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Розроблено модель утворення піноемульсійної системи. Визначено шляхи регулювання міцності міжфазних адсорбційних шарів. Експериментально підтверджено, що для створення піноемульсійної системи необхідно використовувати білки молока та три низькомолекулярні поверхнево-активні речовини з високим і низьким гідрофільно-ліпофільним балансом. За реалізації даних принципів одержано піноемульсію, яка володіє високою піноутворюючою здатністю, стійкістю піни та механічною міцністю

Ключові слова: міжфазний адсорбційний шар, гранична напруга зсуву, збита емульсія, піноутворююча здатність

Разработана модель образования пеноэмульсионной системы. Определены пути регулирования прочности межфазных адсорбционных слоев. Экспериментально подтверждено, что для создания пеноэмульсионной системы необходимо использовать белки молока и три низкомолекулярные поверхностно-активные вещества с высоким и низким гидрофильно-липофильным балансом. При реализации данных принципов получена пеноэмульсия, которая обладает высокой пенообразующей способностью, устойчивостью пены и механической прочностью

Ключевые слова: межфазный адсорбционный слой, предельное напряжение сдвига, пенообразующая способность

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DEVELOPING A MODEL OF THE FOAM EMULSION SYSTEM AND CONFIRMING THE ROLE OF THE YIELD STRESS SHEAR OF INTERFACIAL ADSORPTION LAYERS TO PROVIDE ITS FORMATION AND STABILITY

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1. Introduction

In recent years, the process of Ukraine's European integration as a factor of socioeconomic development of the state has a significant impact on all activities of the industrial sector and trade, including the food industry and restaurant business. It affects primarily the requirements for food products, which must comply with the Ukrainian and European standards, and production technologies – to be investment attractive and competitive.

The aforesaid fully applies to the production of food with the foam-emulsion structure – decorating cream, sweet dishes, production and consumption volumes of which have been increasing substantially. The presence of cow cream, butter, traditionally used in the production of foam-emulsion products became a limiting factor due to the instability of their properties, the dependence on seasonal production, growing cost, limited shelf life of products on their basis, which does not meet requirements of manufacturers.

It should be noted that the use of sweet vegetable cream, dry mixes, complex stabilization systems mainly of foreign origin (as semi-finished products of different degrees of readiness) in the technology of foam-emulsion products has significantly increased. This has considerably affected the composition, production technology, cost and consumer properties of finished culinary and confectionery products on their basis. The above semi-finished products, not fully solving technological problems (low foaming capacity and foam stability under the influence of technological factors) do not meet today's requirements in terms of usefulness and safety – they have partially hydrogenated vegetable oils that contain trans fatty acids, surfactants with a limited maximum permissible level of use; with some exceptions products do not contain raw milk. Therefore, the development of the whipped semi-finished product with the use of non-hydrogenated vegetable oil (cocoa butter), skimmed milk powder, surfactants having the GRAS status (Generally Recognized As Safe – without the limiting factor of use) with a high foaming capacity and mechanical strength will allow expanding the sales markets and the range of new products that is a relevant and urgent problem.

2. Literature review and problem statement

It was found [1–4] that solid vegetable oils are used to obtain foam-emulsion systems. Scientists [1] indicate that the structure of whipped emulsion is stabilized by fat crystals. Thus, the use of palm non-hydrogenated oil provides the foaming capacity of about 290 % in 6...8 min of whipping, prolongation of whipping decreases the foaming capacity to about 160 %. This is undesirable in terms of producing creams based on such systems.

Low foaming capacity and its reduction under a significant mechanical influence are associated with the high content of liquid triglycerides. This is confirmed by the authors' studies of various fats, differing in liquid triglyceride content. It is proved that foam-emulsion systems with fats that contain the maximum amount of solid triglycerides provide elasticity, high strength and even fragility. Therefore, the use of vegetable oils with low liquid triglyceride content, keeping fat crystals on air bubbles by capillary forces between them is reasonable [2–4].

In addition to the ratio of solid and liquid triglycerides to produce foam-emulsion systems with the high foaming capacity and mechanical strength of whipped emulsions, regulation of the emulsion stability is also necessary. The emulsion stability regulation is made by the introduction of low molecular weight surfactants to the system. The authors proved that the addition of surfactants to the β-casein [5] affects its adsorption and viscoelastic modulus of interfacial adsorption layers, the addition of hydrophobin provides the surface viscosity increase and foam stabilization [6].

The use of molecules, similar in HLB but different in packing density in the interfacial layer, including saturated and unsaturated monoglycerides provides opposite interfacial processes, confirming the need to justify the type of surfactant to produce foam-emulsion systems. The introduction of saturated monoglycerides to soy protein isolate weakens the interaction of proteins in the interfacial layer to form mixed adsorption layers due to the competitive adsorption of monoglycerides. The effect of monoglycerides depends on the pH [7]. The authors [8] investigated the influence of saturated and unsaturated monoglycerides on the coalescence of fatty particles during the cream whipping. Rheological studies to identify mechanisms were carried out. It is shown that the rheological methods are an informative tool for determining the properties of whipped creams. It is proved that saturated monoglycerides significantly increase the elasticity modulus of the IAL and promote the desorption of proteins from the interface, while unsaturated ones reduce the elasticity modulus and do not lead to the protein desorption.

In the study of yield stress shear of emulsions based on different proteins such as buttermilk, skimmed milk powder, micro-filtrated buttermilk, sodium caseinate, the scientists [9] found that emulsions based on skimmed milk have the highest value.

The study [10] shows that emulsions based on sodium caseinate, saturated monoglycerides, lecithin's increase the temperature of crystallization of sunflower oil that improves the stability of the foam-emulsion system. The stability of whipped emulsion correlates with the strength of interfacial adsorption layers.

The authors [11] investigated the effect of Span 20, 80, 85 and Tween 20, 80, 85 on the foaming capacity, rheological properties of interfacial adsorption layers of the ice-cream mix. It was found that Tween 85 increases the foam stability, which correlates with the viscosity increase of interfacial adsorption layers, and Tween 20 only slightly increases the foaming capacity. However, the study [12] notes that the strength increase of interfacial absorption layers by the protein increase in the solution, or strength decrease up to complete loss of elastic properties is achieved by the introduction of Tween 20, due to the replacement of protein with Tween 20 in the interfacial layer and weakening of protein bonds. The difference in behavior of Tween 20 is probably associated with the surfactant protein ratio, temperature and other factors. Therefore, it is necessary to choose the conditions of the experiment that simulate process conditions of producing foam emulsions, and methods of quantitative estimation.

It should be noted that the behavior of proteins and surfactants at the water-air interface is different from that at the water-oil interface [13].

The behavior of foams and emulsions depends considerably on the properties of interfacial adsorption layers. Knowledge only of the value of surface or interfacial tension is insufficient for understanding and predicting their behavior. Rheological properties are more informative for evaluating the behavior of these systems [14–16]. Rheological properties of interfacial adsorption layers correlate with rheological properties of foams [17] and the stability of foams and emulsions [18] and theoretical models [19].

The literature review confirms the need to use rheological methods of research of interfacial adsorption layers. The reviews contain the list and the characteristics of rheological methods of research [20–23]. It was found that various methods of research of the rheological properties of interfacial adsorption layers are used depending on the chosen theoretical model [22].

Based on the foregoing, it can be stated that the development of the model for producing the foam-emulsion system is possible only for a certain type of proteins and surfactants and can not be multi-purpose at this stage of scientific concepts. For the functioning of the model, i.e. for its experimental confirmation, the use of rheological methods of research, which provide much information about the behavior of disperse systems is reasonable.

3. Research goal and objectives

The goal of the paper is to produce foam-emulsion systems of high foaming capacity, mechanical strength, using vegetable oils without trans fatty acids and surfactants without the limiting factor of use in food products.

To achieve this goal, it was necessary to solve the following problem:

– to develop a model of the formation of the foam-emulsion system;

– to investigate the effect of milk protein, low molecular weight surfactants on the yield stress shear of interfacial adsorption layers;

– to examine the impact of homogenization and whipping on the fat destabilization degree, foaming capacity and mechanical strength of the foam-emulsion system.

4. Materials and methods of research of the yield stress shear of interfacial adsorption layers

The object of research in the paper is skimmed milk powder with the protein content of 33.0±0.1 %, refined, deodorized, winterized sunflower oil, refined cocoa butter, DATEM (diacetyl tartaric acid ester of mono- and diglycerides of fatty acids), LACTEM (lactic acid ester of mono- and diglycerides of fatty acids), lecithin's (soybean lecithin's) with content of acetone insoluble substances of 73.7±0.1 %, sodium carboxymethylcellulose (Blanose 7H4XF).

Determination of the yield stress shear (YSS) of IAL was performed using the surface viscometer with the flat disk at a fixed shear rate (constant disk rotation speed) [23].

Calculation of the IAL YSS (P_s) was performed according to the formula:

$$P_s = \frac{C_0 \times S_0}{360 \times R_1^2 \times n}, \tag{1}$$

where P_s is the yield stress shear of interfacial adsorption layers, N/m; C_0 is the wire torsion modulus (N×m)/degree; S_0 is the deviation of a photocell of the self-recording device until the maximum displacement of the glass disk, m; R_1 is the radius of the glass disk, m; n is the factor of conversion of angular degrees to meters of the scale.

Determination of the IAL YSS was performed at 4±1 °C in 4×3600 s of exposure, i. e. the time required for the adsorption and formation of IAL. Concentrations of proteins and surfactants were reduced by 10 times of the basic recipe to preserve liquid interfaces while simultaneous preservation of ratios of proteins and surfactants. The difference will be only in absolute values of the IAL YSS, but allow determining the patterns of behavior of the systems, including at the water-oil interface since oil crystallizes at high concentrations of surfactants. To simulate the behavior of proteins and surfactants at the water-oil interface and provide a liquid interface, cocoa butter was replaced with sunflower oil.

Calculation of the foaming capacity was performed according to the formula:

$$FC = \frac{V_f}{V_s} \times 100 \ \%, \tag{2}$$

where FC is the foaming capacity of solution, %; V_f is the volume of foam, ml; V_s is the volume of solution before whipping, ml.

To determine the degree of the destabilized fat in foam-emulsion systems, a sample of 40 g was taken and diluted with distilled water in the 1:9 ratio and filtered. The filtered fat remaining on filter paper was dried up to constant weight in the oven. Calculation of the degree of the destabilized fat was performed according to the formula:

$$D' = \frac{m'f}{mf} \times 100 \ \%, \tag{3}$$

where mf is the mass of fat in the sample, g; m′f is the mass of fat after drying, g.

Microscopy of the samples was performed with the "Biolam R15" microscope with ScopeTekDCM – 130 E 1.3 Mp digital eyepiece camera and photography was made using the ScopePhoto 3.0 software. Processing of data of micrographs was performed automatically using the open source ImageJ 1.47 software.

The average diameter of fat particles was determined according to the formula:

$$d_{avg} = \sum_{i=1}^{n} \frac{N_i}{\sum_{i=1}^{n} N} \times d_i, \tag{4}$$

where N_i is the number of particles in the i-fraction; d_i is the diameter of particles of the i-fractions.

Morphology of the samples was studied using the Jeol scanning electron microscope (Japan). Homogenization of emulsions was conducted on a laboratory ultrasonic disperser at the oscillation frequency of 22 kHz. Mechanical strength of foam emulsions was determined on the Labor penetrometer, calculation was performed according to the formula:

$$\sigma_0 = k \frac{m \cdot g}{h^2}, \tag{5}$$

where m is the mass of the indenter and the rod of the device, which acts on the product under research (minus friction and resistance of the indenter spring), kg; g is the gravitational acceleration, m/s^2; h is the cone immersion depth, m; k is the indenter constant

5. Theoretical and experimental verification of the model of the formation of the foam-emulsion system

5. 1. Development of the model of the formation of the foam-emulsion system

To achieve the goal, development of the theoretical model and experimental confirmation of it is necessary. The main criteria for the model evaluation is the use of rheological methods of research in relation to the technological properties – foaming capacity, mechanical strength of foam emulsion and electron microscopy, which confirms the assumptions made.

Given the analytical research, a working hypothesis was formulated, according to which obtaining products with foam-emulsion structure based on whipped semi-finished product with high foaming capacity, stability and mechanical strength is possible due to the controlled process of the formation of emulsion, destabilization of it during foaming, flotation of fat particles and their adhesion to air bubbles.

Based on the working hypothesis, the model of the formation of the foam-emulsion system by the emulsion whipping was developed. The use of milk proteins only does not provide foam-emulsion systems with high indexes indicated due to the presence of two different disperse air and fat phases. Therefore, the use of surfactants is necessary, and considering the needs of consumers, surfactants must have the GRAS status.

To increase the foaming capacity and stability of foams, surfactants with a high HLB should be introduced to the system, DATEM was selected for this purpose.

To ensure the protein desorption from the water-oil interface and fat destabilization, surfactants with high surface activity, lecithin's, were selected.

To ensure agglomeration of fat particles and foam stabilization by agglomerated fat particles, LACTEM was selected.

The mechanism of the formation of the foam-emulsion system is as follows: the first step is to provide conditions for the formation of a direct emulsion by milk proteins and surfactants with high HLB (DATEM). The use of milk protein only in quantities necessary for the formation of stable direct emulsion will create difficulties in destabilization during whipping. Therefore, for the emulsion destabilization, reduction of the diameter of fat particles below the critical value of the structural and mechanical factor of the emulsion destabilization is necessary, which is achieved by homogenization [24]. Reduction of the diameter of fat particles is a prerequisite for entry to the water-air interface, which is limited by the diameter of the Plateau-Gibbs channels [25].

Homogenization of the emulsion and reduction of the temperature in the presence of surfactants with high surface activity (i. e. fat-soluble lecithin's with low HLB) can provide milk protein desorption from the water-oil interface. That is, whipped semi-finished product will be the emulsion, whipping of which provides the foam-emulsion system.

The first stage of whipping assumes that the milk proteins, desorbed from the water-oil interface, will be involved in foaming of the system (Fig. 1, *a*). In the second stage of whipping of the system, emulsion becomes unstable under the mechanical action (Fig. 1, *b*). Destabilization of the emulsion is a necessary factor in producing foam-emulsion systems with high mechanical strength, which can be achieved by adhesion of destabilized fat particles due to flotation with their aggregation to air bubbles with the replacement of milk proteins in the water-air interface.

Conditions for agglomeration of fat particles can be provided through the use of LACTEM, characterized by the high capacity for agglomeration of fat particles in aqueous media. Flotation can be increased due to the use of flotation agents (macromolecular compounds with surface-active properties). In addition, joint use of surfactants with high and low HLB will promote the high foaming capacity of the protein-containing system. Destabilized fat particles will contribute to the foam stabilization (Fig. 1, *c*) by their adhesion to air bubbles and in the Plateau-Gibbs channels, thereby preventing fluid drainage and forming a plastic consistency of the product, which would increase the mechanical strength of the whipped semi-finished product.

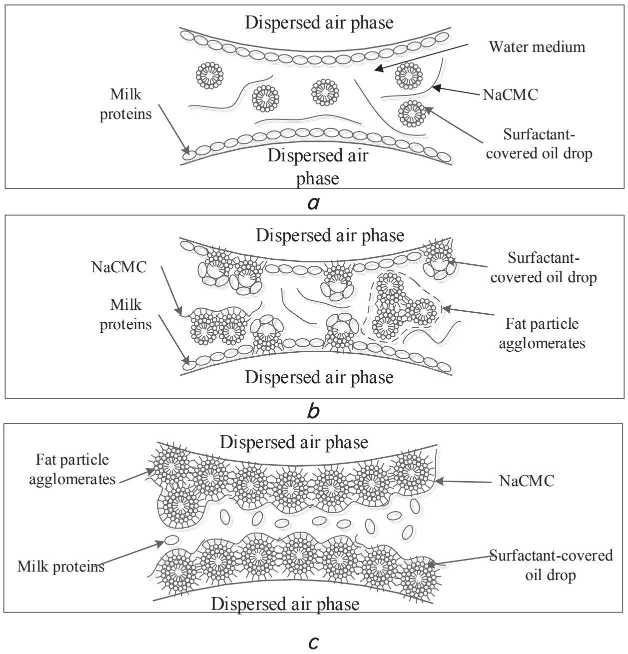

Fig. 1. Model of the formation of the foam-emulsion system of the whipped semi-finished product: *a* — the I stage of whipping (foaming); *b* — the II stage of whipping (emulsion destabilization); *c* — the III stage of whipping (foam emulsion stabilization)

Justification of the type and amount of flotation agent should take into account the provision of flotation agglomeration of fat particles, ensuring the high mechanical strength of the foam-emulsion systems, i.e. it should have surface-active properties for adsorption on fat particles, increasing the flotation effect. NaCMC meets these requirements.

Production of whipped semi-finished products, providing sustainable foam-emulsion products with high quality requires the study of mechanisms of behavior of milk proteins and surfactants at the water-oil and water-air interface. Adsorption and desorption of proteins at the interface depends on the content and type of surfactant (HLB). Lowering the temperature of the product, containing proteins and surfactants with a simultaneous increase in the water-air interface (whipping) requires determination of their behavior and the system as a whole.

The process of production of emulsion semi-finished products with foam structure involves the use of reconstituted skimmed milk, oil emulsification, cooling of prescription mix and whipping. The main prescription components that form the structure of foam-emulsion products are skimmed milk powder as a source of protein, cocoa butter (as vegetable oil containing no trans fatty acids with a high content of solid triglycerides), surfactants DATEM, LACTEM, lecithin's and NaCMC.

5. 2. Results of the study of the yield stress shear of interfacial adsorption layers

The effect of reconstituted skimmed milk on the IAL YSS was determined. It was found that the dependence of the IAL YSS on the content of reconstituted skimmed milk has extreme nature with a maximum corresponding to the content of 4 % and amounts to $(1.04\pm0.05)\times10^{-3}$ N/m at the water-oil interface in the presence of oil in a liquid state (Fig. 2, curve – ◊) and $(0.74\pm0.03)\times10^{-3}$ N/m at the water-air interface (Fig. 2, curve – □). It is evident that absolute strength values of IAL on different interfaces are quite similar and differ only by 1.4 times. The presence of the extremum of milk proteins corresponds to the monomolecular layer formation [24].

The dependence of the foaming capacity of foam-like and foam-emulsion systems is similar in nature to the extreme dependence [26].

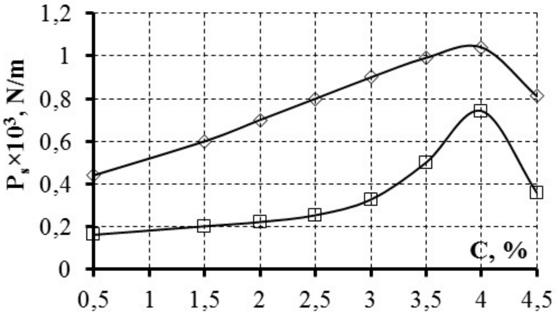

Fig. 2. Yield stress shear of IAL on the content of reconstituted skimmed milk at 4±1 °C at the interface: ◊ – water-sunflower oil; □ – water-air

With an increasing content of DATEM in the system "reconstituted skimmed milk-DATEM" from 0.02 to 0.05 %, the IAL YSS at the water-oil interface increases by 3.9 times (Fig. 3, curve – □). A similar relationship, but with smaller absolute values was obtained at the water-air interface (Fig. 3, curve – Δ), the IAL YSS increases by 4.2 times, that is the introduction of DATEM contributes to stabilization of both foams and emulsions. Thus, it was experimentally confirmed that the introduction of DATEM increases the stability of foam-like systems [26], and the study [17] confirmed the correlation of the yield stress shear of interfacial adsorption layers and yield stress shear of foam.

The IAL YSS of the content of LACTEM at the water-oil, water-air interface was determined. It was found that dependence of the IAL YSS at the interface with oil (Fig. 4, curve – ■) has an extreme nature with a maximum corresponding to the LACTEM content of 0.06 %. However, at the water-air interface, the introduction of LACTEM reduces the IAL YSS (Fig. 4, curve – □). It was confirmed that the introduction of LACTEM reduces the foaming capacity of foam-like systems [26]. The difference in behavior at different interfaces is probably due to variations in functional properties, including the capacity for agglomeration of fat particles.

The introduction of lecithin's to the reconstituted skimmed milk reduces the IAL YSS at both the water-air interface and water-oil interface. It was found that with increasing content of lecithin's from 0.01 to 0.05 % in the system "reconstituted skimmed milk-lecithin's" at the air-oil interface, the IAL YSS decreases by 3.2 times (Fig. 4, curve – ▲) and by 1.2 times at the water-air interface (Fig. 4, curve – Δ), respectively, which confirms the protein desorption capacity of lecithin's from the interface.

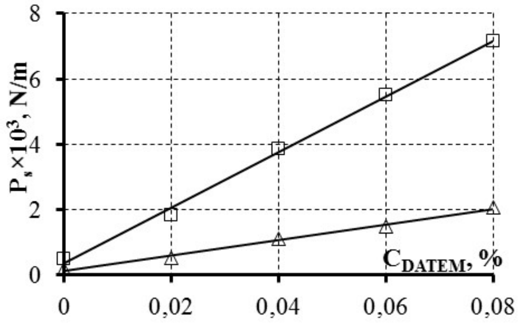

Fig. 3. Yield stress shear of IAL of the system "reconstituted skimmed milk (0.35 %)-DATEM" on the DATEM content at 4±1 °C at the interface: □ – water-sunflower oil; Δ – water-air

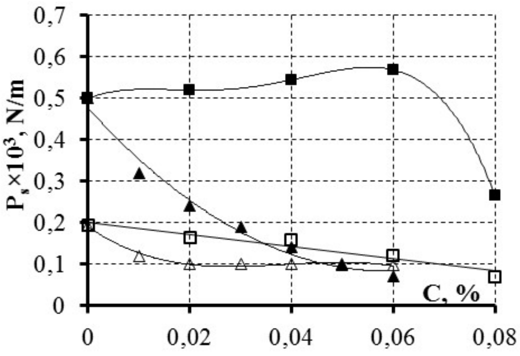

Fig. 4. Yield stress shear of IAL of the system "reconstituted skimmed milk (0.35 %)-surfactants" on the surfactant content at 4±1 °C with the surfactant content: □ – LACTEM; Δ – lecithin's, at the interface: water-sunflower oil – dark markers; water-air – light markers

It was experimentally confirmed that introduction of lecithin's to the reconstituted skimmed milk leads to a significant reduction in the foaming capacity and foam stability of foam-like systems "reconstituted skimmed milk-lecithin's" [26].

With the LACTEM content of 0.04...0.06 %, increase in the DATEM content increases the IAL YSS at the water-oil interface. So, with the LACTEM content of 0.04 %, with the DATEM increase up to 0.08 %, the IAL YSS increases by 23 times compared to systems without DATEM (Fig. 5, curve – ▲). With the LACTEM content of 0.06 %, increase in the DATEM content up to 0.08 % increases the IAL YSS by 24 times (Fig. 5, curve – ■). At the water-air interface with increased DATEM content up to 0.08 % with the LACTEM content of 0.04 %, the IAL YSS increases by 15.8 times (Fig. 5, curve – Δ). With the LACTEM content of 0.06 %, the IAL YSS increases by 21.2 times (Fig. 5, curve – □) compared to systems that do not contain DATEM.

It was experimentally confirmed that the increase in the lecithin's content in the systems "reconstituted skimmed milk-DATEM-LACTEM" increases the foam stability. To confirm the participation of all surfactants in the formation of interfacial adsorption layers, the IAL YSS of the systems “LACTEM-DATEM” was determined. It was found that the IAL YSS of systems without milk proteins are characterized by lower strength by about 2...3 times (Fig. 6), which confirms the participation of milk proteins and low molecular weight surfactants in the formation of IAL.

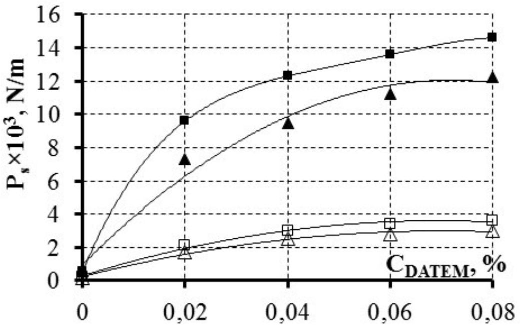

Fig. 5. Yield stress shear of IAL of the system “reconstituted skimmed milk (0.35 %)-LACTEM-DATEM” on the DATEM content at 4±1 °C at the interface: water-sunflower oil – dark markers; water-air – light markers, with the LACTEM content, %: □ – 0.04; Δ – 0.06

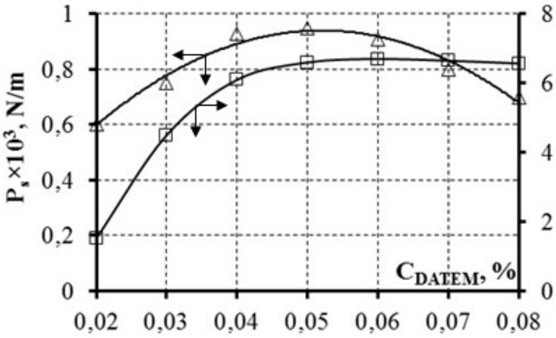

Fig. 6. Yield stress shear of IAL of the system “LACTEM-DATEM” on the DATEM content at 4±1 °C with the LACTEM content of 0.04 % at the interface: Δ – water-air; □ – water-sunflower oil

Thus, it can be argued that the introduction of two pairs of surfactants with high (DATEM) and low HLB (LACTEM) to the reconstituted skimmed milk increases the foaming capacity and foam stability due to increased strength of IAL.

To identify the role of lecithin’s in the formation of IAL, the effect of lecithin’s on the IAL YSS of the systems “DATEM-LACTEM-lecithin’s” was determined (Fig. 7). Analysis of the data showed that lecithin’s reduce the IAL YSS by 5.2 times. Comparison of absolute values of the IAL YSS with milk protein containing systems shows that their strength is about 2 times higher in the presence of protein in the system, which suggests that lecithin’s promote partial desorption of all surfactants, involved in the formation of IAL.

It was determined that the introduction of lecithin’s to the system “reconstituted skimmed milk-DATEM-LACTEM-lecithin’s” at the water-oil interface reduces the IAL YSS. Thus, with increasing lecithin’s content up to 0.05 % in the system “reconstituted skimmed milk-DATEM-LACTEM-lecithin’s” with the DATEM content of 0.06 %, LACTEM 0.04 %, the IAL YSS decreases by 5.7 times (Fig. 8 curve – ■), with the DATEM content of 0.06 %, LACTEM 0.06 %, the IAL YSS decreases by 3.6 times (Fig. 8, curve – ▲). This is probably due to the desorption of milk proteins from the interface, desorbed protein in the emulsion system will contribute to foaming during whipping (as confirmed experimentally). At the interface, there is an opposite trend, so with the increase in the lecithin’s content up to 0.05 % in the system “reconstituted skimmed milk-DATEM-LACTEM-lecithin’s” with the DATEM content of 0.06 %, LACTEM 0.04 %, the IAL YSS increases by 1. 1 times (Fig. 8, curve – Δ). With the DATEM content of 0.06 %, LACTEM 0.06 % (Fig. 8, curve – □), the IAL YSS increases by 1.3 times.

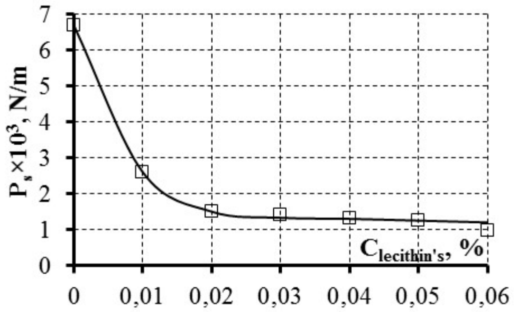

Fig. 7. Yield stress shear of IAL of the system “DATEM-LACTEM-lecithin’s” on the lecithin’s content at 4±1 °C at the water-sunflower oil interface, with the DATEM content of 0.06 %, LACTEM 0.04 %

Comparison of absolute data of the IAL YSS in the system “reconstituted skimmed milk-DATEM-LACTEM-lecithin’s” with the DATEM content of 0.06 %, LACTEM 0.04 %, lecithin’s 0.03...0.06 % at the water-oil and water-air interface shows that the YSS is by 1.3 times higher at the water-air interface, which is a necessary thermodynamic condition for the formation of the foam-emulsion system due to the emulsion whipping on the basis of four surfactants: milk proteins, DATEM, LACTEM, lecithin’s at 4±1 °C.

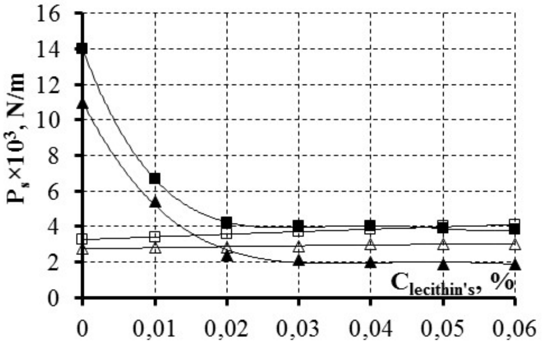

Fig. 8. Yield stress shear of IAL of the system “reconstituted skimmed milk (0.35 %)-DATEM-LACTEM-lecithin’s” on the lecithin’s content at 4±1 °C at the interface: water-oil – dark markers; water-air – light markers

5. 3. The results of the study of the fat destabilization degree, foaming capacity and mechanical strength of foam emulsions

To determine the effect of homogenization on the fat destabilization, the influence of the homogenization intensity of the system "reconstituted skimmed milk-cocoa butter-LACTEM-DATEM-NaCMC" (duration of treatment by ultrasonic disperser) on the fat destabilization degree and average diameter of fat particles was identified (Fig. 9, curve – □). It is seen that the increased homogenization duration from 60 s to 5×60 s increases the fat destabilization degree from 70.2±3.5 % up to total destabilization.

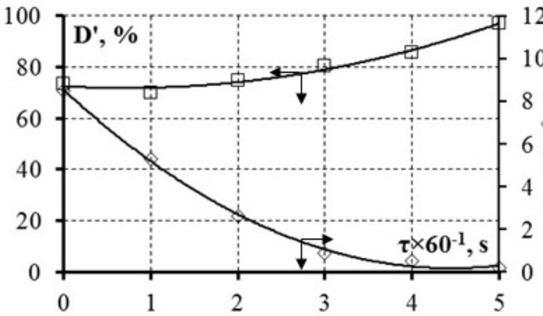

Fig. 9. The dependence of the fat destabilization degree (□) and average diameter of fat particles (◊) on the homogenization duration of the system "reconstituted skimmed milk-cocoa butter-LACTEM-DATEM-lecithin's-NaCMC"

Due to the adhesion on the surface of air bubbles, fat particles should ensure foam stability and mechanical strength of the foam-emulsion system, so conditions for contact of fat particles with the water-air interface should be provided. It was found that the diameter of the Plateau-Gibbs channels in the systems "skimmed milk-surfactants" is about 1.0×10^{-6} m, so the emulsion homogenization is necessary for free contact of fat particles with air bubbles. It was found that under the complete destabilization of fat, the average diameter of fat particles is $(0.20\pm0.01)\times10^{-6}$ m (Fig. 9, curve – ◊). It can be expected that fat particles with such diameter will move freely through the Plateau-Gibbs channels.

The effect of the whipping duration on the foaming capacity, the mechanical strength of the foam emulsion and the destabilization degree of fat were investigated (Fig. 10). It was found that the whipping process can be divided into three stages. The first stage (up to 2×60 s) involves an intensive process of foaming (Fig. 10, curve – □) due to milk proteins, the mechanical strength of the foam is virtually unchanged (Fig. 10, curve – ◊), the amount of the destabilized fat is 47. 8±2.4 % (Fig. 10, curve – Δ), however, the amount of the destabilized fat is probably low and the amount of surfactants that are able to be released during the fat destabilization is insufficient in the aqueous solution. At the second stage (from 2×60×4.5 s to 60 s), the foaming process comes to the end, reaching maximum values of 450±22 %. This stage involves an intensive process of enhancing the mechanical strength of the foam emulsion and increasing the amount of the destabilized fat. Probably, at this stage, there is a replacement of protein in the water-air interfacial layer with fat particles or aggregates, as evidenced by the increased mechanical strength. The third stage provides complete destabilization of fat, the foaming capacity does not change, the mechanical strength of the foam emulsion increases, completing the replacement of proteins with fat aggregates and forming protective adsorption layers on the surface of air bubbles.

So, reasonable duration of whipping of the semi-finished product is (4.5...5.0)×60 s, providing the foaming capacity of 450±22 %, the mechanical strength of the foam emulsion of the semi-finished product of 3200±160 Pa and complete fat destabilization degree. The assumptions concerning the foam emulsion stabilization can be confirmed by electron microscopy. The data of electron microscopy confirm the final structure of the foam emulsion of the semi-finished product (Fig. 11).

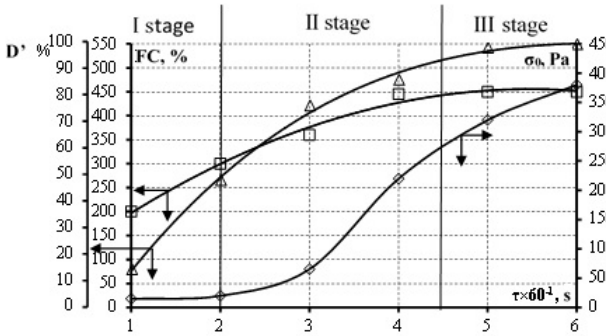

Fig. 10. Foaming capacity (□), mechanical strength of the foam emulsion (◊) and the fat destabilization degree (Δ) of the whipped semi-finished product on the whipping duration

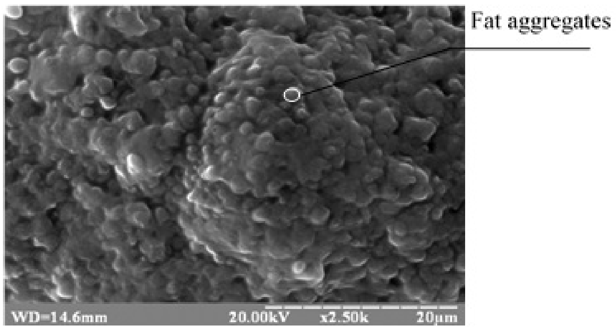

Fig. 11. Photo of the foam emulsion of the whipped semi-finished product at ×2500 magnification

Theoretical and experimental studies confirm the working hypothesis and the developed model of the formation of the foam-emulsion system. It was confirmed that during the emulsion whipping, three stages of whipping that differ in processes can be singled out, foaming involving milk proteins, desorption from the water-air interphase, destabilization of fat and adhesion of destabilized particles to air bubbles providing the high mechanical strength of the foam emulsion.

6. Conclusions

1. The model of the formation of the foam emulsion was developed, three stages of whipping were singled out, which differ in processes, including foaming involving proteins, destabilization of fat particles, agglomeration, flotation and adhesion to air bubbles, providing the high mechanical strength of the foam emulsion.
2. The research allowed determining the mechanism of the formation of interfacial adsorption layers at the water-oil, water-air interface in systems containing milk proteins, surfactants (DATEM, LACTEM, lecithin's) and mixtures thereof at a temperature of 4±1 °C. It was found that in systems containing milk proteins and surfactants

with low HLB (LACTEM, lecithin's), the IAL is characterized by lower yield stress shear compared to systems without surfactants, that is these surfactants promote the protein desorption from the interface. With high HLB (DATEM), the IAL with high yield stress shear are formed, which correlates with the stability of emulsions and foams. The use of the mixture of two surfactants with high HLB DATEM and low HLB LACTEM allows significantly increase the strength of IAL by about 23...24 times at the water-oil interface, and about 15.8...21.2 times at the water-air interface compared to systems with one surfactant. The introduction of three surfactants DATEM, LACTEM, lecithin's to reconstituted skimmed milk allows achieving a higher yield stress shear of IAL at the water-air interface than at the water-oil interface, which is a necessary thermodynamic condition for the formation of the foam emulsion by the emulsion whipping.

3. It was experimentally confirmed that homogenization of emulsions containing protein and low molecular weight surfactants provides destabilization of the emulsion. Experimental determination of the foaming capacity, yield stress shear, fat destabilization degree and electron microscopy have confirmed the developed model of the formation of the foam emulsion, three stages of whipping have been singled out.

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