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FORMATION OF HEAT AND MASS TRANSFER BONDS WHEN MIXING COMPONENTS IN A SUSPENDED STATE

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ABSTRACT

The method of preparation of wheat paste based on discrete and impulse influence on components is revealed. The basis of the research of the vapors preparation method is the formation of a liquid mixture of interacting dosing components in a suspended state. The interaction occurs due to the humidification of the pulverulent suspended state of the layer of flour particles by a scattered jet of liquid under pressure. The development of this technological process and equipment is considered. A thorough analysis of the mixing of components in a suspended state. The influence of a set of experimental and theoretical researches is noted, where the results of the theoretical direction are aimed at the creation of mathematical models, simulation of the process with the use of the possibility of computer engineering. The characteristics of thermal processes for the transition region from the surface of the flour to the massive formed medium are given, taking into account the effective thermophysical characteristics of the medium in the form of dependences obtained theoretically and experimentally. Dependencies are taken into account as well as heat and mass transfer processes when the liquid phase interacts with flour: external heat and mass transfer processes when interacting in a suspended state on the flour surface and change of working environment with the formation of bonds, and internal mass transfer processes when moving moisture and heat inside the flour particle.

Keywords*:* mathematical model; mixing; suspended state; steam; heat and mass transfer

INTRODUCTION

The process of mixing the components is used in the food industry for the formation of homogeneous viscous media during the intensification of the technological process. Mixing of components is carried out in mixers in different ways using different designs of working chambers and working bodies in gas and liquid streams. The mixing mechanism in the mathematical description is represented in the form of dependences on the nature of the hydrodynamic motion of the particles of the components and the factors that cause the deformation movement. Under such conditions, the characteristics which cause a change of position of particles of components or their mix in space with the use of probable physical and chemical parameters are revealed.

The uniformity of the interaction of the components during mixing is estimated by the standard deviation of the concentrations of the components for all elementary volumes of the working chamber, i.e. the mixing index, the intensity of the process. Uniform intensive of components mixing is to obtain a homogeneous mixture affects the quantitative indicators of technological processes of production. Achieving equilibrium during mixing depends on the relative balance between the structural elements of the machine and the interaction of components.

Currently, the mixing of components is provided not only with practical knowledge and extensive experience of specialists but also with theoretical knowledge necessary for detailed study and modeling of the processes that occur during their interaction. Numerical simulation is particularly convenient when describing the processes of gravitational and bulk mixing when it occurs most actively in a thin layer of material in which there is a random transition of the particles of the components in the adjacent layer. An example of such a device is a mixer, the working cylindrical surface of which rotates together with the blades installed inside the working chamber. In this case, the main volume of the mixture filling the lower part of the chamber moves synchronously with the working surface without mixing, and only in the upper layer of material, rolled at an angle down the surface of the layer, there is a chaotic movement and redistribution of particles of different fractions. Among the two-phase methods of making wheat dough, liquid and thick pastes are most often used as the first phase. Schemes with liquid vapors due to several inherent shortcomings **(Hasatani et al., 1993; Dolomakin, 2015)** are not widely used in the baking industry of Ukraine. The main reason is that the units for the preparation of liquid mash are quite conservative, and high-quality using the energy of compressed air and water under pressure **(Lisovenko, 2000)**, unbearable for bakery enterprises in Ukraine.

Sponge dough is a complex hydrophilic colloidal system **(Lisovenko**, **1982; Quail, 2019)**, the state of which depends on the properties of the raw material used for its preparation, design, and technological parameters of the process, changes that occur during the formation of the environment. The state of influence of the liquid phase on the flour is not only theoretical but also practical. Therefore, in our opinion, there is a need to develop similar domestic designs and justify rational modes of their work.

The basis of this development of the method of preparation of sponge dough **(Pat. No 134226, newsletter No 9, 2019; Pat. No 137278, newsletter No 19, 2019)** is the formation of a liquid mixture of interacting dosing components in a suspended state. The interaction occurs due to the humidification of the pulverulent suspended state of the layer of flour particles by a scattered jet of liquid under pressure **(Stadnyk et al., 2019)**.

The offered study presents for the first time the results of process modeling of the interaction of components in the suspended state, characteristic of the transition region of heat and mass transfer.

Analysis of model approximations of medium types

Theoretical dependences and general provisions of the process of mixing and interaction of components with working bodies are given in the works of **Lisovenko (1982)**, **Stadnyk (2015)**, **Dolomakin (2015)**, and others. The mixing process has been covered in studies on the development of the technological scheme **(Danyliuk et al., 2017; Stadnyk, 2015; Kafarov, 1949)** the parameters of mixers **(Stadnyk et al., 2019; Krivoruchko, 2018)**, process modes **(Barabash et al., 2007)** and thermodynamic processes during mixing **(Kornienko, 2011)**. It is also offered to use different rotors for the production of water-flour mixture with the calculation of their technological and design characteristics. Heat engineering calculations and heat transfer processes, in general, are covered quite fully **(Kharlashinet, Beckett and Bendich, 2012; Stadnyk, 2015)** but there are no special works devoted to thermal processes when mixing steam by a new method in a suspended state.

The analysis of research on the development of technology for cooking stew allowed to establish the following:

- insufficiently studied issues of mass heat transfer;
- the use of the suspended state is constrained by the difference in the design of the mixer and the parameters of the technological process concerning the properties of the components;
- there is no thermodynamic model of the interaction of components in the formation of the environment.

The result of active mixing of the prescription components with the formation of the medium in a suspended state is due to the energy dissipation of the input stream. There is no information in the literature on the mutual influences of suspended state flows. Substantiation and improvement of the quality of components interaction in a suspended state are provided by us on the way of new constructive decisions use. This approach requires a review of the dosage of liquid and flour, which simultaneously leads to an increase in the flow of the resulting mixture of components.

It is clear that to increase the degree of mixing of the prepared components, it is necessary to provide an increase in the velocity of the liquid jets at the time of contact with the solid phase. It is obvious that with increasing distance between the nozzle and the line of separation of the jets, the flow rate decreases, which will reduce the degree of mixing.

In our opinion, the main reason why the interaction of the sprayed liquid during its dosing in the working chamber does not have time to reach equilibrium is that of the large droplet size, i.e insufficient degree of liquid dispersion by nozzles. During the stay (dosing) in the chamber, the large droplets do not have time to interact with the flour to equilibrium and, in addition, the falling time of large droplets in the chamber is significantly longer than small ones. This, in turn, leads to the fact that a significant amount of liquid during its dosing in the chamber does not have time to fully ensure the speed of interaction with the flour.

In addition, depending on the flow rate of the liquid, the width of the groove of the vibrating batcher of bulk components, the physical and mechanical properties of the components, can be formed areas in the form of dead zones. The trajectories of large droplets (of the order of 1 mm) are practically independent of the action of gravity due to their high inertia. For all droplets, regardless of the angle of departure, their trajectories are straight lines in the direction of the angle of departure from the nozzle. Due to the short residence time in the chamber, these droplets settle on the wall of the chamber with a noticeable formed medium, and it is the greater the bigger the angle of departure. The interaction of the components at the time of their collision is schematically shown in Figure 1.

These studies establish the fact that is revealed in the work of the author **(Stadnyk et al., 2019)**. The interface of the phases "solid raw material-liquid" depends on the degree of grinding and will be larger the smaller the size of its particles. At the same time **(Quail, 2019)** notes that the difference in concentration in the components is the driving

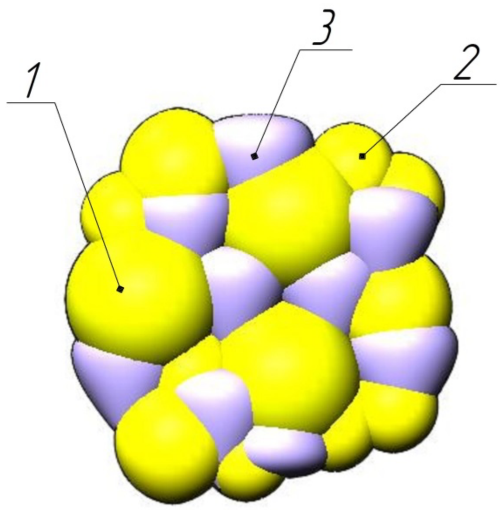

Figure 1 The scheme of formation of the liquid phase-vapor: 1 – flour, 2 – the connection of components in the mixture, 3 – drops of liquid.

force of the mixing process. During mixing, it is necessary to strive for the maximum difference in concentrations, countercurrent process, etc .. Note that for the weighing state of mixing is important to ensure optimal contact time between phases. From the basic equation of mass transfer, it follows **(Aerov and Todes, 1968)** that the amount of the substance diffused through a layer of raw materials is directly proportional to the duration of the process.

The results of the numerical experiment show **(Kharlashin et al., 2012; Stadnyk, 2015)** that small droplets (of the order of 100 μm) have time to interact to an equilibrium state in the upper part of the chamber even before the collision with the wall. This spray ensures that the conditions of the ideal mode in the chamber are met. Large drops (about 1 mm), regardless of the angle of departure, hit the wall of the chamber without interaction with the flour with a noticeable property. Note that the conditions for achieving equilibrium depend on the behavior of the liquid and flour in the chamber. Some of the drops return to the chamber volume after contacting with the flour and without contacting the wall. The rest of the droplets settle on the wall and flow down in a thin pellicle to the bottom of the chamber under the action of gravity. From the central part of the working chamber, the interacting components are fed to the rotating working bodies, ie intensive mechanical mixing. Therefore, the subsequent process of mixing the liquid phase with flour particles and drops of the mixture to equilibrium depends on the thickness and velocity of the film and its heat exchange with the working body and the chamber wall. In our opinion and the authors **(Kornienko, 2011)** increasing the energy efficiency of mixing is possible provided that the definition and establishment of rational parameters of the jet device and technological parameters of the mixing process. This result can be obtained by discrete-pulse dosing of components with the introduction of the design of the ejector nozzle system of the component mixer (jet device). The design of the device is based on the creation of the maximum difference of speeds of phases that allows reducing energy expenses for carrying out dispersion. The degree in the first minutes of binding a small amount of liquid phase of the active hydrophilic groups of flour particles promotes the formation of water shells. The interaction of the liquid phase with hydrophilic groups occurs not only on the surface of flour particles but also in volume. The process proceeds with the release and absorption of heat (exothermic). The amount of retained liquid phase is about 30% does not lead to a large increase in particle volume.

Therefore, the water absorption capacity of flour is affected by its dispersion, ie particle size. As the particle size decreases, the specific surface area per unit mass of flour increases, so more water may be adsorbed. Water absorption by small particles is much faster. Therefore experimental researches of the offered design of the mixer of discrete are impulse influence on uniformity of giving of the sprayed liquid components and weight of the dosing by a router of flour on their interaction in a suspended state are an actual direction of researches.

Scientific hypothesis

The basis of the method of mixing under consideration is the moistening of dust particles of flour, which are in a suspended state, the flow of liquid under pressure, and the conditions of the thermodynamic model of interaction of components aimed at the intensity of heat and mass transfer in the model steam composition.

MATERIAL AND METHODOLOGY

Samples

Experimental and theoretical studies were performed based on research laboratories of the Department of Food Technology Equipment of Ternopil National Technical University. The dough was kneaded according to the recipe of shaped bread **(Drobot, 2010)**. The mixture was prepared from high-quality wheat flour, flour moisture was 13.9 ±0.2%, with a crude gluten content of 24% and a stretch of 14 cm. First-grade wheat flour was produced following **DSTU 46.004-99**. Manufacturer private enterprise "ZAKHID-KHLIB-ZBUT-2002", Ternopil, Ukraine. Yeast pressed bakery classic according to **TU U 10.8-00383320-001**. Manufacturer: Enzyme Company PJSC, Lviv, Ukraine. Granulated sugar – **GOST 21-94** Rivne, Ukraine, Factory of confectionery jewelry "Decoration" – **TU U 10.8-40570177-001 (2016)**.

Chemicals

Water (chemical formula H_2O) was used to mix the components in the preparation of the paste. Water meets the national standard **TU U2.14-0051232-098 (2007)**.

Instruments

The temperature was measured with a thermometer of Ukrainian TLS Figure 2. Devices for research manufacturer "Glassware". It is designed to accurately measure temperature. Dosing of dough components was performed on electronic scales with a measuring range up to 0.1g. Determination of temperature regimes in the process of preparation of the dough used the device Benetech GM533A; to determine the quality of scattering of liquid components and their interaction with flour in a suspended state used a digital camera CANON EOS Wi-Fi 4000D 18-55 DC III (3011C004AA; setting the quality of interaction of the components of the formed mixture was determined using a microscope My First Lab MFL-06 Duo-scope (Fig. 2).

Studies of the mixing process were carried out according to the Box-Benken plan. This is one of the types of statistical plans used in the planning of scientific experiments. This plan allows you to get the maximum amount of objective information about the influence of the studied factors on the mixing process with the least number of experiments.

Box-Benken plans belong to the second-order plans, ie they provide a regression model in the form of a complete quadratic polynomial:

$$Y = b_0 + \sum_{i=1}^{k} b_i \cdot x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} \cdot x_i \cdot x_j + \sum_{i=1}^{k} b_{ii} \cdot x_i^2 ,$$

Where:

Y – target function; b_i, b_{ij} b_{ii} – calculated coefficients of the model; k – factor number.

Based on the constructed regression equation, the contribution of each independent variable to the variation of the studied dependent variable is determined, ie the influence of factors on the performance indicator.

The experimental data set was processed using the Statistica-12 software package for the computer. The coefficients of the regression or approximating function equation, under the condition of orthogonality and symmetry of the plan-matrix of the planned factorial experiment, were determined according to the standard method according to known dependences.

The obtained results were statistically processed using the standard Microsoft Office software package.

Laboratory Methods

Sampling was performed according to DSTU 4803:2013, Organoleptic evaluation "Descriptive (qualitative) method of profile analysis" GOST 5897-90. The quality of flour was determined according to GOST 9404-60 **(Drobot, 2010; Lisovska et al., 2020)**. Determination of the "strength" of the flour was performed by the vagueness of the dough ball **(Drobot, 2010)**. The moisture content of flour and semi-finished products was determined using an HF device according to GOST 21094-75 **(Lisovska et al., 2020)**.

Method for determining the amount of raw materials

The required amount of raw material was dosed by weight. The amount of water introduced during mixing Gv (in mL) was determined by the formula:

The Benetech GM533A device with a range of measurements to 0.1 °C.

The digital camera CANON EOS Wi-Fi 4000D 18-55 DC III (3011C004AA) specular/CMOS (KMOH)/depends on the lens/Wi-Fi/FullHD (1920x1080) Pix/HD (1280 x 720) Pix/VGA (640x480) Pix. Microphone – built-in (stereo)

The My First Lab MFL-06 Duo-scope training microscope is a biological monocular microscope with a full-fledged optical system with optical glass lenses. Country of origin of the USA.

$$G = G_c(W_0 - W_c)/(100 - W_c)$$

Where:
Gc is the total weight of flour, gr; W_0 is moisture content of pre-ferment, %; Wc is the average weighted moisture content of raw materials, %.

The water temperature (t_0, ^{0}C) of water consumed for mixing the pre-ferment, provided its temperature is 280 °C, was calculated by the formula:

$$t_o = t_n + c_b G_b (t_n - t_b) / c_b G_b + K$$

Where:
To is set temperature, ^{0}C; c_b is heat capacity of flour, kJ.kg^{-1} К, (c_b =1.257); G_b is heat capacity of water, 4.19; t_b is flour temperature, °C; Gm– the amount of water, g; K is correction factor (in summer 0 – 1, spring and autumn – 2, winter – 3).

The ratio of the amount of flour and water for steam of different humidity is summarized in Table 1.

FlowVision software was used to determine the required design parameters and modes of operation and modeling of the corresponding process. FlowVision is based on a finite-volume method for solving hydrodynamic equations and uses a rectangular adaptive mesh with local grinding. To approximate curvilinear geometry with increased accuracy, FlowVision uses technology with a grid resolution of geometry. This technology allows you to import geometry from CAD systems and exchange information with finite element analysis systems.

Morphometric examination and microphotography were performed using a "Konus Biorex-3" microscope with a digital Sigeta UCMOS 5100 with Toup View software adapted for research data.

Description of the Experiment. According to the results obtained during experimental research on a new mixer (Figure 3) in determining the rational values of qualitative indicators of mixing components in a suspended state (homogeneity), the parameters were optimized based on thermodynamic.

The purpose of optimizing experimental studies was to determine the effect of the interaction of components in the suspended state on the process of heat and mass transfer. It should be noted that the technological process of the first stage of preparation of the paste is based on the fact that the accelerated jet of liquid components in the air meets with the sprayed particles of flour in free fall. The interaction time of flour and liquid components in the pre-mixing chamber and before they are in the lower part of the chamber is τ_1 = 5 - 10 s.

We have already mentioned that the interaction of flour with the scattered jet of the liquid phase is mainly a chaotic process, ie their interaction with mixing. Thus, in our case under the action of vibration and stirring in the suspended state, the mixture tries to go into a quasi-equilibrium state. This takes into account the transformations of the forces of internal friction. However, the state of equilibrium is significantly affected by the gravitational forces arising in the process, which determine not only the size and density but also the shape and other parameters of the mixture (Figure 4).

Therefore, to study the temperature field and the homogeneity of the mixture, a layout of thermometers for measuring temperatures in the area of the suspended state of the interaction of the dosing components was developed. Using thermometers T_1, temperature measurements were performed in the coordinates Y = 0.15 m, Z = 0.2 m. T_1 was measured in the range of change X = 0.1 m, and T_2 in the range of change X = 0.1 - 0.3 m. The results are shown in Figure 5. The peculiarity of hydrodynamics is that in the range of values $0 \leq X \leq 0.1$ m there is a movement of components with a constant k = 0.8 (homogeneity). In the zone of axial interaction $0.1 \leq X \leq 0.3$, there is a 3D surface mixing of components at a temperature of 30.2 °C and k = 0.7. And at $0.3 \leq X \leq 0.4$ also became k = 0.8 and creates a downward movement along the wall of the chamber of the formed mixture.

Note that such hydrodynamics of the interaction of components due to the increase in the distribution zone of the liquid phase and flour provided a mechanically symmetrical geometric shape of the temperature zone from 32 to 32.2 °C, at a distance of 0.001 m from the working chamber wall.

Figure 2 Devices for research.

Table 1 Recipe for cooking sponge dough.

Raw material	The amount of raw materials for sponge dough moisture		
	65%	70%	75%
Flour, gr	2400 (40%)	2100 (35%)	1800 (30%)
Water, mg	3600 (60%)	3900 (65%)	3900 (65%)
yeast, gr	100	100	100
Concentration, kg.kg^{-1}	0.666	0.538	0.428

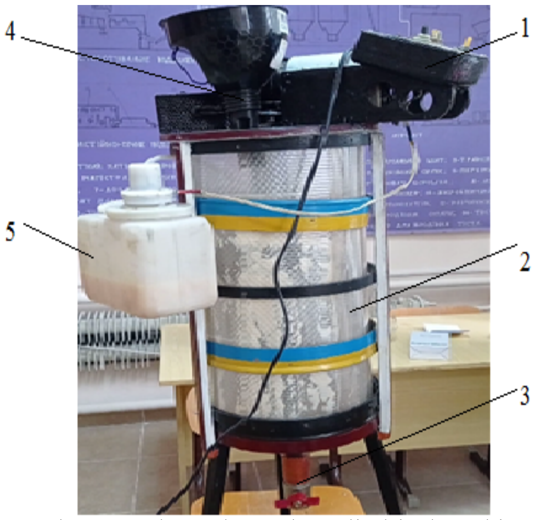

Figure 3 General view of the mixer: 1 – the control panel, 2 – the cylindrical working chamber, 3 – a branch pipe for unloading of a paste, 4 – the flour vibrating batcher, 5 – the batcher of liquid components.

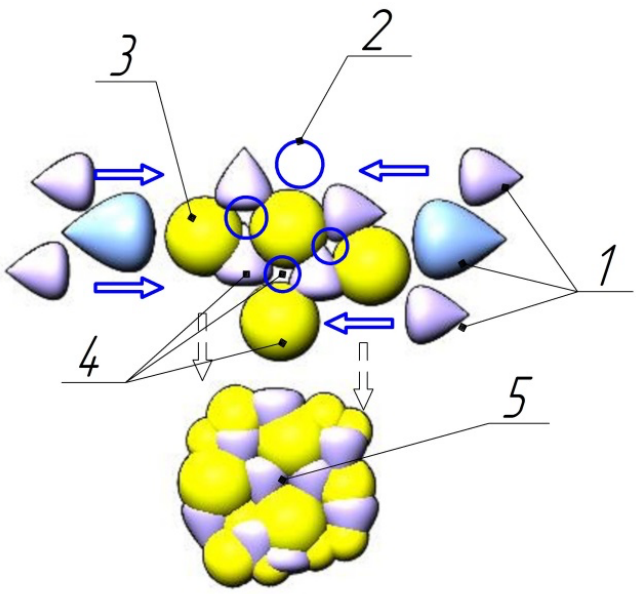

Figure 4 The scheme of interaction of components in the formation of a mixture: 1 – liquid components, 2 – bubbles; 3 – part flour, 4 – mixing components, 5 – mixture.

Number of repeated analyses: All measurements of instrument readings were performed 5 times.
Number of experiment replication: The number of repetitions of each experiment to determine one value was also 5 times.

Statistical analysis

To establish rational regime parameters of the component mixing process in the suspended state, a multifactor experiment was performed to determine the effect of mass flow rate Q, the oscillation amplitude of dosing flour A, height of their interaction h, flour mass m, filling factor K (homogeneity) on the quality of the mixture.

The target function Y is selected homogeneity-k. According to the program of experimental researches, 27 experiments were performed in five repetitions **(Response surface regression (Electronic resource)**.

The asymmetric Box-Benkin plan matrix for four factors and three levels of factor variation with the total number of experiments equal to 27 is given in table 2. The regression equation, which is written as a complete polynomial of the second degree has the form:

$$k(Q,A,h,m)=-1.83-207.94Q-15.01A-10.84h+662.19m+1246.72QA-501.53Qh+6239.84Qm+41.57Ah+409.76Am+18146.45Q^2+4.22A^2+16.53h^2-35053.24m^2$$

With the probability level p = 0.95 and the value of the t-alpha criterion equal to 2.365, the following statistics were obtained (Figure 6): coefficient of multiple determination D = 0.926; multiple correlation coefficient R = 0.962; standard deviation of the estimate s = 0.084; Fisher's F-test is 10.776. The coefficient D is significant with the probability level p = 0.99961.

All factors influencing the homogeneity of the mixture are important from the point of view of the interests of increasing the contact area of the components because the driving factor is the weighted state of interaction.

The importance of factors influencing the passage of the technological process is to create an objective control of the interaction of components. They direct the impact on the economy of material and energy resources. The state of the heterogeneous medium can be imagined in the diagram-illustration of the driving factors influencing the weighted state of mixing (Figure 6).

A graphical representation of the change in the homogeneity of the mixture according to experimental data, ie the response surface of the functional change in the homogeneity of the mixture as a functional:

$F_k = f(Q, h, m, A)$ is shown in Figure 7.

The simulations confirm the validity of the accepted assumptions of the origin and motion of the resulting mixture. The interaction of the phases in the liquid volume is high, there are pulsations of the solid phase in the liquid, which will additionally have a positive effect on the intensity of its dispersion. Therefore, the response surface shows that the factors influencing the homogeneity of the mixture are important for establishing and determining the area of interaction of the components in the weighing state. The interaction of the components in the suspended state quite clearly depends on the number of dosing components. It should be noted that the factors influencing (Q, kg.s^{-1}; A, mm; h, m; m, kg) on a more uniform interaction and increasing the contact area of the components, determined the change in the dosing method. Thus, the liquid components accelerated their interaction by installing two additional nozzles. Thus, without increasing the flow rate, we achieved an increase in the axial average influence of the liquid phase on the influence of mass transfer processes. The effect of the average scattered leakage also increased the area of contact with the flour in the working chamber of the machine. At the same time, a large part of the liquid mixture as a result of the formed inertial influence from the liquid side is in faster contact with the surface of the cylindrical working chamber. The action of gravitational forces contributes to the additional mixing of the formed mixture when it flows to the bottom of the chamber.

RESULTS AND DISCUSSION.

Heat and mass transfer processes are widely used in the technology of preparation of liquid mash in the baking industry. Each process of dissolving flour is accompanied by a positive or negative thermal effect. Therefore, the physicochemical parameters of the medium, such as density, viscosity, thermal, and diffusion parameters, differ significantly from the center of the flow of the liquid phase. According to the data **(Dolomakin, 2016)**, there is a direct contact between the particles of dispersed systems and a connection occurs. The nature of the bond between water and flour refers to coagulation contacts through a layer of liquid. The phase separation between the particles is preserved.

From the above, we can see that the mode of mixing in the suspended state directly affects the heat and mass transfer in the mixture layer. Therefore, the design parameters of the mixer in the working chamber facilitate mixing. The formed homogeneous mode is characterized by the dosing of flour and liquid phase in the scattered state in the chamber space. The flour is on a uniformly distributed plane, ie the concentration of particles is scattered evenly in the volume of the chamber. Figure 8 shows the torch of the liquid spray during its flow from the device into the chamber and the interaction with the flour. You can see the particle size distribution zones of the sprayed liquid (A) and the formed droplets with flour (B).

Figure 8 quite clearly shows the pronounced zones of dense and dilute phases. The boundaries of their separation move gradually, mainly due to the interaction of the scattered liquid phase, which more quickly affects the interaction around the perimeter of the chamber. The formed liquid medium changes along the cross-section of the chamber as follows: in the central part the density changes sharply, near the sidewalls the flour slides with the liquid, closer to the working bodies their interaction decreases to the nature of a fixed layer and loose state. The central part of the chamber has a density of almost constant, the best property, which is explained by the input flows of flour on the axis of the velocity flow of the average liquid.

A detailed description of the formation of the liquid medium and the impact of the equipment is given in the paper **(Stadnyk, 2015)**.

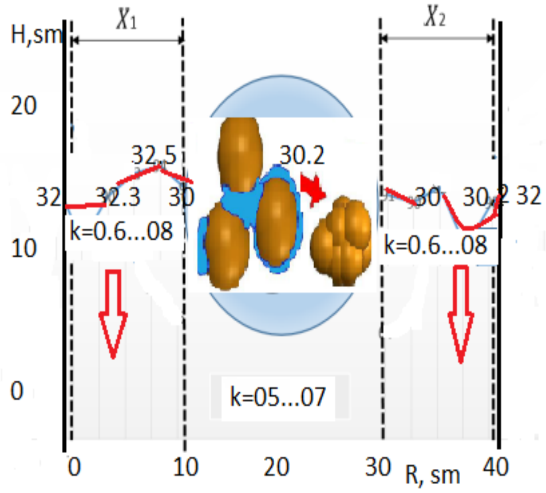

Figure 5 The value of temperatures in the zone of suspended state.

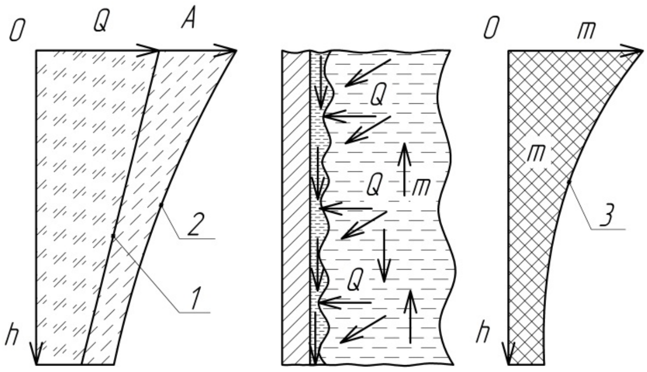

Figure 6 Scheme-illustration of driving factors influencing the weighing state of mixing: 1 – dependence Q = Q (h); 2 – dependence A = A (h); 3 – dependence m = m (h).

Table 2 Asymmetric Box-Benkin plan matrix for four factors and three levels of factor variation.

No	Q.kg.s^{-1}	A.m	h.m	m.kg	к
1	(+) 0.007	(+)0.11	(0) 0.15	(0) 0.011	1.05
2	0.007	(-) 0.05	0.15	0.011	0.9
3	(-) 0.003	0.11	0.15	0.011	0.65
4	0.003	0.05	0.15	0.011	0.8
5	(0) 0.005	(0) 0.08	(+) 0.2	(+) 0.013	1.05
6	0.005	0.08	0.2	(-) 0.009	0.65
7	0.005	0.08	(-) 0.1	0.013	0.55
8	0.005	0.08	0.1	0.009	0.45
9	0.005	0.08	0.15	0.011	0.75
10	0.007	0.08	0.15	0.013	1.0
11	0.007	0.08	0.15	0.009	0.65
12	0.003	0.08	0.15	0.013	0.6
13	0.003	0.08	0.15	0.009	0.35
14	0.005	0.11	0.2	0.011	1.15
15	0.005	0.11	0.1	0.011	0.7
16	0.005	0.05	0.2	0.011	0.7
17	0.005	0.05	0.1	0.011	0.5
18	0.005	0.08	0.15	0.011	0.75
19	0.007	0.08	0.2	0.011	1.05
20	0.007	0.08	0.1	0.011	0.9
21	0.003	0.08	0.2	0.011	0.95
22	0.003	0.08	0.1	0.011	0.6
23	0.005	0.11	0.15	0.013	0.85
24	0.005	0.11	0.15	0.009	0.55
25	0.005	0.05	0.15	0.013	0.65
26	0.005	0.05	0.15	0.009	0.45
27	0.005	0.08	0.15	0.011	0.75

The performed simulations confirm the validity of the accepted assumptions during the theoretical calculation of the origin and motion of the liquid medium and the dissipation of its energy in the working chamber of the machine.

At the same time in the work of the authors **(Dolomakin, et., al., 2017)** the formation of the semi-finished product depends on both the hydration of the flour components and the structural changes that occur as a result of mechanical mixing.

No less important is the fact that mixing leads to aeration of the mixture, during which the nuclei of bubbles are formed, which in turn form the final structure of the finished product.

We also observed that the homogeneity of the suspended state can be ensured only partially. At each point of the real layer of the suspended state, there are pulsating changes, pressure, velocity, temperature.

There are cases when due to poor distribution of dosing components (especially at the beginning and end) insufficient uniformity of weight distribution. This unevenness in the volume of the flow is compensated by the plate working bodies. Thanks to this design, dead zones are avoided and heat and mass transfer processes take place more intensively.

It is known **(Aerov amd Todes, 1968)** that the relatively small particle size of the bulk material and a small bulk density at low humidity of the material itself give them significant mobility. In our opinion, under the action of

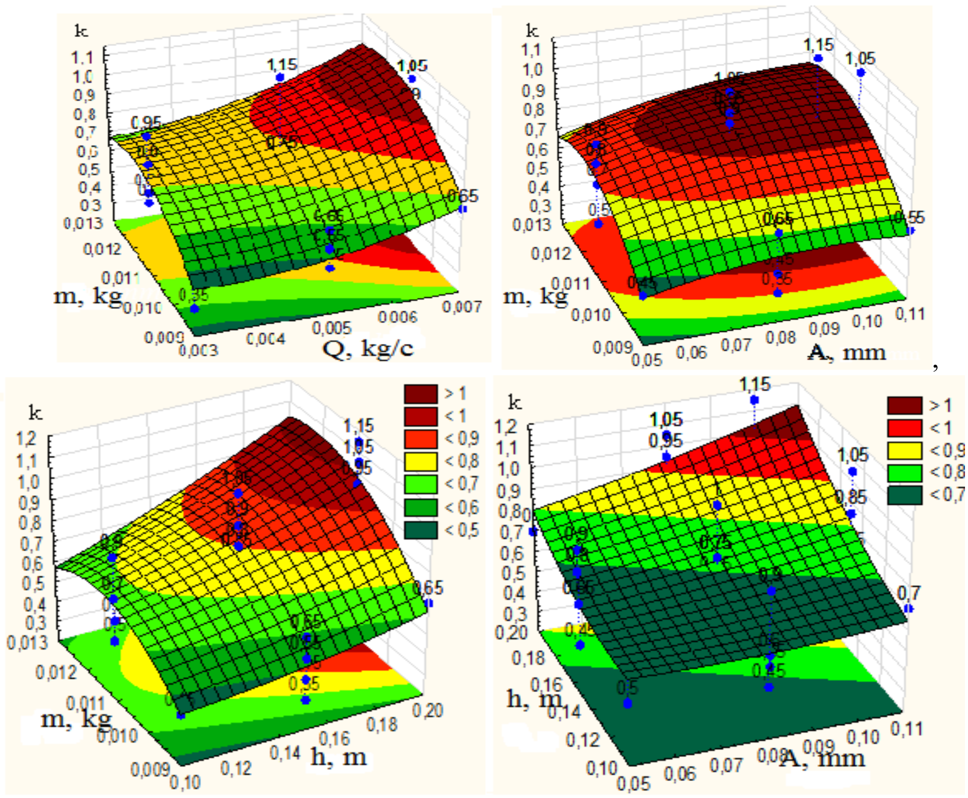

Figure 7 The response surface changes the homogeneity of the mixture from the influencing factors: Q, kg / s; A, mm; h, m; m, kg.

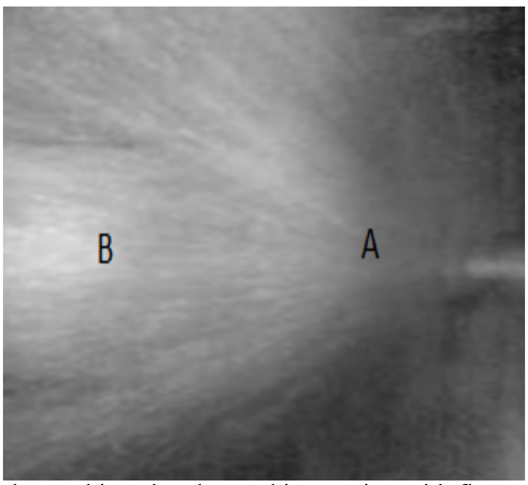

Figure 8 Photo of spraying liquid into the working chamber and interaction with flour.

liquid flow - also volatility, where the rate of fall, the rotation of the particles of bulk material (flour) will significantly affect the intensity of mixing during convective heat supply by the liquid phase. Due to intensive mixing and direct contact of individual particles, the temperature in the volume of the layer is equalized.

Using the relationship between the liquid flow rate and the particle diameter d of flour at different values of the porosity of the layer ε, as studies have shown **(Baum and Bekmuradov, 1976)**, you can achieve the appropriate state of mixing.

According to the data **(Galle et al., 2011)**, the fragmentation of flour leads the system to a sharp increase in the phase interface and an excess of surface energy that causes various surface phenomena. The main ones are wetting, adsorption, and the formation of a double electric layer.

At the same time, using the concept of equivalent diameter when calculating the velocity of the onset of rarefaction (whirling), it should be borne in mind that the rarefaction of large particles is influenced by previously rarefied small fractions, which transmit part of their motion. This means that the rate of rarefaction depends on the total particle diameter distribution. In **(Gvozdev, 2008)**, based on the theory of similarity, a formula for calculating the velocity of a polydisperse material consisting of fractions of different densities is obtained.

The energy of fluidization **(Kornienko, 2011; Orishkevich and Sobchenko, 2017)** is transferred to the liquid mixture and causes its turbulent movements. This energy goes from large-scale turbulence to small-scale and is eventually dissipated in a given volume of solution without causing temperature changes.

From the analysis **(Symak et al., 2017; Grishkov, 2015)** and our research, we see that the mixing of flour is characteristic without considerable resistance to internal diffusion. In this case, it is necessary to solve the heat and mass transfer equations, which leads to difficulties in solving the corresponding differential equations. Therefore, when solving the differential equations of heat and mass transfer in the suspended layer, various approximate methods are used, as well as formulas obtained by mathematical processing of experimental data under different mixing conditions. However, these calculation formulas are usually presented in criterion form.

The authors **(Singh and MacRitchie, 2001)** revealed the effect of flour polymers to respond to three main stress processes: unraveling (a special form of bonding), reorientation of chains, and breaking the chains. Therefore, the authors of the work **(Piskunov et al., 2020)** showed that the rate of mixing and introduction of work must be above some critical value for the development of the gluten network to further a satisfactory process of manufacturing the final product.

Thus, to ensure optimal operation, it is necessary that the dosing liquid in the working chamber was as close as possible to the equilibrium state with the dosing flour. The solution of these conditions is based on compliance with the dosing regime, during which the particle size of the sprayed liquid will have the same speed and number of all the holes of the spray device. This contact contributes to the optimal flow of heat and mass transfer processes to ensure a high level of surface contact of the phases in the chamber of the machine in the first minutes of the process. Operation of batchers in the discrete mode close to ideal allows reducing expenses for all processes.

The nature of the spray takes place with an initial liquid velocity at the outlet of the nozzle of 50 $m.s^{-1}$ at an angle of opening of the torch up to 60°. When studying the trajectory of droplets in the volume of the chamber, the diameter of which is 0.4 m and the location of 6 nozzles in the upper part of the chamber at the same distance, it was found that for small droplets (about 0.1 m), the trajectories are determined mainly by gravity. high initial speed. When settling on the wall of the chamber, all the drops, regardless of their angle of departure have time to interact to equilibrium, which provides the conditions for the ideal mode.

The hydraulic spraying method is the most economical, simple, and reliable, given that the requirements for the average droplet size in the spray torch are not too strict (about 0.1 m). Therefore, a mathematical description of the heat transfer process when mixing components in a suspended state is not possible due to the large number of variables that determine the process. We decided on simplified theoretical models that will allow to some extent to approach the solution of the problem.

Heat transfer model with heat transfer by liquid and flour particles.

To ensure the most uniform distribution of the concentrations of the components in the mixing chamber, it is necessary to supply bulk components at a speed of 2 $m.s^{-1}$ and liquid at a speed of 50 $m.s^{-1}$. The rate of exchange processes and mixing are directly related to the frequency of dissipation of mechanical energy in the chamber. Due to the use of liquid under pressure, the surfaces of the interacting phases are continuously renewed, which causes a significant acceleration of the process of mixing the components. The conversion of energy into heat when kneading the dough should not lead to its overheating, because the optimal fermentation temperature of the dough and dough is 28-32 °C.

Jets of viscous liquid phase with a speed of 40 – 50 $m.s^{-1}$ hit the sprayed flour particles. At the same time, drops of the mix are formed, the size fluctuates in parameters of 0.3 – 0.8 mm depending on the viscosity of liquid and flour.

Based on the process of interaction in the suspended state and the shock-reflecting action of the spray, we can assume that the average diameter of the formed drop of viscous medium is a function of the following values:

$$d_{sr}=f(K_1,V_1,V_2,L,\sigma,\mu,\rho)$$

The value d_{cp}often have the view:

$$d_{sr}=K(V_1)^{\alpha 1},(V_2)^{\alpha 2},(L)^{\alpha 3},(\sigma)^{\alpha 4},(\mu)^{\alpha 5},(\rho)^{\alpha 6}$$

Where:

L – is the specific productivity of spraying, the output of the nozzle holes, $kg.s^{-1}$; ρ – is the density of the liquid mixture, $kg.m^{-3}$; σ– is the tension surface, $N.m^{-1}$; μ – is the viscosity of the formed mixture, PA s; V_1 – is the velocity of the viscous liquid phase to the interaction, $m.s^{-1}$; V_2– is the speed of flour movement to interaction, $m.s^{-1}$; n – is a parameter that characterizes the design of the mixer; $\alpha_1 - \alpha_6$

is a coefficient that takes into account the influence of quantities.

The formed drop of the medium as a result of the greater speed of the liquid, and the low speed of the flour, receives a rotational-translational motion. The two velocities of interaction create the rotation of the droplet. Given these conditions, to determine the average diameter of the droplet formed by the interaction, we use the proposed equation Chernyakova LM, Pashchenko VA, which considers the dependence of the average droplet on generalized number complexes.

$$d_{cp}=K(-\frac{\mu}{\sigma\rho})\,(\frac{n\mu}{\sigma})^{k1}\,(\frac{L\sigma\rho 2}{\mu 3})^{k2}$$

This equation has two dimensionless complexes and a dimensional coefficient $A=\frac{\mu}{\sigma\rho}$, which establishes the physical properties of the formed viscous drop of liquid.

An objective assessment of the droplet formation process is established by two main factors which are the intensity of interaction (mixing) and the time spent in a suspended state. In addition, the change in temperature during hydration is significant. The liquid phase arrives at a temperature of 320 °C, the particle size of the flour is 18 – 20 microns. The residence time of the formed drop is up to 5s.

Since the spraying of the liquid phase is discrete, the change in temperature during the interaction (dispersing phase) with the flour components can be determined by:

$$t=12+9.44\cos(\frac{\pi\tau}{12})$$

Where:
τ – is time.

At an ambient temperature of 250 °C, the heat loss of the liquid phase when fed into the working chamber is determined by the expression:

$$t_1=\alpha\, S(T_1-T_2)$$

Where:
α – is the heat transfer coefficient for the formed medium,

α=132.3Вт/mK.

T_1 – is the temperature of the liquid phase entering the chamber, ^{0}C; T_2 – is the temperature of flour, °C.

The rate of heat loss when mixing the components (dispersed phase) is determined by the expression

$$v_1=\alpha_1 S\,(T_1 - t) \qquad (1)$$

Where:
S – is camera area, m^2;

The rate of heat accumulation by the mixture:

$$v_2=Vc\rho dT/d\tau \qquad (2)$$

Equating expressions 1 and 2,:

$Vc\rho dT/d\tau = \alpha_1 S\ (T_1 - t)$ and using the numerical data of these quantities, we obtain:

$$dT/d\tau=-\ \alpha_1 S/Vc\rho(T_1- t) \qquad (3)$$

Where:
V – is the volume of the mixer, m^3; ρ is phase density, 980 kg.m^{-3}; c – heat capacity of the environment 1.657 kcal.kg^{-1} K.

Then $dT/d\tau+0.93T=6.7\ 0.93+\cos(\frac{\pi\tau}{12})\ 9.44\ 0.93= 6.23+8.5\cos(\frac{\pi\tau}{12})$ (4)

This expression is linear diffraction that can be solved using the integral factor $e^{0.93}$ as follows:

$$Te^{0.93}= 6.23\int e^{0.93}d\tau + 8.5\int e^{0.93}\cos\left(\frac{\tau\pi}{6.23}\right)d\tau$$

The second term of the right-hand side of the equation can be integrated in parts, we obtain:

$$T=6.7\frac{8.5\ 0.93}{0.93^2+0.262^2}cos0.263\tau+\frac{8.5\ 0.262}{0.93^2 0.262^2}\sin 0.262\tau+29.3e^{-0.93}$$

Due to the small values of the second and third terms of the equation, we can use the simplified equation $T = 6.7 + 29.3e^{-0.93\tau}$ and construct a graphical dependence of temperature change (Figure 9).

The theoretical and experimental analysis of heat transfer in the interaction of components in the suspended state allowed us in our case to establish its value when reaching the dosing rate of the liquid and solid phases at a small distance from the place of their entry into the working chamber. According to the process of dosing and structure of the mixer, the considered dynamics of the forming medium do not affect the temperature change, both theoretically and experimentally (Figure 11).

From Figure 9 and calculated data of temperature change during contact and formation of the environment, it is established that their data change by insignificant value. Therefore, the data of temperature formations do not affect the change in the viscosity of the medium but allow to more active influence the biochemical processes under the action of the working bodies of the machine.

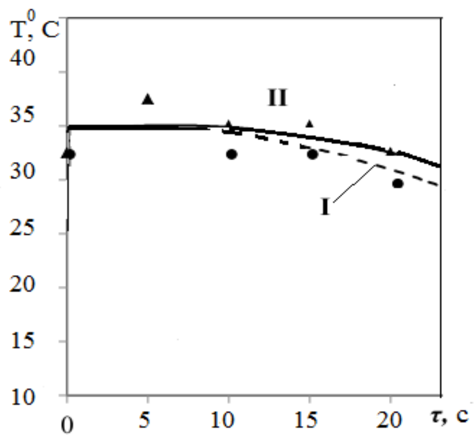

Figure 9 Change in ambient temperature: 1 – experimental data; 2 – settlement.

Heat and mass transfer during the interaction of flour with liquid components.

The heat of reaction from the surface of the flour is distributed by thermal conductivity and convection into the environment. The task of determining the surface temperature of flour, temperature distribution in the medium and flour, determining the heat fluxes to the flour and the liquid allows to establish the process in the developed machine.

The hydrodynamics of the process of interaction of components suggests that there is an analogy between these two processes. Thermal phenomena during mass transfer during mixing in the liquid-solid system are determined by the laws of thermal processes. The processes of flour dissolution occurring in the diffusion region are determined mainly by the laws of molecular and convective diffusion. At the same time, each interaction is accompanied by a certain thermal effect, and its values are facilitated by positive values. In some cases, as noted in **(Zanoni, Pierucci and Peri, 1994)** for minor thermal effects, heat release can be neglected and the temperature can be estimated by the average value.

In the first approximation, we can assume that the mass transfer coefficient β changes its value depending on the temperature T according to the linear law **(Ved and Ponomarenko, 2014; Mallyk and Gumnitsky, 1986)**:

$$\beta = \beta_0\,(1 + \sigma \mathrm{T_п})$$

Where:
β_0 – ismass transfer factor for $\mathrm{T_п}$; σ– is coefficient of proportionality.

The amount of heat Q emitted per unit area per unit time is determined from the dependence **(Ved and Ponomarenko, 2014; Orishkevich et al., 2017)**

$$Q = \beta_0\,(1 + \sigma \mathrm{T_п}) C_R\, Q_R \,, \tag{5}$$

Where:
C_R – is concentration; Q_R – is thermal effect of interaction.

The scheme of temperature distribution in flour and in a liquid medium is shown in Figure 10. Given the surface interaction, the highest temperature will be observed on thesurface of the spherical flour. This significantly changes all the physicochemical characteristics used in the calculation of heat transfer and mass transfer coefficients,as well as diffusion coefficients.

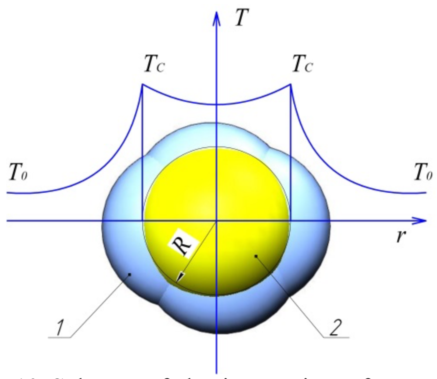

Figure 10 Scheme of the interaction of components in the formation of a mixture: 1 – liquid components, 2 – particle flour.

The heat distribution in a spherical solid is a determined differential equation of thermal conductivity **(Baum and Bekmuradov, 1976)**:

$$\frac{\partial \mathrm{T}}{\partial \tau} = a\left(\frac{\partial^2 y}{\partial r^2} + \frac{2}{r}\frac{\partial \mathrm{T}}{\partial r}\right)$$

$$r>0;\ 0 < r < R \tag{6}$$

Where:
T – is temperature; r – is current radius; R – is the radius of flour; a is coefficient of thermal conductivity.

The boundary condition is determined by the distribution of heat released on the surface and which is distributed between the solution and the solid particle is written in the form of an equation **(Baum and Bekmuradov, 1976)**:

$$\beta_0\,(1 + \sigma \mathrm{T_п}) C_R\, Q_R = \boldsymbol{\lambda}\left(\frac{\partial \mathrm{T}}{\partial r}\right) + \alpha(T_b - T_r)$$

Where:
λ– is a coefficient of thermal conductivity of a solid body;
a is heat transfer coefficient; T_b,T_r – is the surface temperature of the flour and the temperature of the liquid medium.

The initial conditions for this case of interaction will be as follows:

$$T(r,\tau=0) = T_0;\ T_1(\tau) = T_0$$

We enter dimensionless parameters:

$$\varphi = \frac{r}{R}$$

dimensionless radius;

$$F_0 = \frac{a\,\tau}{R^2}$$

Fourier number;

$$B_i = \frac{aR}{\lambda}$$

Bio number;

$$T^* = \frac{\beta_0 C_R Q_R R}{\lambda}$$

parameter having a dimension of temperature.

Hence, we obtain a differential equation with boundary and initial conditions, written in the dimensionless form **(Baum and Bekmuradov, 1976)**:

$$\begin{cases} \dfrac{\dfrac{\partial T}{\partial Fo} = \dfrac{\partial^2}{\partial \varphi^2} + \dfrac{2}{\varphi}\dfrac{\partial T}{\partial \varphi}}{Bi(T_n - T_0) + \left(\dfrac{\partial T}{\partial \varphi}\right)_{\varphi-1} = T^1(1+\sigma T_n)} \\ T(\varphi, o) = T_0; T_1(Fo) = 0. \\ \left(\dfrac{\partial T}{\partial \varphi}\right)_{\varphi-1} = 0. \end{cases} \tag{7}$$

When modeling the formed shape of the drop, the diameter of which is much smaller (d = 0.015 – 0.03 m), it can be considered as an unlimited cylinder. It has its characteristics, which are due to its shape, size and thermophysical properties. In this case, the value of the Fourier test **(Mallik and Gumnitsky, 1986; Orishkevich**

et al., 2017) for the minimum value of the diameter (d = 0.015 m.):

$$F_0 = \frac{a\tau}{R^2} = \frac{22\ 10^{-8}60}{0.0075^2} = 0.2347$$

Where:
A – is thermal conductivity, $m^2.sec^{-1}$; R – is determining size, m; τ is time, sec.

The Fourier criteria in this context reflect dimensionless time.

At the beginning of the process of interaction of components with the dimensions characteristic of mixing components in a suspended state, they can not be considered as a semi-limited body and neglect the increase in temperature of their center. In the non-stationary process of heat transfer in an unrestricted cylinder of radius R, heat is transferred to the surface of the formed droplet. The condition of uniform initial temperature distribution is accepted.

The system of equations (7) was solved by a method based on Laplace transforms. The solution consists of the zero root and other roots of the characteristic equation, which for this case when the volume of the liquid phase was assumed to be large, has the form:

$$tg\mu = -\frac{\mu}{Bi - T^1\sigma - 1}$$

The heating of a cylindrical droplet is described by the differential equation of thermal conductivity in cylindrical coordinates. The temperature distribution in the droplet-based on the solution of the system of equations (7) has the form:

$$\frac{T - T_0}{(1+\sigma T_0)T^1} = \frac{1}{Bi - T^1\sigma} - \sum_{H-1}^{H} \frac{2(1 - Bi + T^1\sigma)}{[\mu_H^2 + (1 - Bi + T^1\sigma)(T^1\sigma - Bi)\cos\mu_n]\cos\mu_n} \frac{\sin\mu_n\varphi}{\mu_n\varphi} e^{-\mu_n^2 Fo} \qquad (8)$$

In the case when the mass transfer coefficient β changes slightly, the solution (8) is simplified and can be written as:

$$\frac{T - T_0}{T^1} = \frac{1}{Bi} - \sum_{n-1}^{\infty} \frac{2(Bi-1)}{[\mu_n^2 + Bi(Bi-1)]\cos\mu_n} \frac{\sin\mu_n\varphi}{\mu_n\varphi} e^{-\mu_n^2 Fo} \qquad (9)$$

Solution (9) makes it possible to theoretically determine the temperature in the center of the droplet particle, which allows us to experimentally test the theoretical solution and assume a slight change in the mass transfer coefficient in the liquid phase. In the center of the value of φ = 0, and:

$$lim \lim_{\varphi \to 0} \frac{\sin\mu_n\varphi}{\mu_n\varphi} = 1$$

therefore, the solution for T = Tn will look like this:

$$\frac{T_n - T_0}{T^1} = \frac{1}{Bi} - \sum_{n-1}^{\infty} \frac{2(Bi-1)}{[\mu_n^2 + Bi(Bi-1)]\cos\mu_n} e^{\mu_n^2 Fo}$$

Under the conditions of modeling the thermophysical characteristics received by an experimental way take part. They depend on temperature and take into account mass transfer processes when mixing. We determined the nature of changes in the thermophysical characteristics of the vapor. The equations describing the properties of the sponge dough for the temperature range (293 – 305 K) are obtained:

$$C = 2866 + 1.571\ t; \qquad (10)$$

$$\lambda = 0.219 + 0.00025t; \qquad (11)$$

$$\alpha = 6.345 + 0.003t; \qquad (12)$$

We see that the dependence of the coefficients of thermal conductivity λ, thermal conductivity a, and heat capacity c on temperature is linear. Humidity has a greater effect on the experimental coefficients than temperature. The analysis of dependences (10 – 12) shows that their values increase with increasing temperature. The effective density of the formed drop of the medium was determined at t = 25 - 35 °C:

$$\rho(t) = -6.875t + 952.5$$

The relationships between the coefficients of mass transfer and heat transfer are determined by the same hydrodynamic situation that arises due to the interaction of phases formed at the interface of the phases. The only difference is that the mass transfer takes place by transporting the reagent to the surface of the solid phase of the flour, and heat transfer from the surface of the solid phase to the liquid reagent.

The results of the computational experiment of the formed droplet of components with a diameter of 0.002m at a temperature of 29 °C are presented in Figure11.

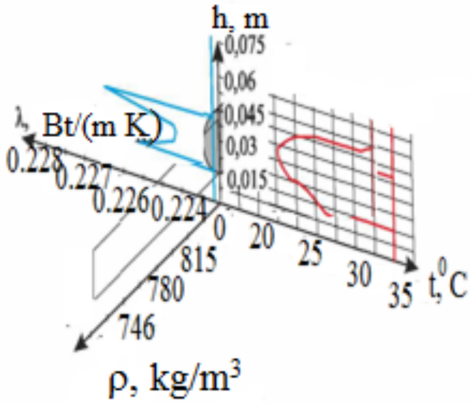

Figure 11. The results of a computational experiment of the interaction of components at times τ, p.

For the initial moment of time (τ = 0s) there is a uniform distribution of temperature, density, and thermal conductivity in the cross-section of the droplet. Under the action of the heat flow of the liquid phase on the surface of the flour is heating it with a simultaneous change in thermophysical characteristics, which depend on the temperature of the heated layers. Visualization of the process of droplet formation after 3s mixing is shown in Figure 11.

The obtained experimental values of mass transfer and heat transfer coefficients are of the same type, which allows confirming the analogy between the mass transfer and heat transfer processes for mass transfer processes, which are accompanied by the formation of phase interactions on the surface.

Analysis of the process of preparation of the paste, performed in a suspended state, showed that due to energy dissipation there is no increase in the temperature of the paste during mixing from the initial 32 °C to 32.8 °C, which is acceptable. Temperature regimes occur almost unchanged.

CONCLUSION

Based on the results of the process of mixing the components, the functions performed by the mixer, first of all, are the even distribution of prescription components (flour, yeast, water) and the creation of favorable conditions for the formation of the structure of the paste. To achieve the desired result - a homogeneous paste - in the considered design of the mixer, the feed rate of the flour should be 2 $m.s^{-1}$, the feed rate of the liquid - 50 $m.s^{-1}$.

From the point of view of kinematics, it is possible to conclude that in the chamber of the car there is a formation of homogeneous liquid mix in the presence of four ways:

- direct flow method, where the speed of liquid components exceeds the speed of flour or their fixed particles;
- gravitational method, where the falling particles of flour are in contact with moving liquid components;
- inertial, where the change in the direction of movement of liquid components and flour occur during their interaction;
- convective method, where the movement of liquid components by the difference in specific gravity, ie, natural convection.

The proposed mathematical model allows the calculation of the duration of the interaction of components depending on the temperature of the medium, thermophysical parameters, and the size of the formed droplet, which helps to determine the rational parameters of the environment of the working chamber in a suspended state. This allows for different shapes and sizes of droplets without conducting a physical experiment to establish the process of mass heat transfer when mixing components.

The results of experimental research and the proposed mathematical model, which takes into account the effective thermophysical characteristics, confirm the feasibility of using a mathematical model to calculate the mixing process.

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