This study investigates the process of making low-calorie dairy desserts based on buttermilk and retentate using multicomponent stabilization systems containing protein and carbohydrate components.

The influence of the modes of thermomechanical processing of the milk mixture on the structure formation of dairy desserts and the formation of complexes between protein and carbohydrate components in the stabilization system remains incompletely explored.

It has been established that thermomechanical processing of the milk mixture at a temperature of 85°C and a mixer rotation speed of 2800 rpm made it possible to obtain dessert samples with the most acceptable organoleptic indicators. The viscosity of the cream and pudding based on buttermilk was 2950 mPa·s and 8120 mPa·s, respectively; based on retentate – 4150 mPa·s and 10050 mPa·s, respectively.

It has been proven that the interaction of the components in the stabilizer during thermomechanical treatment leads to the formation of "protein-polysaccharide" complexes with the subsequent formation of a homogeneous structure of the dairy dessert. Thus, in the case of pudding production, particles with a size of 50–100 microns made up to 60%, based on the retentate, up to 90% – based on the buttermilk. In the case of cream production, particles with a size of 50–100 microns made up to 80%, based on the retentate; less than 10 microns – up to 90% – based on the buttermilk.

A positive effect of the combination of protein and carbohydrate components in the stabilization system on the structural indicators of dairy desserts with the formation of protein-carbohydrate complexes has been established.

The results could be used by dairy processing enterprises when developing structured dairy products for dessert purposes using protein milk raw materials and polysaccharides as structure-forming agents and stabilizers

Keywords: structured dairy desserts, thermomechanical treatment of the mixture, polysaccharides, protein concentrates, rheology

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DETERMINING THE INFLUENCE OF THERMAL-MECHANICAL TREATMENT ON THE STRUCTURE FORMATION OF LOW-CALORIE DAIRY DESSERTS

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1. Introduction

Nutrition is an integral part of ensuring human health. Given that today there is a problem of a deficiency of complete protein in the world, which affects two-thirds of humanity, significant attention should be paid to the creation and inclusion in the diet of products with a high protein content [1]. A potential natural source of complete protein is secondary dairy raw materials (buttermilk, retentate, etc.), which are used incompletely, as well as protein concentrates, in particular whey and milk proteins, dry demineralized whey, etc. [2].

Dessert products are very popular among consumers of all ages. Such products, in particular those based on milk, have a certain structure, which can be achieved with the help of stabilizers. For this purpose, polysaccharide complexes are widely used in the dairy industry, which make it possible to adjust the consistency of the product, preventing syneresis during its storage due to increased moisture retention, and

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improving rheological properties without increasing fat content [3].

An important role in the formation of the structure of dessert dairy products with stabilizers is played by thermomechanical treatment, during which hydration and dissolution of polysaccharide and protein components occur, their interaction with each other, as well as partial denaturation of whey proteins. The parameters of thermomechanical treatment – temperature, holding time, and shear rate – determine the degree of unfolding of stabilizer macromolecules and formation of a gel network. This affects the consistency, moisture retention capacity, and stability of the product during storage. Violation of optimal thermomechanical treatment modes causes insufficient swelling of stabilizers, structural instability, syneresis and delamination of the product, which negatively affects its quality and shelf life. Therefore, a scientifically substantiated choice of thermomechanical treatment modes taking into account the type and concentration of the protein-carbohydrate stabilizer is a necessary condition for obtaining dairy desserts with stable structural, mechanical, and organoleptic indicators [4].

Thus, the process of structuring dessert dairy products is actively researched, but the range of products with multicomponent protein-carbohydrate stabilizers remains limited.

Therefore, it is a relevant task to establish patterns in the influence of thermomechanical treatment parameters on the structuring of dairy desserts with multicomponent protein-carbohydrate stabilizers.

2. Literature review and problem statement

Structure stabilizers include plant polysaccharides (starch, flour, inulin, pectin, etc.) and protein products (gelatin, skimmed milk powder, whey protein concentrate powder, etc.). They perform important functions of thickening and gelling solutions, stabilizing foams, emulsions, and suspensions, slowing down or completely preventing the crystallization of ice and sugar, regulating aroma, etc. The optimal dosage of the stabilizer depends on the mass fraction of fat in the product, its dispersion, heat treatment modes, etc. [4].

A large body of research considers various combinations of substances in the composition of structure stabilizers for the production of dessert products. Thus, technologies for dessert products based on the stabilizing properties of cellulose and cellulose esters are reported in [5]. However, the authors limited themselves to evaluating the viscosity characteristics and did not consider the influence of thermomechanical treatment on the structure formation of the finished product. The use of cellulose ester salts and their salts has also been considered [6]; however, the data relate mainly to aqueous systems and do not take into account the specifics of the milk matrix. It has been shown that sodium alginate is no less widespread in the technology of structured food products, which already at a concentration of 1% forms very stable gelatin. At the same time, such structuring agents as carrageenan, agar, agaroid, furcellaran, have not gained traction because of their high cost, which limits their practical application in industrial production.

The combination of structure stabilizers is used at the stage of interaction between food additives or the manifestation of synergism, which significantly enhances individual properties, for example, foaming or stabilizing. This gives the compositions universal characteristics due to chemical interaction and the formation of new substances with high functional indicators [7]. Thus, it has been shown that the use of a composition consisting of gelatin, dry whey, and starch provides an increase in the foaming ability of whipped milk desserts by 1.7 times. The authors associate this effect with the formation of a protein-carbohydrate complex with high surface-active properties. A similar effect was established in the case of using a binary system of carrageenan and various dietary fibers with casein proteins [8].

There is a compositional system whose stabilizing, foaming, and complexing properties are based on protein-carbohydrate interaction and the synergistic effect of substances such as gelatin, starch, carrageenan, guar gum, and lactic acid ester [9]. However, the authors do not provide quantitative ratios of the components, which complicates the reproduction of the composition in other formulation systems.

The stabilizing and foaming properties of gelatin and methylcellulose compositions in the ratio of 1:(0.37–0.50) [10] or 1:(0.07–0.10) [11] are based on protein-carbohydrate interaction. In [10, 11], an increase in foam stability was shown, but the effect of processing temperature on these properties was not studied.

The compositions of gelatin and potato starch [12], gelatin, and apple pectin [13], as well as proteins of milk protein concentrate from buttermilk with xanthan or gelatin [14] were studied. In [12], the effect of the composition of gelatin and potato starch on the organoleptic characteristics of the product was mainly evaluated, but the regularities of the interaction of these hydrocolloids and their role in the formation of the spatial structure were not sufficiently studied. Reference [13] shows the feasibility of combining gelatin with apple pectin to improve the consistency of the product but does not provide a proper justification for the mechanism of structure formation depending on the ratio of components and environmental parameters. In [14], a positive effect of the interaction of buttermilk concentrate proteins with xanthan or gelatin on the organoleptic characteristics of the product was established, while the features of protein-polysaccharide interaction and the effect on rheological characteristics were partially revealed. Therefore, in [12–14], most attention is paid to the organoleptic indicators of products, while the mechanisms of structure formation, the interaction of components, and the patterns of the formation of rheological properties require further study.

The combination of carboxymethylcellulose with whey proteins (58–61%) or sodium caseinate (3%) leads to a significant increase in structural stability [15]. A composition of starch and gelatin is known, which form a mixed gel with casein, consisting of interpenetrating networks of each polymer, which prevents the compression of the casein gel, the convergence of casein particles and the separation of whey [16]. However, the cited studies did not consider the influence of thermomechanical treatment parameters on the kinetics of the formation of such a gel.

The issue of the influence of thermomechanical treatment on the properties of milk mixtures for the production of desserts is also the subject of separate studies. Thus, in [17], the results of studies on the influence of pressure and homogenization temperature on the dispersion of the fat phase and the viscosity of milk-protein mixtures are reported. It was shown that increasing the homogenization pressure to 15–20 MPa provides a decrease in the average diameter of fat globules and an increase in emulsion stability; however, the authors did not consider the effect of these parameters on

structure formation in the presence of stabilizers. In [18], the effect of pasteurization regimes of whey protein concentrates on the degree of protein denaturation was studied. It was found that holding at a temperature of 85–90°C for 5–10 min provides a level of denaturation sufficient for the formation of a protein gel skeleton; however, the study was limited to individual protein systems without taking into account the interaction with carbohydrate components. In [19], the effect of shear rate during mechanical mixing of milk-protein systems on the rheological characteristics of the finished product was studied. It was found that increasing the shear rate causes the destruction of the partially formed gel structure and a decrease in viscosity; however, the study concerned only monocomponent systems. In [20], the influence of the sequence of technological operations, namely the introduction of a stabilizer before or after homogenization, on the distribution of particles of the dispersed phase and the intensity of syneresis was analyzed. It was shown that the introduction of a stabilizer at the stage preceding homogenization reduces the risk of syneresis by 15–20%. In study [21], the complex effect of the temperature of 72–95°C and the duration of exposure on the gelation of the gelatin-starch system in a dairy medium was considered. It was shown that with an increase in the duration of heat treatment, the strength of the structure increases to a certain limit, after which its decrease is observed due to the destruction of the polysaccharide component.

However, despite numerous studies on individual combinations of stabilizers, the question of the influence of protein-carbohydrate components in multicomponent stabilization systems on the structure formation of dairy desserts under conditions of thermomechanical treatment remains unresolved. The reason for this may be objective difficulties associated with the diversity of raw material systems and the lack of unified approaches to assessing their interaction.

Our review of the literature [5–21] showed that combinations of proteins and hydrocolloids in the composition of structure stabilizers are the most common for the production of dessert products. At the same time, most studies focus on individual pairs of components, while the issue of the joint influence of thermomechanical treatment on the formation of the structure remains insufficiently covered.

To overcome these challenges, an integrated approach to the selection of multicomponent compositions of protein-carbohydrate stabilizers, taking into account the modes of thermomechanical treatment of the dairy mixture, could be used. This confirms the feasibility of a study aimed at determining the regularities of structure formation in dairy dessert products with the use of protein and carbohydrate components as structure stabilizers during thermomechanical treatment.

3. The aim and objectives of the study

The aim of our study is to establish patterns in the influence of thermomechanical treatment of milk mixture on the structure formation of milk desserts (cream, pudding) based on secondary milk raw materials (buttermilk, retentate) using multicomponent protein-carbohydrate stabilization systems. This will make it possible to choose rational technological modes that enable the manufacturing of products with stable structural-mechanical and organoleptic indicators.

To achieve the set goal, it is necessary to solve the following tasks:

– to investigate the influence of temperature and mixer rotation speed during thermomechanical treatment of milk mixture on the rheological indicators of cream and pudding obtained on the basis of buttermilk and retentate;

– to investigate the microstructure of milk desserts, in particular the distribution of particles of the dispersed phase by size, depending on the type of product (cream, pudding) and the type of raw materials (buttermilk, retentate).

4. The study materials and methods

The object of our study is the process of making low-calorie dairy desserts based on buttermilk and retentate using multicomponent stabilization systems containing protein and carbohydrate components.

The principal hypothesis assumes that the thermomechanical treatment of the milk mixture has a decisive influence on the structure formation of low-calorie dairy desserts. The thermomechanical treatment modes: temperature and speed of rotation of the mixer determine the degree of interaction of the protein and carbohydrate components of the stabilization system with the formation of "protein-carbohydrate" complexes.

It is assumed that the establishment of rational thermomechanical treatment modes could make it possible to obtain desserts with a stable, homogeneous structure and predicted rheological parameters while simultaneously reducing the calorie content of the product.

When planning and conducting the research, the following assumptions were adopted:

– the use of secondary dairy raw materials (buttermilk and retentate) is considered a priority due to their high biological value and the presence of complexes of full-fledged proteins;

– it is assumed that the structure formation of low-calorie dairy desserts during thermomechanical treatment depends mainly on the interaction of selected protein and carbohydrate components (CSB, SSD, rice flour, starch, gelatin, inulin, pectin) with the dairy base;

– it is believed that the effective viscosity indicators are the main criterion for the quality of the formed structure of low-calorie dairy desserts and its stability in general;

– it is assumed that the size and nature of the distribution of particles of the dispersed phase, identified according to microstructural analysis, reflect the degree of interaction of protein and carbohydrate components of the stabilization system and can serve as additional confirmation of the quality of the formed dessert structure.

To ensure the adequacy of the study on the influence of thermomechanical treatment on structure formation, the following simplifications were accepted:

– structure formation was assessed by the generalized result of the interaction of protein and carbohydrate components of the stabilization system – the formation of "protein-starch" complexes in the case of pudding and "protein-dietary fiber" in the case of cream, without differentiating the contribution of each individual component of the multicomponent system;

– the range of studied parameters of thermomechanical treatment was limited by technologically feasible values of temperature (20–85°C) and mixer rotation speed (2800–7200 rpm),

which correspond to the operating modes of industrial equipment of this type;

– the quality of the resulting structure was assessed by indicators of effective viscosity and organoleptic characteristics of the finished product, without a detailed analysis of the full range of rheological properties (elasticity, plasticity, etc.);

– the microstructure of the samples was characterized by the results of the analysis of individual representative fields of view of microphotographs before and after processing. This allowed us to qualitatively and semi-quantitatively assess the distribution of particles of the dispersed phase by size groups without the use of instrumental methods of granulometric analysis.

The materials of the research were secondary dairy raw materials – buttermilk and retentate; the finished product – low-calorie dairy dessert. Components for the stabilization system – dry whey protein concentrate (WPC), dry demineralized whey (DW), rice flour, highly methoxylated pectin, inulin, corn starch, gelatin.

For the production of cream, the stabilization system consisted of WPC, DW, inulin, and pectin, for pudding – of WPC, starch, gelatin, and rice flour [22].

Thermomechanical treatment of milk mixtures with carbohydrate and protein components was carried out in a rotary-vortex emulsifier Ya5-OEV (Institute of Food Resources at the National Academy of Sciences of Ukraine). The speed of the mixer of the rotary-vortex emulsifier Y5-OEV was 2800, 4300, 5700, and 7200 rpm at processing temperatures of 20, 45, 65, and 85°C.

The effective viscosity was determined on a rotational viscometer ATAGO-895 VISCO (Japan) using S/S_2 measuring cylinder devices; viscosity readings were recorded from an electronic display. The measuring cylinder (rotor) S_2 was selected in such a way that the gradient layer extended over the entire thickness of the product layer placed in the annular gap of the measuring device of the viscometer. For each experiment, a new portion of the product was selected and after reaching the set temperature, it was thermostated for 20 minutes.

The microstructure of milk mixtures before and after thermomechanical treatment was studied by microphotographing samples at ×200 and ×400 magnification using a measuring grid scale. The resulting micrographs determined the distribution of particles of the dispersed phase by size groups (less than 10, 10–50, 50–100, 100–300, 300–500, and 500–800 μm) separately for cream and pudding based on buttermilk and retentate.

All studies were performed five times in three identical samples of dairy desserts. Tukey-Kramer multiple comparison was used to compare the mean values, taking into account that significant differences were observed at $p < 0.05$. Experimental data were processed by methods of mathematical statistics using Microsoft Excel (Microsoft 365 package, USA; licensed to Ivan Pulyuy Ternopil National Technical University).

5. Results of the study on determining the influence of thermomechanical treatment on the structure formation of low-calorie dairy desserts

5. 1. The influence of temperature and speed of rotation of the mixer during thermomechanical treatment of the milk mixture on the rheological parameters of cream and pudding obtained on the basis of buttermilk and retentate

The study of surface phenomena at liquid phase boundaries allows us to substantiate the parameters of obtaining structured systems and determine the role of complexation of proteins with carbohydrate components. Achieving equilibrium adsorption values and its irreversibility leads to the formation of two-dimensional structures characterized by certain structural and mechanical properties. The formation of two-dimensional structures, that is, interfacial structure formation of proteins, is based on the processes of construction of bonds between polypeptide chains [18].

Structural and mechanical properties of dairy products are one of the main components of quality assessment [19]. They must be taken into account in order to choose the optimal modes of processing raw materials and obtain high-quality finished products, design rational structures of technological equipment, etc. For raw materials, semi-finished products, and finished products, the structure of the product depends on many factors: temperature, humidity, duration and modes of thermomechanical treatment, means and terms of storage, type of packaging, transportation techniques, and many other reasons.

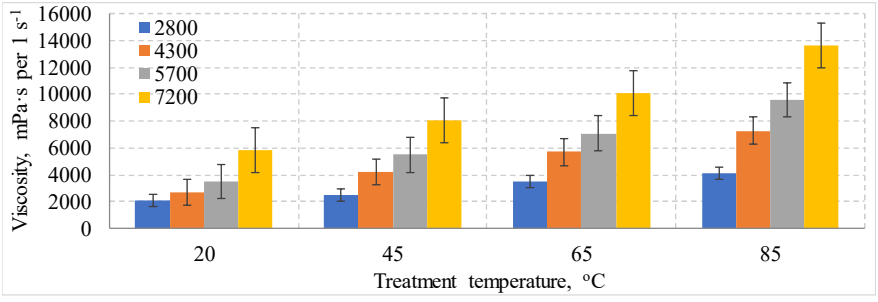
Cohesive-dispersed (solid-like products) systems, which include dairy desserts, have certain rheological properties – viscosity, strength, elasticity, and plasticity. Shear properties (describe the behavior of the product when exposed to shear, tangential stresses) of solid-like products are characterized by effective viscosity [18]. Therefore, in assessing the qualitative changes in the structure of dairy desserts, effective viscosity was chosen as the most objective indicator of the quality of the structured system.

Fig. 1 shows the results of experiments on the influence of thermomechanical treatment modes of milk mixtures on the viscosity of milk desserts (cream and pudding).

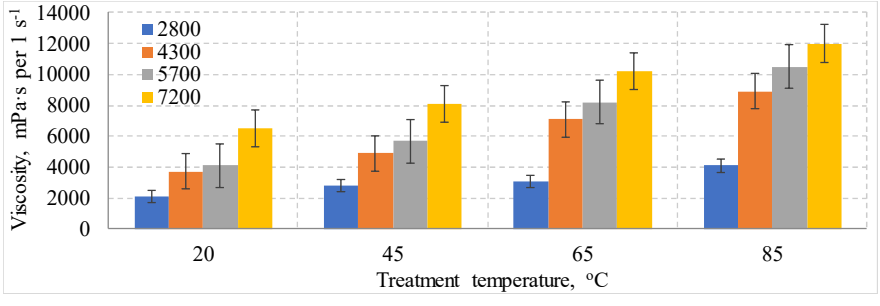
Analysis of graphical dependences (Fig. 1) reveals that processing mixtures at an increase in temperature to 85°C leads to a significant increase in viscosity values regardless of the number of mixer revolutions compared to the initial values at a temperature of 20°C. Thus, in samples of pudding based on retentate or buttermilk, the viscosity increases by 2.7–3.0 times (up to 13800 mPa·s or 12100 mPa·s), respectively; in cream samples – by 1.3–1.7 times (up to 6900 mPa·s or 6500 mPa·s), respectively. It should be noted that with an increase in the mixer revolution speed to 7200 rpm in all samples of milk desserts, the consistency acquired increased fluffiness with an excessive number of air bubbles, which subsequently led to delamination. The research results allow us to state the participation of proteins and carbohydrates in the formation of the spatial network of the pudding and cream gel and indicate the thixotropic properties of the system, which contribute to the strengthening of the structure over time [20, 21].

In addition, a similar trend was observed in the studies on the influence of combinations of hydrocolloids on the rheological properties of dairy desserts during thermomechanical treatment of the mixture at different temperatures [23–26].

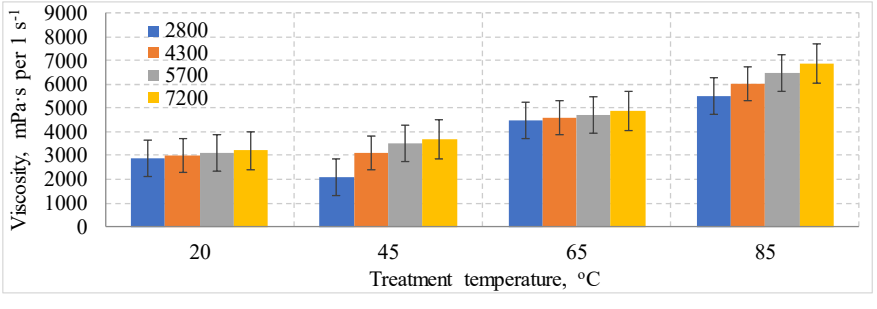
It should be noted that thermomechanical treatment of the dairy mixture at a temperature of 85°C and a mixer speed of 2800 rpm (Fig. 1) allowed us to obtain pudding and cream samples with the most acceptable organoleptic indicators, as well as recommended viscosity indicators, which is confirmed by studies [22].



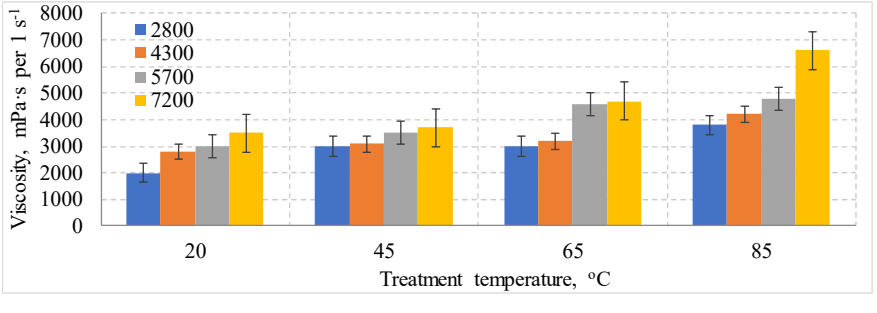
a



b



c



d

Fig. 1. Viscosity of dairy desserts based on different milk bases depending on the thermomechanical treatment modes: *a* – retentate-based pudding; *b* – buttermilk-based pudding; *c* – retentate-based cream; *d* – buttermilk-based cream (mean ± standard error of the mean, $n = 3$, $p < 0.05$)

5. 2. Studying the microstructure of low-calorie dairy desserts depending on the type of raw material and processing

The quality of structured products is determined by such factors as the shape, size, and uniformity of particle distribution in the dispersed system. The organoleptic and physicochemical properties of dairy dessert products provide limited information about the physical state of their internal structure. In turn, information about the structural-functional relationships of components is necessary to achieve high quality of any food product. Scientists have established a positive effect of hydrocolloids on the structure of dairy desserts [27]. Thus, it was shown that the increased reactivity of pectin to calcium led to a microstructure with increased co-localization of pectin and protein and reduced phase separation [28]. In work [29], by analyzing the microstructure of low-calorie dairy desserts, the use of inulin was justified by particle size distribution.

Therefore, it is important to study the microstructure of the systems formed during the production of low-calorie dairy desserts (cream and pudding) based on secondary dairy raw materials (retentate and buttermilk).

Fig. 2, 3 show micrographs of the structure of dairy dessert mixtures before and after thermomechanical treatment, based on buttermilk and retentate, respectively.

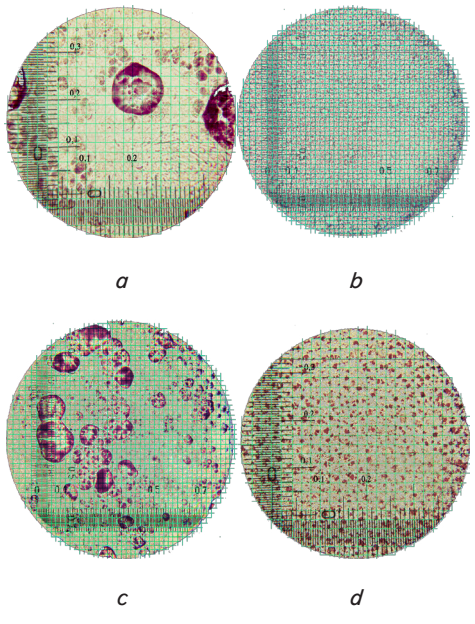


Fig. 2. Microstructure of a dairy dessert based on buttermilk: *a* — cream before processing; *b* — cream after processing; *c* — pudding before processing; *d* — pudding after processing

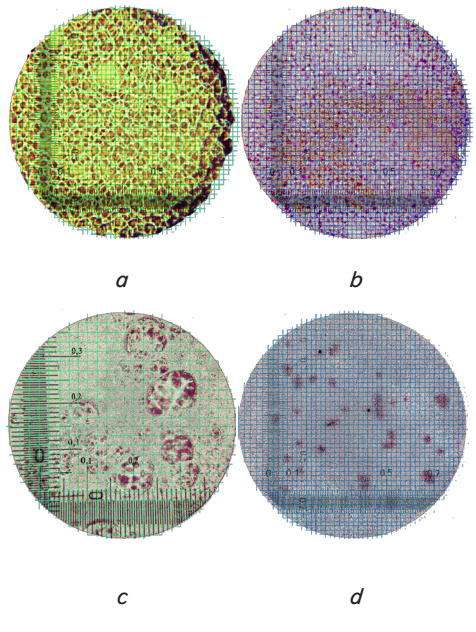


Fig. 3. Microstructure of a dairy dessert based on retentate: *a* — cream before processing; *b* — cream after processing; *c* — pudding before processing; *d* — pudding after processing

Summary data on the portion size of dairy desserts are given in Table 1.

In the obtained micrographs of milk mixtures based on both buttermilk and retentate, before thermomechanical treatment, large structural components are observed against the background of a finely dispersed homogeneous mass, which change the overall micropattern of the samples (Fig. 2, 3, *a*). Micrographs of milk mixtures after treatment illustrate the structural arrangement, high degree of dispersion, and uniformity of distribution of structural components in each sample (Fig. 2, 3, *b*).

Table 1

The size of particles in dairy desserts during production

Product	Particle size (μm), %					
	<10	10–50	50–100	100–300	300–500	500–800
Before thermomechanical processing						
Cream based on: – retentate	–	–	10[1]	30[1]	30[1]	30[1]
– buttermilk	35[1]	50[1]	15[1]	–	–	–
Pudding based on: – retentate	–	20[1]	–	10[1]	20[1]	50[1]
– buttermilk	–	35[1]	–	5[1]	10[1]	50[1]
After thermomechanical treatment						
Cream based on: – retentate	10[2]	10[2]	80[2]	–	–	–
– buttermilk	90[2]	10[2]	–	–	–	–
Pudding based on: – retentate	40[2]	60[2]	–	–	–	–
– buttermilk	10[2]	90[2]	–	–	–	–

Notes: [1] – statistically not significantly different ($p \geq 0.05$); [2] – statistically significant difference compared to the corresponding value before thermomechanical treatment for the same product and particle size interval ($p < 0.05$); "–" – particles of the corresponding size were not detected.

It should be noted that samples of pudding mixtures based on buttermilk before thermomechanical treatment are characterized by a heterogeneous structural arrangement due to the presence of a large number of large structural components that merge, overlap, and form complexes up to 600–800 μm in size (Fig. 2, *a*). Mostly these are large particles up to 200–300 μm in size (Fig. 2, *a*). In the field of view, about 50% of particles with a size of 30–100 μm and single particles with a size of less than 10 μm are observed. In contrast to pudding, samples of buttermilk-based cream are characterized by a fairly homogeneous structural arrangement, the detected large structural components reach a maximum size of up to 90 μm, their boundaries are somewhat blurred (Fig. 2, *a*). Also visible are single rounded particles with a size of up to 100 μm and about 50% of particles with a size of 8–20 μm.

Samples of cream mixtures based on both buttermilk and retentate, after processing, are characterized by a relatively homogeneous structural arrangement with the presence of large structural elements with clearly defined boundaries up to 100 microns in size (Fig. 2, 3, *b*). Samples of pudding mixtures based on both buttermilk and retentate, after processing, are characterized by a homogeneous finely dispersed arrangement, in which large associates up to 150 microns in size are detected, which do not affect the overall microstructure of the sample (Fig. 2, 3, *b*). We suggest the possibility of interaction of polysaccharides and proteins with the formation of surface-active protein-carbohydrate complexes, which is confirmed by studies [20, 21, 28].

Analysis of the microstructure of milk dessert mixtures after thermomechanical treatment revealed their thermody-

namic stability. So, in pudding – it is a homogeneous system with the formation of "protein-starch" complexes and a homogeneous structure with evenly dispersed air bubbles. In cream, there is also a homogeneous system, but with the formation of "protein-dietary fiber" complexes and a homogeneous, delicate, airy structure. In all samples, no signs of syneresis were detected.

6. Discussion of results based on the study of the influence of thermomechanical treatment on the structure formation of low-calorie dairy desserts

Our research results indicate that increasing the temperature of thermomechanical treatment of the milk mixture to 85°C causes a significant increase in the effective viscosity of desserts regardless of the speed of rotation of the mixer (Fig. 1). Thus, for pudding based on retentate and buttermilk, the viscosity increased by 2.7–3.0 times (up to 13800 and 12100 mPa·s, respectively), for cream – by 1.3–1.7 times (up to 6900 and 6500 mPa·s, respectively). This is explained by the fact that with increasing temperature, there is a more intensive hydration and unfolding of protein macromolecules (WPC, DW, gelatin) and carbohydrate (starch, inulin, pectin, rice flour) components of the stabilization system. Thus, their interaction with the formation of a spatial gel network is accelerated and gives the system pronounced thixotropic properties. At the same time, increasing the mixer rotation speed to 7200 rpm causes excessive whipping of the mixture and the accumulation of air bubbles, which further leads to stratification of the structure. Therefore, the most acceptable technological mode was determined to be processing at a temperature of 85°C and a mixer rotation speed of 2800 rpm. Data on the distribution of particles of the dispersed phase by size groups (Table 1) and microphotographs (Fig. 2, 3) confirm this conclusion. Thus, before processing, large, heterogeneous structural complexes (up to 600–800 μm) prevail in all samples. Whereas after processing, the particles are enlarged to finely dispersed homogeneous fractions (up to 100 μm in cream, up to 150 μm in pudding). This is consistent with the nature of the viscosity change and indicates the formation of protein-carbohydrate complexes "protein-starch" for pudding and "protein-dietary fiber" for cream.

The established dependence of the increase in the viscosity of milk mixtures with an increase in the temperature of thermomechanical treatment is consistent with the results of studies on the influence of combinations of hydrocolloids on the rheological properties of milk desserts [22–25]. At the same time, unlike the aforementioned papers, which mainly considered the influence of individual polysaccharides (starch, carrageenan) on rheological parameters, this study established the effect of the joint action of protein and carbohydrate components of the stabilization system. That has made it possible to achieve acceptable organoleptic indicators and the necessary structural and mechanical characteristics at lower concentrations of each individual stabilizer. This is consistent with information about the positive influence of hydrocolloids on the structure of milk desserts [26, 27]. The obtained micrographs confirm and supplement the data on the increased co-localization of protein and polysaccharide phases established for "pectin-protein" systems [28]. In study [22], a similar effect was observed for the systems "protein-starch" and "protein-dietary fiber". Unlike [29], in which the justification of the use of inulin in low-calorie desserts was carried out only by the distribution of particles of the dispersed phase, in this work the microstructural analysis was supplemented with a quantitative assessment of rheological parameters. This gives a more comprehensive idea of the quality of the resulting structure.

Our results have certain limitations regarding their application. The established rational thermomechanical treatment modes (temperature 85°C, mixer rotation speed 2800 rpm) are correct within the studied range of parameters (temperature 20–85°C, mixer rotation speed 2800–7200 rpm). Thermomechanical treatment is carried out at specific technological equipment – rotary-vortex emulsifier Ya5-OEV. The results were obtained for a specific composition of stabilization systems (WPC, DW, inulin, pectin – for cream; WPC, starch, gelatin, rice flour – for pudding) and specific types of secondary dairy raw materials (buttermilk, retentate). In view of this, their reproducibility for other stabilizer compositions or other types of dairy raw materials requires additional experimental verification.

The disadvantage of our study is that the quality of the formed structure was assessed mainly by the effective viscosity index, without a detailed analysis of the full spectrum of rheological properties (elasticity, plasticity, yield point, etc.). And the microstructure was characterized qualitatively and semi-quantitatively based on the results of the analysis of individual fields of view of microphotographs, without the use of instrumental methods of granulometric analysis (in particular, laser diffraction). In the future, this drawback could be eliminated by involving rotational rheometry with the determination of the full range of structural and mechanical characteristics and instrumental methods of quantitative analysis of the size distribution of particles of the dispersed phase.

Further studies involve establishing mathematical relationships between the parameters of thermomechanical treatment (temperature, mixer rotation speed, holding time) and structural and mechanical indicators of dairy desserts. This will make it possible to predict the quality of the finished product without conducting a full range of experimental studies. Another promising direction is to expand the range of raw materials under study (other types of dairy raw materials, combined stabilization systems with a different ratio of protein and carbohydrate components). Difficulties along this path might be associated with the multifactorial nature of the processes of protein-carbohydrate interaction during thermomechanical treatment, which would require the involvement of additional instrumental research methods (differential scanning calorimetry, etc.) and mathematical modeling methods.

7. Conclusions

1. The influence of temperature (20–85°C) and mixer rotation speed (2800–7200 rpm) during thermomechanical treatment of milk mixture on rheological parameters of cream and pudding based on buttermilk and retentate has been established. It was determined that the rational processing mode is a temperature of 85°C and a mixer rotation speed of 2800 rpm, at which the most acceptable organoleptic parameters and recommended values of effective viscosity are achieved. Thus, for cream based on buttermilk and retentate – 2950 and 4150 mPa·s, respectively, for pudding – 8120

and 10050 mPa·s, respectively. Increasing the processing temperature to 85°C causes an increase in the viscosity of pudding by 2.7–3.0 times, and of cream – by 1.3–1.7 times compared to the initial values at 20°C. This is explained by the intensification of hydration and unfolding of macromolecules of protein and carbohydrate components of the stabilization system with the formation of a spatial gel network and the manifestation of thixotropic properties of the system.

2. The microstructure of dairy desserts has been studied and the nature of the distribution of particles of the dispersed phase by size has been established depending on the type of product (cream, pudding) and the type of raw material (buttermilk, retentate). It was shown that before thermomechanical treatment, the structure of the mixtures is heterogeneous, with the presence of large structural complexes up to 600–800 μm in size. After processing, a homogeneous finely dispersed structure is formed with particles up to 100 μm in size in cream and up to 150 μm in pudding. It was established that this is due to the formation of protein-carbohydrate complexes, namely, "protein-starch" in the case of pudding with a homogeneous structure and evenly dispersed air bubbles, "protein-dietary fibers" in the case of cream with a homogeneous, delicate, airy structure.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

In the process of writing the manuscript, the authors used the artificial intelligence tool ChatGPT (version GPT-5) to check grammar, spelling, punctuation, without changing the text, and to search for sources using keywords and criteria.

The entire text of the manuscript, including the formulation of the goal, objectives, description of materials and methods, presentation of research results, their discussion, and conclusions, was written by the authors independently based on their own experimental data.

Author contributions

Tetiana Rudakova: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Visualization**,** Supervision, Project administration; **Iryna Romanchuk: Conceptualization; Methodology,** Data Curation, Writing – review & editing, Project administration; **Antonina Minorova: Conceptualization; Methodology;** Data Curation, Writing – review & editing, Project administration; **Sergiy Narizhnyy:** Formal analysis; Resources, Data Curation, Writing – review & editing, Funding acquisition; **Halyna Kalinina:** Formal analysis**,** Resources, Data Curation, Writing – review & editing, Funding acquisition.

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