrt{Re}, \quad (30)$$

Where

$$A = 0.8 \dots 0.95.$$

The dimensionless Prandtl number $Pr = \nu/D$.

The most important factor determining the thickness of the diffusion layer is the Reynolds number, since it includes the flow velocity, the magnitude of which we can directly or indirectly control. There are many modifications of this criterion, which traditionally use the speed of the fluid mixing, determined by geometrical parameters of the mixer and the mode of its operation.

In some cases, the appearance of a flow velocity that is variable in time is due to the inertial properties of the particle itself [18]. When moving from one flow to another, differing from the first in the magnitude and direction of velocity, the particle does not immediately acquire the characteristic velocity for the new flow. In addition, each of the streams may have a time-varying velocity vector. Thus, a variable in time velocity of a fluid flow around the surface of a particle is formed, and on the particle surface a velocity and diffusion layer variable in time as well as a variable mass transfer coefficient are formed. Hydrodynamic conditions in the boundary layer have the character of small-scale turbulent pulsations, which are known to be unsteady in hydrodynamic and diffusion relations. In this case, another modification of the Reynolds criterion is usually used, which is determined specifically to describe the mixing of disperse systems. The main parameter here is not the absolute velocity of the

fluid, but local velocity fluctuations along the path, commensurate with the particle size d_r [20, 22, 23]:

$$Re = \frac{d_r^{\frac{4}{3}} \cdot \rho^{\frac{2}{3}}}{\eta} \cdot \left(\frac{N}{V} \right)^{\frac{1}{3}} \quad (31)$$

From this definition of Re the property of self-similarity follows, the independence of the mass transfer coefficient from the geometric parameters of the mixing device, since the value N / V , equal to the intensity of mixing (the specific power per unit volume), takes into account the dimensions of the device.

To test a mathematical model, it is necessary to determine its parameters. Below are the basic numerical parameters of the model (all values are given in SI-system).

Geometrical parameters of the model are as it follows: 1) the characteristic size of the dissolved bee bread particle (initial granulometric composition): $d_r = 6 \cdot 10^{-3}$ (whole bee bread granules) and $2 \cdot 10^{-3}$ m (crushed bee bread); 2) the characteristic pollen grain size $d_r = 2 \cdot 10^{-6}$ m (another value should be explained by the effect of adhesion).

Physical parameters of the model are as it follows: 1) medium temperature $T = 300$ K; 2) density of the solvent (water) $\rho = 1,000$ kg / m^3 ; 3) dynamic viscosity of the solvent (water) $\eta = 1.006 \cdot 10^{-3}$ $Pa \cdot s$.

Calculated values are as it follows: 1) kinematic viscosity of the solvent (water) $\nu = \eta / \rho$, m^2 / s ; 2) diffusion coefficient D , m^2 / s . Having accepted the assumption that the component consisting of pollen grains and diffusing from the mass transfer surface is Brownian particles, we use the Einstein formula (2); 3) the Nusselt number is determined by the expression (30); 4) the Reynolds number is determined by the expression (31); 5) the thickness of the boundary (turbulent) layer is found from (29) taking into account (30); 6) the concentration of pollen particles C . The concentration of the dissolved substance is the ratio of the amount of dissolved substance or its mass to the volume of the solution (mol / l , g / l), that is, the ratio of heterogeneous values. In this paper, the percentage of the mass of undissolved bee bread to its total mass in solution, that is, a dimensionless ratio is considered. For standardization, this value is normalized according to (3).

The next stage of the research is planning and conducting a multiple-factor experiment that establishes the influence of three factors - mixing intensity I (W / m^3), mixing time t (s) and particle size distribution d (mm) - on the degree of dispersion in water, which is estimated by the percentage of the undissolved material from its initial mass in terms of dry matter (optimization criterion is minimized).

The levels and intervals of variation by the factors were determined by conducting preliminary single-factor experiments. The variation levels of factor X1 "mixing intensity" is determined using the previously established empirical dependence given in [24]. There is



also a description of the laboratory setup for studying the processes of dissolution of solids in water and the geometrical parameters of the apparatus with a mixer. It has been established that mixing bee bread in water at a mixer rate speed below 400 rpm contributes to incomplete wetting of the material with water and some of the particles of the small and medium fractions remain on the water surface while mixing. It is also impractical to increase the frequency of rotation of the mixer above 2,000 rpm, since the dissolution efficiency does not increase due to this, and energy costs increase. The specified boundary values of the rotational speed of the mixer correspond to the intensity values of 270 and 18,770 W / m^3 for a mixing device with specified geometric parameters [24].

The upper level of variation by factor X2 "mixing time", according to preliminary studies, is limited to 10 minutes.

Experimental material was prepared in the following way. Extracted from the combs by means of mechanized technology [25-27] bee bread with a relative humidity of 14-15 % was kept in the freezer for 3 ... 4 hours and then crushed in a pin grinder. The ground mass was fractionated using a sieve machine having three sieves with holes of 1 mm, 3 mm and 4.5 mm in diameter. Thus, three fractions of bee bread were obtained with an average particle size of 5.75 mm (whole granules), 3.75 mm (from an average sieve) and 1.75 mm (from the bottom sieve). These values correspond to three levels of variation by factor X3 "initial particle size distribution". Before the start of the experiment, the fractionated material was sealed in polypropylene bags and stored at room temperature.

The levels and intervals of variation of the three factors studied are presented in Table-1.

Table-1. Factors and levels of their variation.

Factor	Indication	Unit	Level of variation			Interval
			low (-1)	zero (0)	upper (+1)	
Mixing intensity	X1	W / m^3	270	9520	18770	9250
Mixing time	X2	s	60	330	600	270
Particle size distribution	X3	mm	1.75	3.75	5.75	2

The experiment was carried out at a temperature of +20 ... + 23 ° C. Based on previous studies [8, 10], it was established that at a lower temperature, the dissolution process slows down significantly, and temperatures close to 30 ° C and higher are not of interest within the research topic, as they approach a critical level at which the wax raw material softens and cleaning becomes impossible.

The experiment was carried out as follows. Bags with bee bread of various granulometric composition were unpacked immediately before the experiment and weight samples of 20 ± 2 g were formed, which were immersed in the working chamber of a mixing device, filled with water. Then the electric motor was turned on and with the help of laboratory transformer the required frequency of rotation of the shaft was set. After the time set in accordance with the plan of the experiment, mixing was stopped, and the contents of the tank was filtered on a sieve with a cell size of 0.5×0.5 mm. The residual particles of bee bread remaining on the sieve were washed with cold water into a separate container, from which the water mixture was subjected to vacuum filtration in accordance with the procedure described in [8, 10].

The percentage of undissolved bee bread (optimization criterion) C (%) was determined by the following formula:

$$C = \frac{M_o}{M_{II}} \cdot \left(1 - \frac{W}{100}\right)^{-1} \cdot 100, \quad (32)$$

Where

M_o is the mass of undissolved sediment after drying, g; M_{II} is the weight sample of bee bread, g; W is the relative humidity of bee bread, %; $(1 - W/100)$ is dry matter conversion.

Experiments were performed with triplicate at each point of the plan of the experiment.

RESULTS AND DISCUSSIONS

Below are the main results of numerical simulation using the constructed model? All calculations are made using the mathematical package Matcad 14.0. The model includes three variables: the intensity of mixing, the time of the process and the residual concentration at an arbitrary point in time. The choice of two arbitrary quantities as independent ones will make it possible to determine the dependent third quantity.

Figures 1-2 show the dependence of the residual concentration on the intensity of mixing and the time of the dispersion process, obtained when using the constructed theoretical model.

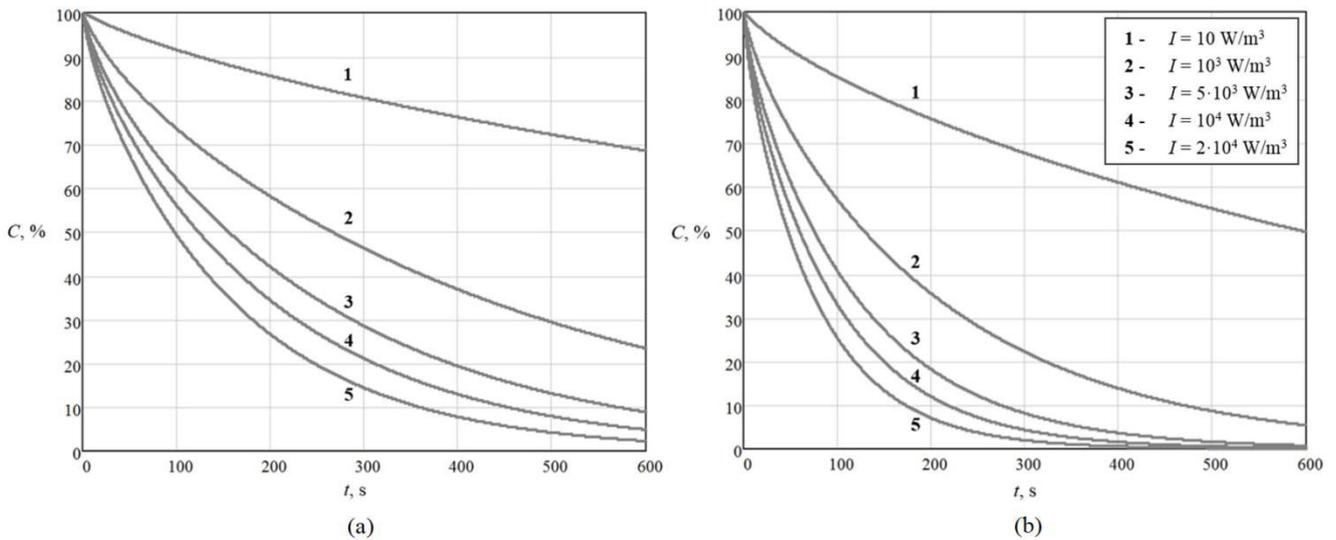


Figure-1. The results of numerical simulation of the dependence of the percentage of undissolved bee bread C , % on mixing time t , s for various values of mixing intensity I , W / m^3 and different values of initial particle size distribution d_r , mm: a) with $d_r = 6$ mm (whole granules of bee bread); b) with $d_r = 2$ mm (crushed bee bread).

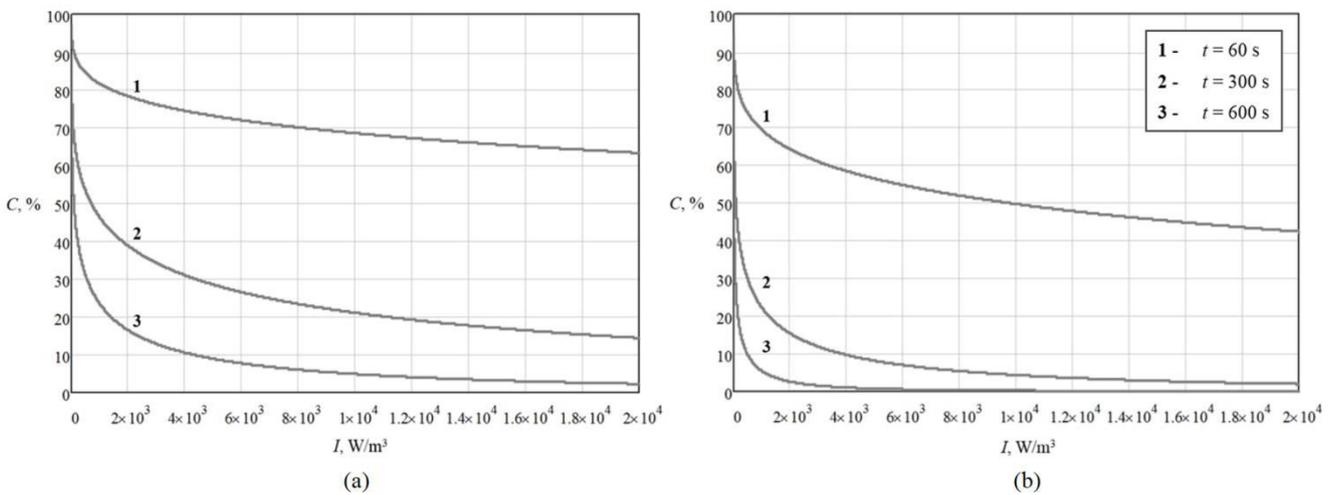


Figure-2. The results of numerical simulation of the dependence of the percentage of undissolved bee bread C , % on mixing intensity I , W / m^3 for various values of mixing time t , s and different values of initial particle size distribution d_r , mm: a) with $d_r = 6$ mm (whole granules of bee bread); b) with $d_r = 2$ mm (crushed bee bread)

The simulation was carried out with the initial particle size distribution $d_r = 6 \cdot 10^{-3}$ m. As noted above, the desired value, that is, the residual concentration should be interpreted as the relative value of the amount (volume or mass) of undissolved bee bread at an arbitrary mixing time.

Figure-1 shows the graphs of residual concentration dependence on the mixing time at various intensity values and different initial particle size distribution of the dissolved component (bee bread). Figure-2 shows the dependences of the relative amount of undissolved bee bread on the mixing intensity at various fixed values of the process time and different initial particle size distribution of bee bread.

The following are the results of processing a multifactor experiment to determine the effect of mixing

intensity I (W / m^3), mixing time t (s) and the initial particle size distribution d (mm) on the optimization criterion, which is the percentage of undissolved sediment C (%) from initial mass of the material in terms of dry matter. As a result of statistical processing of experimental data, a regression equation is obtained:

$$C(I, t, d) = 3.05 \cdot e^{0.58 \cdot d - 2 \cdot 10^{-7} \cdot I \cdot t + 7.59 \cdot 10^{-7} \cdot I \cdot d - 4.49 \cdot 10^{-4} \cdot t \cdot d} \quad (33)$$

All studied factors were significant at $\alpha = 0.1$. The linear coefficients for factors I and t , as well as quadratic effects I^2 , t^2 and d^2 turned out to be statistically insignificant. Thus, an exponential model is obtained that adequately approximates the experimental results at significance level $\alpha = 0.05$.



Optimization of the regression model (33) yielded the following results:

$$C_{\min}(I, t, d) = C(18,770; 600; 1.75) = 0.58 \%$$

$$C(I, t, 6) = 99 \cdot e^{45.54 \cdot 10^{-7} \cdot I - 26.94 \cdot 10^{-4} \cdot t - 2 \cdot 10^{-7} \cdot I \cdot t}$$

Figures 3-4 show the graphical dependencies built upon fixing one of the three factors.

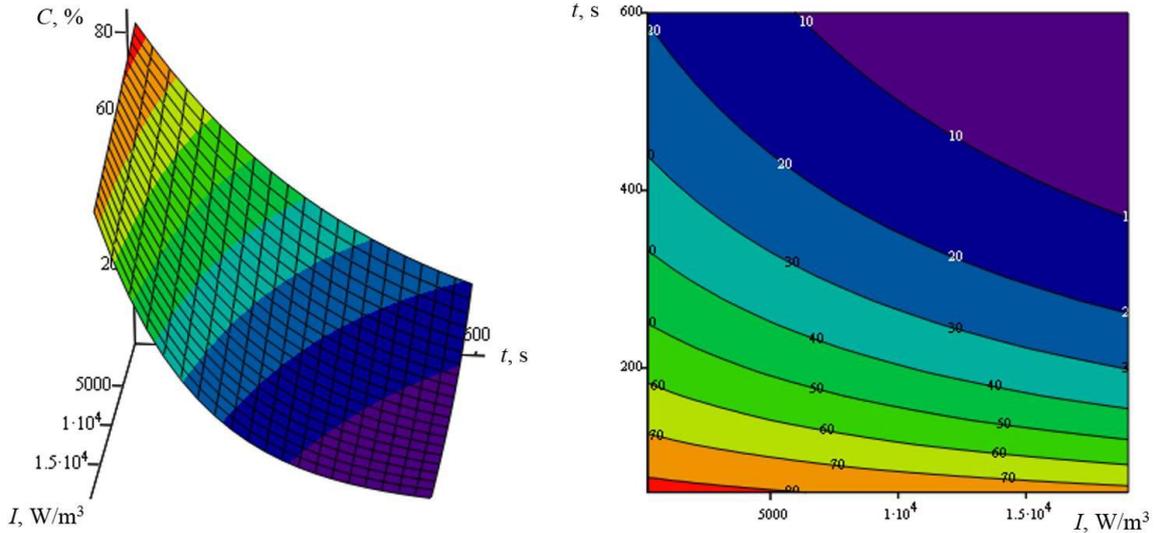


Figure-3. The dependence of the percentage of undissolved sediment on the intensity and time of mixing with the value of the initial particle size distribution of the dissolved bee bread $d = 6$ mm (whole granules).

$$C(10^4, t, d) = 3.05 \cdot e^{0.58 \cdot d - 2 \cdot 10^{-3} \cdot t + 7.59 \cdot 10^{-3} \cdot d - 4.49 \cdot 10^{-4} \cdot t \cdot d}$$

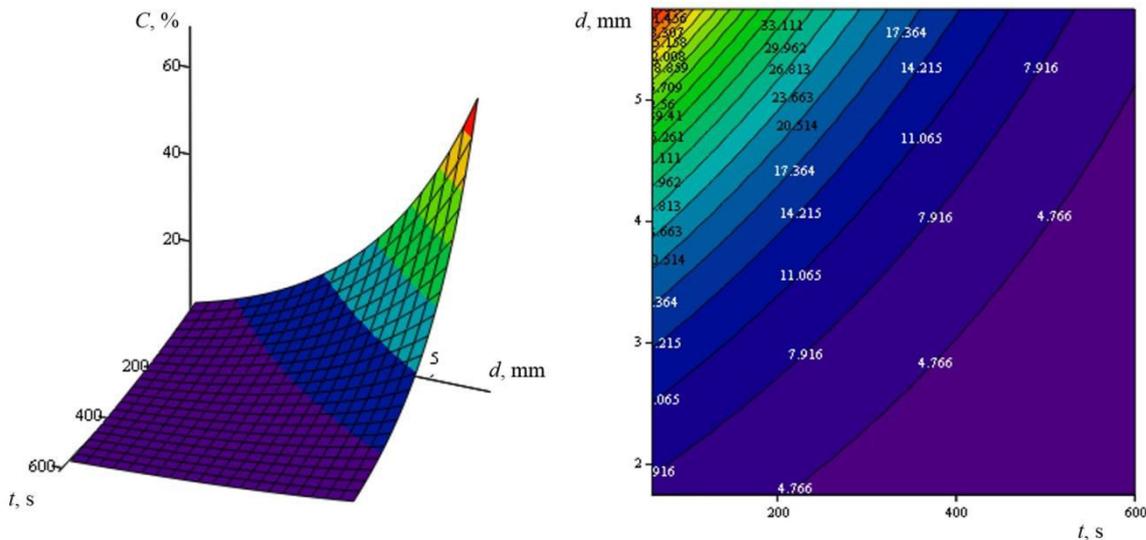


Figure-4. The dependence of the percentage of undissolved sediment on the time of mixing and the initial particle size distribution of the dissolved bee bread at mixing intensity $I = 10,000$ W / m³.

Figure-5 shows the result of a comparison of dependences of the relative content of the undissolved precipitate on the time and intensity of mixing, obtained as a result of numerical simulation and experiment (two

factors out of three are fixed). The calculation is made for the bee bread fraction, consisting of whole granules ($d = 6$ mm).

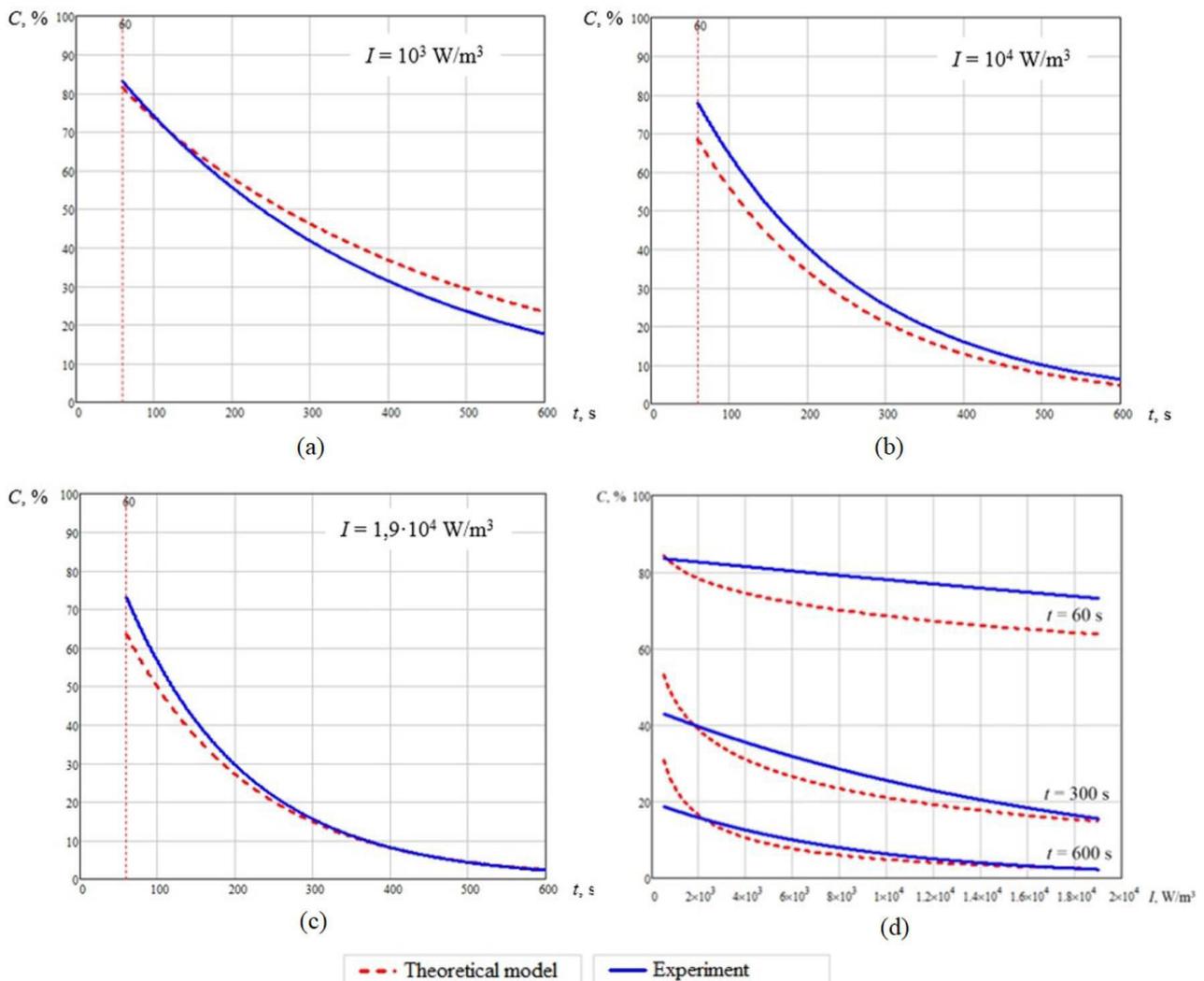


Figure-5. Comparison of the results of theoretical and experimental studies of the effect of the mixing process on the relative residual concentration of dissolved bee bread for three different values of the intensity of mixing (a, b, c) and the effect of the intensity of mixing on the relative residual concentration for three different values of the mixing time (d).

From the analysis of the graphs presented in Figures 1-2, it follows that the nonlinear effect of the dependence of the residual concentration on the time and intensity of the dispersion process is clearly manifested in the theoretical model obtained. The increase in intensity significantly reduces the time for complete dissolution, with the highest rate of increase in mass transfer observed when the intensity changes from 0 to $2,000 W / m^3$, then the growth slows down (Figure-2). At the same time, an increase in the intensity of more than $15,000 W / m^3$ does not have any significant effect on the speed of the process. The initial granulometric composition has a significant effect on the time of the complete dissolution of bee bread. So, at a mixing intensity value of $I = 10,000 W / m^3$ the weight sample consisting of particles with an average size of 2 mm completely dissolves after 6-8 minutes, whereas complete dissolution of large fractions takes more than 10 minutes.

The results obtained during the laboratory experiment, in general, confirm the data of theoretical modeling. With the optimal combination of the factors studied, the optimization criterion - the percentage of sediment consisting of particles not dissolved when mixing - reaches a minimum value of 0.58 %. As expected, the optimum is on the border of the factor space, which corresponds to the physical essence of the process under study. The percentage of undissolved sediment tends to the minimum value when increasing intensity of mixing from the lower level to the upper level, as well as increasing the mixing time to 7-7.5 minutes, after which (at optimal values of other factors), the bee bread completely decomposes to individual pollen grains, and water-insoluble components remain in the sediment - wax flakes, fragments of cocoons and organic shells (Figures 3-4). A decrease in the initial average size of the dissolved particles also contributes to the intensification of the dissolution process (Figure-4). The optimization criterion



naturally decreases with the change in the size of the fraction from the whole bee bread granules to the fraction of 1.75 mm.

The discrepancy between the theoretical and experimental curves does not exceed 5 % on average, which indicates that the developed theoretical model is sufficiently consistent with the results obtained during the laboratory experiment (Figure-5).

CONCLUSIONS

A mathematical model describing the process of dispersing solid organic impurities of wax raw materials in water has been obtained. This model is a one-dimensional diffusion model that includes three variables: mixing intensity, mixing time, and residual concentration of contaminants at an arbitrary time. In the model obtained, the nonlinear effect of the dependence of the residual concentration on the time and intensity of the dispersion process is clearly manifested. It is theoretically established that increasing the intensity significantly reduces the time for complete dissolution. In accordance with the accepted model with the given initial parameters, the highest rate of increase in mass transfer is observed when the intensity changes from 0 to $2,000 \text{ W / m}^3$, then the growth slows down. One should not increase the intensity of more than $15,000 \text{ W / m}^3$, since this excess does not affect the speed of the process. At the time of complete dissolution of the dispersed component (bee bread) a significant effect is made by the initial particle size distribution. So, at a mixing intensity value of $I = 10,000 \text{ W / m}^3$ the weight sample, consisting of particles with an average size of 2 mm completely dissolves after 6-8 minutes, whereas complete dissolution of large fractions takes more than 10 minutes.

The results of the laboratory study showed that all the factors involved in the experiment (intensity, mixing time and initial particle size distribution of the material) significantly affect the process under study. The process studied is adequately described by an exponential model. The optimization criterion is the percentage of undissolved sediment which takes a minimum value of 0.58 % at the boundary of the factor space under investigation, with corresponding values of the factors $1.9 \cdot 10^4 \text{ W / m}^3$, 600 s and 1.75 mm.

Comparison of dependences of the relative content of undissolved sediment on the mixing intensity and time, obtained experimentally and by means of numerical modeling, has showed good convergence, which indicates that the developed theoretical model complies with the results obtained during the laboratory experiment.

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