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IDENTIFYING THE INFLUENCE OF THE CONCENTRATION OF SURFACTANTS ON THE TECHNOLOGICAL INDICATORS OF AEROSOL EMULSION

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The object of the study is an emulsion system containing emulsifiers (Emulgin B2, Lanett SX), wetting agents (propylene glycol, glyceryl cocoate) and sodium laureth sulfate as a foaming agent. The main problem solved in the study is to ensure rational technological properties of emulsion systems in aerosol form under variable storage and use conditions. The results obtained showed that to ensure maximum emulsion stability during 7 and 30 days of storage, the optimal concentrations of Emulgin B2 are 2.75…3.0 %, and Lanett SX is 2.0…2.5 %. To achieve the desired foaming ability (80…85 %) and foam stability (75…80 %), it is recommended to use sodium laureth sulfate at a concentration of 0.20…0.22 %. It was found that the wetting agents – propylene glycol (7 %) and glyceryl cocoate (1.5 %) – provide optimal system viscosity within 35…40 mPa•s. The stability of the emulsion is ensured by the formation of strong interfacial films using Lanett SX, while Emulgin B2 improves the thermal stability of the system. Foaming properties are provided by the ability of sodium laureth sulfate to reduce interfacial tension, however, too high concentrations can lead to foam oversaturation and deterioration of its stability. The features of the obtained results are that specific concentration limits of the components are justified, at which the necessary stability and functionality of the emulsion system are ensured. This allows solving the problem of achieving optimal characteristics of the emulsion system during storage and use, ensuring comfortable application to the skin and a stable foam structure. The scope of application of the obtained results is the cosmetic industry

Keywords: emulsion system, Emulgin B2, Lanett SX, sodium laureth sulfate, moisturizing agents, propylene glycol, glyceryl cocoate

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1. Introduction

Emulsions are a type of heterogeneous disperse systems common both in nature and in industry. Like other disperse systems, emulsions are widely used in various industries: chemical, food, pharmaceutical, cosmetic, textile, oil and gas, paint and varnish, agrochemical and construction industries [1]. Due to their properties, such as the ability to stably maintain various components in a phase, emulsions are also used in water purification technologies, the creation of new materials and in the production of household chemicals. They are obtained by dispersing a mixture of two mutually insoluble liquids [2].

The physical properties of emulsions depend on a number of factors: the ratio of phase volumes, particle size, particle size distribution, etc. The difficulty in obtaining stable emulsions lies in the fact that it depends on a number of factors, such as the surface tension of the phases, the viscosity of the dispersion medium, temperature, and particle dispersion. One of the problems in ensuring the stability of emulsions is their tendency to coalescence, flocculation, and sedimentation [3].

The use of emulsifiers is one of the methods for increasing the stability of emulsions and reducing the risk of coalescence. To achieve a uniform distribution of the dispersed phase, the value of the interfacial surface tension must be reduced using the minimum possible emulsifier concentrations. In addition to the process of diffusion of emulsifier molecules from the liquid phase to the interfacial surface, an important factor is also the speed of their distribution over the surface. Emulsifiers significantly increase the viscoelasticity of the interfacial film, which complicates its deformation and reduces the speed of coalescence of the dispersed phase [4]. This leads to the fact that the effective viscosity of the dispersed phase can significantly exceed the viscosity of the bulk phase, sometimes by several orders of magnitude. The method of preparing the emulsion also significantly affects its stability. In general, the dispersed phase is formed by the one in which the emulsifier dissolves better. The ratio of polar and non-polar groups in the structure of the emulsifier molecule is crucial for its choice. With increasing emulsifier concentration, interfacial surface tension decreases, which contributes to emulsion stabilization [5].

Emulsions are considered thermodynamically unstable systems, therefore, establishing technological criteria for selecting appropriate components and their concentrations to achieve kinetic stability is a difficult task. For the formation of a complex of stabilizers of emulsion systems, there are certain criteria according to which emulsifiers are selected. The synergistic effect of emulsifier mixtures is observed when two emulsifiers form complexes at the interface that do not occur in any of the phases [6].

For the possibility of using emulsions in aerosol form, it is important to consider not only the combination of surfactants, but also the stability of the emulsion system under elevated pressure. It is necessary to ensure the stability of the emulsion system, maintaining its homogeneity and effectiveness in the form of a spray [7]. For this purpose, it is advisable to use complex emulsifiers that are able to stabilize both the aqueous and oily phases, preventing emulsion separation. Therefore, studies aimed at identifying the influence of surfactant concentrations on the technological parameters of an aerosol emulsion will allow predicting product stability, optimizing rheological parameters and foaming properties of the emulsion system. Scientific studies aimed at identifying the patterns of the influence of surfactant complex concentrations on technological parameters are relevant. The results of such studies are needed by production due to the need to predict the shelf life of the commercial form of such products, as well as improving the technologies of emulsion systems in aerosol form.

2. Literature review and problem statement

In [6], the effect of a complex of three emulsifiers *Tween* 80, gum arabic and polyethylene glycol on the preparation of nanodispersions with specified properties was investigated. Using the proposed model of the composition of surfactants, a nanodispersion was obtained that had a minimum particle size, as well as additional antibacterial activity against *E. coli* and *S. aureus* strains. However, issues related to the long-term stability of nanodispersions under different storage conditions and interaction with other components of the emulsion system remained unresolved. The reason for this may be objective difficulties associated with the sensitivity of nanodispersions to temperature fluctuations and storage conditions, which limits their application in practice. An option to reduce the corresponding difficulties may be to optimize the composition of emulsifiers to increase the stability of the system during long-term storage. This is the approach used in [8], which investigated the combination of different emulsifiers to improve oxygen stability.

In the study [8], the effect of a complex of *Tween* (*Polysorbate*) emulsifiers – *Tween* 20, 40, 60 and 80, on sodium alginate dispersions encapsulated with fish oil and calcium alginate capsules was studied. All model emulsion samples with the *Tween* series induced higher creaminess stability than the dispersion stabilized with sodium alginate. It was found that the combination of *Tween* series emulsifiers increases the oxidative stability of fish oil in capsules. However, questions related to the long-term stability of such systems under changing external conditions, such as prolonged storage at elevated temperatures or exposure to light, remain unresolved. Such conditions may promote the oxidation of fatty acids and the degradation of emulsifiers, which requires further research. This is the approach used in [9], where a complex of emulsifiers (anionic, cationic, and nonionic) was used to increase the kinetic stability of cosmetic emulsions.

In the study [9], the kinetic stability of a cosmetic emulsion containing three different emulsifiers (anionic, cationic and non-ionic) was determined using rheological analysis. The emulsifiers were tested at different concentrations, and model emulsion samples were kept at different temperatures (5...60 °C). The rheological results show the influence of the concentrations and chemical properties of the emulsifiers on the stability of the emulsion. The best indicators were observed for samples with cationic and anionic emulsifiers. The correlation between rheological and sensory results confirmed the effectiveness of predictive studies based on rheological analysis, which can eliminate or reduce the long periods of time required for kinetic studies (aging) and sensory tests on humans. However, issues related to predicting the stability of such emulsions during long-term storage under real-world conditions remain unresolved. An option to reduce these difficulties may be to expand the range of emulsifiers in the complex of mono- and diacylglycerols of fatty acids, which are food additives E 471. Due to their surface-active properties, E 471 is used as emulsifiers in various products to regulate and stabilize technical and functional properties [10]. However, a number of unresolved issues remain, in particular, the influence of mono- and diacylglycerols of fatty acids on the stability of oil-fat systems during long-term storage and under different temperature conditions. One of the reasons for this is the objective difficulties associated with controlling oxidative processes in products containing a high amount of unsaturated fatty acids. In addition, the chemical instability of mono- and diacylglycerols of fatty acids during technological processing (for example, at high temperatures) [3] can lead to the formation of undesirable by-products. An option to overcome these problems may be to study the chemical composition of emulsifiers to monitor the stability to oxidation of fat systems. This approach has already been tested in [11], which presents the results of the analysis of the composition of mono-, di-, triacylglycerols and fatty acids in food emulsifiers using high-performance liquid chromatography with mass spectrometry. It is shown that these methods allow to determine the composition of emulsifiers with high accuracy and identify the presence of individual components, in particular oxidation products, in complex systems. However, issues related to predicting long-term storage and stability of emulsion systems under various conditions, in particular, under the influence of mechanical factors, remain unresolved. The reason for this may be objective difficulties associated with the complexity, which involves the interaction between the components of emulsion systems, as well as the high cost of conducting comprehensive studies. An option to overcome the relevant difficulties may be the result described in [12].

In [12], the results of the study of the kinetic stability of cosmetic emulsions created using different emulsifiers, using rheological and sensory analyses, are presented. In addition, a similar approach is used in [13], where the behavior of emulsifiers (mono- and diacylglycerols of fatty acids and lecithins) in whipped cream in aerosol form is investigated. It is shown that changes in the composition of emulsifiers affect the properties of the emulsion and foam, which allows optimizing their stability and properties in industrial applications. It is determined that the selection of an emulsifier can optimize the properties of whipped cream, providing the necessary balance between emulsion stability and foam quality in model emulsion systems. However, there are unresolved issues related to the optimization of the composition of emulsifiers to achieve maximum stability under different temperature regimes and storage conditions, which is critical for ensuring long-term product quality. An option to solve this issue may be the use of new biocompatible polymers or natural emulsifiers that can provide emulsion stability at a reduced cost. This is the approach used in [14], which investigated the use of plant-animal extracts and biocompatible polymers to form oil-in-water emulsions for the food and pharmaceutical industries. It was shown that such emulsions can provide a high level of stability for consumers when using natural components that are biodegradable, together with traditional synthetic emulsifiers. However, issues related to quality control of emulsion systems and optimization of the production process remain unresolved. The reason for this may be objective difficulties associated with the instability of natural components in the long term, which complicates their industrial wide-scale application. In addition, the described extracts can be more expensive to produce and use special storage conditions, which increases production costs. An option to overcome these difficulties may be the introduction of new analytical methods for controlling the composition of emulsions, which allows to better understand the processes occurring in the system at the molecular level and optimize their stability. This approach was used in [15], where the interaction of lecithins with mono- and diacylglycerols of fatty acids in whipped cream was studied using high-performance thin-layer chromatography with fluorescence detection. It was shown that this technique allows to accurately and quickly determine the composition of emulsions, which is important for controlling their quality and optimizing the production process. In addition, such a technique can significantly improve the process of production control and meet food safety standards. There are still unresolved issues related to the development of new stabilizer complexes that can maintain the stability of emulsions in more complex systems. An option to solve this issue may be the development of a new stabilizer that can provide greater stability of emulsion systems. This is the approach used in [16], which investigated the development of a mixture of stabilizers-emulsifiers to improve the quality of ice cream at a structured level. A complex of emulsifiers (monoglycerides of fatty acids (0.33 %), guar gum (0.16 %), carrageenan (0.16 %), carboxymethylcellulose (0.16 %), tapioca fiber (0.33 %), corn starch (0.33 %)) was substantiated, which had the best technological characteristics in ice cream technology. In addition, the developed composition reduced industrial costs, allowing to replace commercial stabilizers and emulsifiers. However, an unsolved problem is the long-term stability of such disperse systems under different storage conditions, as well as the influence of temperature fluctuations on the physicochemical properties.

All this gives grounds to assert that there is not enough scientific data on the composition of the emulsion system and its influence on the given technological characteristics. In particular, it is advisable to identify the influence of the ratios of surfactants on the stability of emulsion systems, their rheological indicators and foaming properties. Such development will allow to rationalize a number of technological processes for the production of emulsion systems, including for aerosol use, as well as to guarantee a consistently high quality of emulsion-based products.

3. The aim and objectives of the study

The aim of the study is to determine the influence of surfactant concentrations on the stability, rheological and foaming properties of an aerosol emulsion system of the oil-in-water type. The results obtained will allow optimizing the composition of aerosol emulsions to ensure their stability, foaming efficiency and improvement of technological characteristics during use.

To achieve the set aim, the following objectives were solved:

– to investigate the influence of the ratios of emulsifiers Emulgin B2 and Lanett SX on the stability of the emulsion system;

– to investigate the influence of the ratios of wetting agents on the rheological parameters of the emulsion system;

– to determine the influence of the concentration of sodium laureth sulfate on the foaming properties and foam stability of the emulsion system.

4. Materials and methods

4. 1. The object and hypothesis of the study

The subject of the study is the composition of an aerosol emulsion with moisturizing properties, which includes the sodium salt of hyaluronic acid, stabilized by emulsifiers and a foaming agent to ensure stability and optimal rheological parameters.

The main hypotheses of the study are:

– the possibility of optimizing the stability of an emulsion system of the "oil-in-water" type by selecting the ratios of emulsifiers Emulgin B2 and Lanett SX, which will ensure a uniform distribution of the dispersed phase and reduce the tendency to coalescence;

– the influence of the ratios of moisturizing agents, such as propylene glycol and sodium hyaluronate, on the rheological properties of the emulsion system. It is assumed that changing their concentrations will improve the viscosity and fluidity of the emulsion, which will contribute to improving the sensory characteristics and stability during use;

– determination that the concentration of sodium laureth sulfate has a significant effect on the foaming properties of the emulsion system. It is expected that increasing its concentration will increase the volume and stability of the foam, but excessive dosage may lead to destabilization of the system due to a decrease in the interfacial surface tension below the critical limit.

The study assumes that the stability of the emulsion system and its rheological properties, determined under accelerated aging conditions, are proportional to its stability and rheology during long-term storage under recommended conditions.

The study adopts the following simplifications:

– the effect of external factors, such as temperature and humidity, on the stability and foaming properties of the emulsion system is not taken into account;

– the effect of the interaction between sodium laureth sulfate and other surfactants is not analyzed in detail, focusing only on its effect on foaming;

– moisturizing properties are studied within selected concentrations without taking into account the possible influence of other hydrophilic components presented in real products.

4. 2. Materials used in the experiment

The following materials were used during the research:

– sodium salt of hyaluronic acid (manufactured in China), according to CAS 9067-32-7;

– emulsifier Emulgin B2 (manufactured in China), according to CAS 9004-98-2;

– emulsifier Lanett SX (manufactured in China), according to CAS 68855-56-1;

– sodium laureth sulfate (manufactured in China), according to CAS 9004-82-4;

– glyceryl cocoate (PEG-7) (manufactured in China), according to CAS 68201-46-7;

– vaseline oil (manufactured in Ukraine), according to CAS 8012-95-1;

– trilon B (manufactured in Ukraine), according to CAS 60-00-4;

– methylparaben (manufactured in China), according to CAS 99-76-3;

– sodium phosphate dibasic 12-hydrate (manufactured in Ukraine), according to CAS 10039-32-4;

– distilled water (manufactured in Ukraine), according to CAS 7732-18-5.

4. 3. Method of manufacturing emulsion system samples

The oil phase of the emulsion consists of Emulgin B2 (2.0…3.0 %), Lanett SX (1.0…2.0 %) and glyceryl cocoate (1.0…2.0 %). These components are placed in a heat-resistant beaker and heated in a water bath to 75 °C until they are completely melted and form a homogeneous mixture. It is important to control the temperature to avoid overheating, which can destroy the structure of the components. The aqueous phase is prepared separately, which includes propylene glycol (5.5…8.5 %) and distilled water. The aqueous phase is also heated in a water bath to 75 °C. Sodium salt of hyaluronic acid (0.3 %) is added to the aqueous phase during its heating. It must be thoroughly dissolved in the aqueous phase at a temperature of 75 °C to ensure uniform distribution and effective moisturizing. Sodium laureth sulfate (0.1…0.3 %) is added to the aqueous phase at the time of dissolution of hyaluronate in the aqueous phase, providing foaming properties of the emulsion system. Sodium phosphate dibasic 12-hydrate (0.05 %), which acts as a pH stabilizer, and Trilon B (0.4 %), which acts as a complexing agent, are also added to the aqueous phase. Methylparaben (0.2 %) is added to the aqueous phase as a preservative to ensure microbiological stability of the product.

After reaching the same temperature (75 °C) of the aqueous and oil phases, they are gradually combined. The aqueous phase is added to the oil phase with constant stirring using a homogenizer (2000…3000 rpm) for 10…15 minutes. After emulsification, the mixture is gradually cooled to room temperature, continuing to stir at a lower speed (500…1000 rpm) to ensure system stability and prevent stratification.

4. 4. Methods for determining the stability of an emulsion system

Determination of emulsion stability by centrifugation is implemented as follows. 10 ml of the sample is placed in a centrifuge tube and centrifuged at a speed of 3000…5000 rpm for 20 minutes. The stability of the emulsion is determined by the volume of the separated phase (aqueous or oily), which is measured as a percentage of the total volume.

To study thermal stability, temperature cycles of heating the sample to +45 °C and cooling to 0 °C are carried out. The samples undergo 5 such cycles, after which the volume of the stratified phase is estimated. Each cycle lasts approximately 7 hours. Heating to +45 °C and cooling to 0 °C lasts 3 hours to ensure uniform heating and cooling of the sample. The transition between temperature stages takes an additional 1 hour.

4. 5. Method for determining the viscosity of an emulsion system

The effective viscosity of model samples of model emulsion systems was determined on a rotational viscometer "Rheotest 2" (Germany). This device is designed to measure the rheological properties of non-Newtonian liquids in a system of coaxial cylinders. Before determination, the model samples were kept for 2 hours at a temperature of 20 °C. The emulsion sample is thoroughly mixed until homogeneous to avoid phase separation. The sample volume should be sufficient to completely immerse the viscometer rotor in the liquid. The rotational viscometer is prepared for operation by installing the appropriate rotor and programming the measurement parameters, in particular the rotation speed. The rotor type and speed are selected depending on the expected viscosity of the liquid. It is important to maintain a constant temperature during measurement. The emulsion sample is placed in the measuring chamber of the viscometer. It is important to avoid air bubbles when immersing the rotor, as they can affect the accuracy of the measurement. After establishing a stable rotation speed, the viscosity of the emulsion is measured. The viscosity is measured several times to ensure the accuracy of the data obtained, and the results are averaged [17].

4. 6. Method for determining the foaming properties of an emulsion system

To assess the foaming ability of an emulsion system, the shaking method is used. First, a sample of the emulsion is prepared according to the specified composition. 100 ml of the emulsion system is poured into a 250 ml graduated cylinder. Then the cylinder is shaken vigorously 30 times for 30 seconds to create foam. After that, the volume of the foam formed is measured in milliliters. The foaming ability is calculated as a percentage, as the ratio of the volume of the foam to the initial volume of the liquid, multiplied by 100 %.

To determine the stability of the foam, observations are made of the decrease in the volume of the foam over time. After foam formation, as described in the foaming method, the cylinder with the sample is left alone and the volume of the residual foam is measured after 1 minute. Foam stability is calculated as a percentage as the ratio of the volume of foam remaining after a certain time to the initial volume of foam, multiplied by 100 %.

4. 7. Research planning and statistical processing of results

The experiments were carried out in triplicate. To determine the dependences of stability, thermal stability, rheological parameters and foaming parameters of the emulsion system on the concentrations of emulsifiers Emulgin B2, Lanett SX, wetting agents, propylene glycol and glyceryl cocoate, as well as sodium laureth sulfate, the multivariate regression method was used. Statistical dependence models were constructed by approximating experimental data using trend lines using the Statistica (StatSoft, USA) and Microsoft Excel (Microsoft, USA) software packages. The quality of the obtained dependence equations (1)–(7) was assessed using the approximation reliability coefficients, which in all cases exceeded 0.95. This allows to conclude that the models are highly accurate and the factors under study have a significant impact on the parameters of the emulsion system. In particular, variations in the concentrations of emulsifiers, wetting agents and sodium laureth sulfate demonstrate a direct impact on the key indicators of stability and viscosity of the system, which was confirmed by the constructed models. The significance of the coefficients of the approximation dependence equations was checked by the least square method. The adequacy of the obtained equations was confirmed using the Fisher criterion, which allows the use of models to predict the behavior of emulsion systems under production and storage conditions.

5. Results of determining the influence of surfactant concentrations on the technological indicators of an aerosol emulsion

5. 1. Study of the influence of the ratios of emulsifiers Emulgin B2 and Lanett SX on the stability of the emulsion system

The influence of the ratios of emulsifiers Emulgin B2 and Lanett SX on the stability of a model emulsion system was studied. During the experiment, the concentrations of Emulgin B2 were varied in the range of 2.0...3.0 % and Lanett SX in the range of 1.0...2.0 %. The stability of model samples of emulsion systems was assessed by the results of centrifugation and thermal stability after 7 and 30 days of storage.

Table 1 shows the experimental planning matrix, as well as experimental and calculated values of the stability and thermal stability of the emulsion system from the ratio of emulsifiers Emulgin B2, Lanett SX.

Table 1

Experiment planning matrix, experimental and calculated values of stability and thermal stability of the emulsion system from the ratio of emulsifiers Emulgin B2, Lanett SX

Experiment No.	Emulsifier content		7 days storage				30 days storage			
	Emulgin B2, %	Lanett SX, %	stability		thermal stability		stability		thermal stability	
			exp.	calc.	exp.	calc.	exp.	calc.	exp.	calc.
1	2.0	1.0	92.5	92.57	90.7	90.78	92.0	92.17	90.2	90.29
2	2.0	1.5	94.0	94.46	92.2	93.05	93.5	93.93	91.5	92.20
3	2.0	2.0	97.0	96.47	96.3	95.36	96.5	95.89	96.1	95.41
4	2.5	1.0	98.0	97.57	96.2	95.36	97.6	97.00	95.4	94.60
5	2.5	1.5	99.0	98.67	97.3	96.96	98.5	98.13	96.7	96.13
6	2.5	2.0	99.1	99.27	97.4	98.18	98.5	99.46	96.9	97.76
7	3.0	1.0	98.7	99.07	97.1	97.86	98.0	98.22	96.4	97.10
8	3.0	1.5	99.5	99.37	99.3	98.79	99.0	98.93	98.4	98.07
9	3.0	2.0	100.0	99.77	100.0	99.75	100.0	99.84	100.0	99.63

Using statistical equations, approximate dependences of the stability of the emulsion system on the ratios of emulsifiers Emulgin B2 and Lanett SX are presented:

– stability of the emulsion system after 7 days on the ratio of emulsifiers:

$$S(c_E,c_L)_7 = 27.6667 + 44.70 \cdot c_E + 9.70 \cdot c_L - -7.00 \cdot c_E^2 - 3.20 \cdot c_E \cdot c_L + 0.20 \cdot c_L^2; \quad (1)$$

– thermal stability of the emulsion system after 7 days from the ratio of emulsifiers:

$$TS(c_E,c_L)_7 = 41.9639 + 30.45 \cdot c_E + 9.7833 \cdot c_L - -4.1333 \cdot c_E^2 - 2.70 \cdot c_E \cdot c_L + 0.6667 \cdot c_L^2; \quad (2)$$

– stability of the emulsion system after 30 days from the ratio of emulsifiers:

$$S(c_E,c_L)_{30} = 30.9583 + 42.75 \cdot c_E + 7.5167 \cdot c_L - -6.80 \cdot c_E^2 - 2.50 \cdot c_E \cdot c_L + 0.40 \cdot c_L^2; \quad (3)$$

– thermal stability of the emulsion system after 30 days from the ratio of emulsifiers:

$$TS(c_E,c_L)_{30} = 48.0417 + 27.1167 \cdot c_E + 5.8167 \cdot c_L - -3.60 \cdot c_E^2 - 2.30 \cdot c_E \cdot c_L + 1.2 \cdot c_L^2, \quad (4)$$

where c_E – content of Emulgin B2, %;

c_L – content of Lanett SX, %.

Fig. 1, *a–d* show graphical dependences of the stability of the emulsion system on the ratios of emulsifiers Emulgin B2 and Lanett SX.

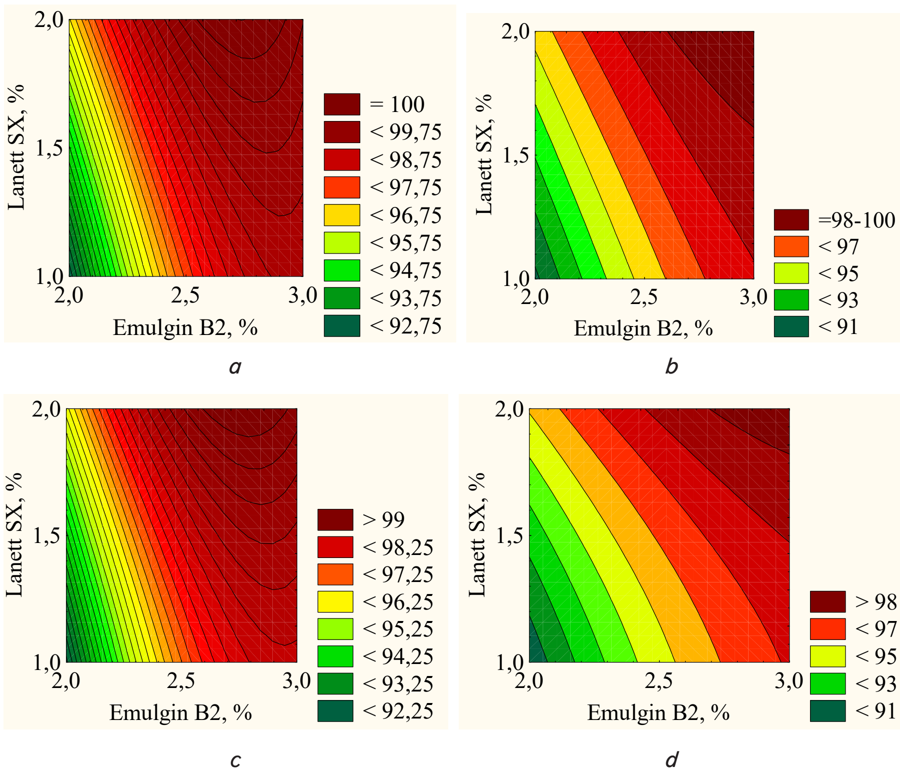

Fig. 1. Dependence of the stability of the emulsion system on the ratios of emulsifiers Emulgin B2 and Lanett SX: *a* – stability of the emulsion system after 7 days on the ratio of emulsifiers, (%); *b* – thermal stability of the emulsion system after 7 days on the ratio of emulsifiers, (%); *c* – stability of the emulsion system after 30 days on the ratio of emulsifiers, (%); *d* – thermal stability of the emulsion system after 30 days on the ratio of emulsifiers, (%)

The mean square errors (σ) for the dependences of stability and thermal stability of emulsion systems (1)–(4) were calculated:

– stability after 7 days: 0.933;
– thermal stability after 7 days: 0.781;
– stability after 30 days: 0.438;
– thermal stability after 30 days: 0.564.

Low values of σ (less than ±1.0) show that the models are reliable for predicting stability and thermal stability under the conditions of this experiment. The obtained dependences allow to adequately predict the stability of the emulsion system depending on the ratio of emulsifiers within the range of varied concentrations of Emulgin B2 in the range of 2.0...3.0 % and Lanett SX in the range of 1.0...2.0 %.

5. 2. Study of the influence of the ratios of wetting agents on the rheological parameters of the emulsion system

The influence of the ratios of wetting agents on the rheological parameters of the emulsion system was studied. As the main components that, in addition to wetting, affect the viscosity of the emulsion system, propylene glycol in the range of 5.5...8.5 % and glyceryl cocoate in the range of 1.0...2.0 % were studied. The approximate dependence of the viscosity of the emulsion system on the concentrations of wetting agents is presented using the equation:

$$\eta(c_{PG},c_{GC}) = -66.4259 + 17.6852 \cdot c_{PG} + 7.3333 \cdot c_{GC} - 0.3704 \cdot c_{PG}^2 I - 2.3333 \cdot c_{PG} \cdot c_{GC} + 4.6667 \cdot c_{GC}^2 I, \quad (5)$$

where $\eta(c_{PG}, c_{GC})$ – the viscosity of the model emulsion system containing the wetting agents propylene glycol and glyceryl cocoate;

c_{PG} – concentration of propylene glycol, %;

c_{GC} – concentration of glyceryl cocoate, %.

Fig. 2 shows the graphical dependence of the viscosity of the emulsion system on the concentrations of wetting agents.

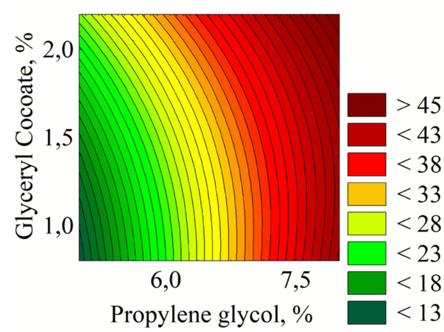

Fig. 2. Dependence of the viscosity of the emulsion system (Pa·s) on the concentrations of wetting agents (%)

The mean square error (σ) for dependence (5) is ±0.86. The given equation allows to adequately predict the viscosity of the emulsion system in the intervals of variation of the concentrations of propylene glycol (5.5...8.5 %), glyceryl cocoate (1.0...2.0 %).

5. 3. Determination of the influence of sodium laureth sulfate concentration on the foaming properties and foam stability of the emulsion system

The influence of sodium laureth sulfate concentrations on the foaming properties and foam stability of the emulsion system in the range of 0.1...0.3 % with a step of 0.05 % was studied. As the main component responsible for foam formation, sodium laureth sulfate was tested to optimize the foaming properties of the emulsion system intended for use in aerosol form. Using equations (6), (7), approximate dependences of the foaming ability and foam stability of the emulsion system on the concentration of sodium laureth sulfate are presented:

$$FA(c_{SLS}) = 59.67c_{SLS}^3 - 46.22c_{SLS}^2 + 1{,}392.06c_{SLS} - 2814.81,$$

$$(R^2{=}0.987); \qquad (6)$$

$$FS(c_{SLS}) = 58.00c_{SLS}^3 - 248.89c_{SLS}^2 + 2{,}904.76c_{SLS} - 5{,}777.78,$$

$$(R^2{=}0.994); \qquad (7)$$

where $FA(c_{SLS})$ – foaming ability of the emulsion system containing sodium laureth sulfate, %;

$FS(c_{SLS})$ – foam stability of the emulsion system containing sodium laureth sulfate, %;

c_{SLS} – concentration of sodium laureth sulfate, %.

Fig. 3 shows graphical dependences of foaming ability and foam stability of the emulsion system on the concentration of sodium laureth sulfate.

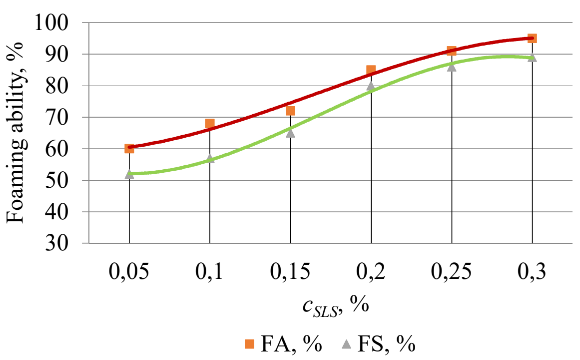

Fig. 3. Dependence of foaming characteristics of the emulsion system (%) on the concentration of sodium laureth sulfate (%)

The given equations allow to adequately predict the foaming ability and foam stability of the emulsion system in the range of sodium laureth sulfate concentrations of 0.1...0.3 % (the values of the approximation reliability R^2=0.961 for dependence (6) and R^2=0.940 for dependence (7) indicate a high quality of the approximation of the models). With an increase in the concentration of sodium laureth sulfate, an increase in both foaming indicators is observed, but the effect is nonlinear. The maximum values of foaming ability and foam stability are achieved at concentrations close to 0.3 %. According to [18], values of foaming ability of 85 % and above, as well as foam stability of 80 % and above are satisfactory for aerosol emulsions. Thus, the priority, from an economic point of view, in the technology of this aerosol emulsion is the concentration of sodium laureth sulfate within 0.20...0.22 %.

6. Discussion of the results of determining the influence of surfactant concentrations on the technological parameters of an aerosol emulsion

The specifics of the influence of surfactant concentrations on key technological parameters of an aerosol emulsion system, such as foam stability, viscosity and foaming ability, have been established. Experiments with varying concentrations of Emulgin B2 and Lanett SX (Fig. 1, *a–d* and equations (1)–(4)) have revealed a significant influence of these emulsifiers on the stability of the emulsion system during storage. Equation (1) demonstrates that Lanett SX has the greatest positive influence on the stability of the emulsion system after 7 days. Lanett SX is an emulsifier that promotes the formation of stable interfacial films that improve the stability of the emulsion. Emulgin B2, which is a nonionic emulsifier with high hydrophilicity, also has a positive effect on the stability of the emulsion system. The presence of quadratic terms in the c_E^2 and c_L^2 equations indicates the nonlinear nature of the effect of the concentrations of these emulsifiers on the stability of the system. For example, the coefficient at c_L^2 (–7.00) means that too high a concentration of Lanett SX can have a negative effect on stability due to too high a stiffness of the interfacial film, which can lead to its destruction or delamination.

Equation (2) demonstrates that the thermal stability after 7 days is largely dependent on Emulgin B2 (+30.45·c_E). This is explained by the fact that Emulgin B2, as a non-ionic emulsifier, has high thermal stability and works well at different temperatures, which allows maintaining the homogeneity of the emulsion under cyclic thermal loads. It is worth noting the negative effect of simultaneously increasing the concentrations of both emulsifiers, which can lead to a decrease in the thermal stability of the system, which is confirmed by the negative coefficient (–2.70·c_E·c_L).

Equation (3) shows a similar trend in the stability of the emulsion system as (1), but the influence of the emulsifiers is slightly different. Lanett SX has a positive effect (+7.5167·c_L), unlike Emulgin B2 (–6.80·c_E), which confirms its role in ensuring long-term stability through the formation of stable interfacial films. However, the quadratic term·c_E^2 (–6.80) confirms that too high a concentration of Emulgin B2 can negatively affect the long-term stability of the emulsion, which can be explained by the possible excessive hydrophilicization of the emulsion system, which can lead to its destabilization.

Equation (4) shows a similar trend in the dynamics of the thermal stability of the emulsion system to equation (2), where the greatest positive effect is exerted by Emulgin B2 (+27.1167·c_E). Since its high thermal stability contributes to maintaining the homogeneity of the system during long-term storage under conditions of temperature fluctuations. A negative effect is also confirmed with a simultaneous increase in the concentrations of both emulsifiers (–2.30·c_E·c_L), which emphasizes the need for a balanced ratio of these emulsifiers.

Analyzing equations (1)–(4), it was determined that the emulsifier Lanett SX has a significantly greater effect on the stability of the emulsion system after 7 and 30 days. High stability is achieved at Lanett SX concentrations of 2.0 %. In turn, the emulsifier Emulgin B2 has a decisive effect on thermal stability, but at the same time negative interactions when using high concentrations with Lanett SX reduce its effectiveness. Thus, the rational concentration of Emulgin B2 for the specified emulsion system is 2.75...3.00 %.

The specifics of the influence of wetting agent concentrations on the rheological properties of the emulsion system have been established. Experiments with varying concentrations of propylene glycol and glyceryl cocoate (Fig. 2, equation (5)) have revealed a significant influence of these components on the viscosity of the emulsion system. Equation (5) shows that propylene glycol (c_{PG}) has a significant positive effect on the viscosity of the emulsion system through a linear term (+17.6852·c_{PG}). This indicates that with an increase in the concentration of propylene glycol in the system, the viscosity of the emulsion increases. This is logical from a chemical point of view, since propylene glycol is a powerful wetting agent and has the ability to retain a large amount of water, increasing the resistance to the flow of the system. However, the presence of a negative quadratic term in equation (5) $\left(-0.3704\cdot c_{PG}^2\right)$ indicates that the effect of propylene glycol is nonlinear, and with an excessive increase in concentration, this component begins to lose its ability to increase viscosity. This may be due to the fact that at high concentrations, propylene glycol can excessively reduce the interfacial tension between the oil and water phases, contributing to the destabilization of the system and a decrease in viscosity. In turn, glyceryl cocoate (c_{GC}) also plays an important role in increasing viscosity, which is confirmed by its positive linear coefficient (+7.3333·c_{GC}). Glyceryl cocoate has emollient properties and helps to improve the texture of the emulsion, making it smoother and thicker, provides more stable interfacial films, increases the structural integrity of the system and, accordingly, its viscosity. The presence of a positive quadratic term $\left(+4.6667\cdot c_{GC}^2\right)$ indicates that glyceryl cocoate has an even greater effect on viscosity as its concentration increases, in contrast to propylene glycol. This indicates that glyceryl cocoate increases viscosity even at high concentration levels, since its ability to stabilize the emulsion increases with increasing amount. Simultaneously increasing the concentrations of propylene glycol and glyceryl cocoate has a negative effect on viscosity (–2.3333·c_P·c_{GC}). This can be explained by the fact that the simultaneous increase of both wetting agents leads to oversaturation of the system with wetting components, which can weaken the interfacial films and contribute to emulsion destabilization. This effect can be explained by exceeding the critical concentration at which both wetting agents begin to compete for water retention, which can lead to phase dispersion and a decrease in viscosity. To ensure optimal viscosity of the emulsion system in aerosol form, it is necessary to achieve a viscosity level in the range of 35…40 mPa·s. This ensures easy spraying of the emulsion system, while maintaining its stability and uniformity. Since propylene glycol at low concentrations reduces viscosity, it is optimal to use it at a level of about 7 %. The concentration of glyceryl cocoate is justified at a level of 1.5 %, which will allow achieving the necessary rheological properties for both emulsion stability and its effective spraying.

The specifics of the influence of sodium laureth sulfate concentrations on the foaming properties and foam stability of an aerosol emulsion system have been established. Experiments with varying sodium laureth sulfate concentrations in the range of 0.1…0.3 % (Fig. 3, equations (6), (7)) have revealed a significant influence of this component on the system's ability to form foam and maintain its stability. Increasing the sodium laureth sulfate concentration has a positive effect on the foaming ability and foam stability, however, these indicators demonstrate a nonlinear dependence, which indicates possible limitations in the effectiveness of the component at high concentrations. Equation (6) shows that the foaming ability initially has a positive trend with increasing sodium laureth sulfate concentration (c_{SLS}). Equation (7) is also cubic and shows a similar dependence of foam stability on the sodium laureth sulfate concentration. Foam stability increases to a certain limit (80 %). For cosmetic moisturizers, not only foaming properties are important, but also the ability of the foam to settle quickly and not leave a sticky or excessively dry feeling on the skin. A foaming ability in the range of 80…85 % allows for easy distribution of the emulsion during application to the skin. It is worth noting that emulsion systems with higher foaming ability may be difficult to apply or leave foam on the skin surface. In turn, foam stability of about 80 % is important for the foam to remain stable for a sufficient time for application, but then dissipate without leaving traces. Taking into account the experimental results (equations (6), (7)), the concentration of sodium laureth sulfate in the emulsion system at the level of 0.20…0.22 % is rational for achieving the desired foaming properties (85…88.5 %) and foam stability (80…83 %). This will ensure easy application of the product, its even distribution and comfortable use without residual foam on the skin.

The peculiarities of the obtained results in comparison with the known data [11, 12, 16–18] are in the integrated approach to varying the concentrations of emulsifiers and wetting agents, which allows to achieve optimal stability and rheological properties of the aerosol emulsion system. Compared with the results of work [11], where the influence of the *Tween* series of emulsifiers on the stability of sodium alginate dispersion was investigated, the obtained results showed that the use of Emulgin B2 and Lanett SX allows to achieve high stability of the emulsion system, including during long-term storage. Compared with the results of the studies described in the works [12, 16], where the complex of emulsifiers was used to stabilize emulsion systems without taking into account their interaction with simultaneous influence, the obtained results showed that Emulgin B2 and Lanett SX are able to stabilize emulsion systems using nonlinear interaction. For example, too high a concentration of Emulgin B2 and Lanett SX has a negative effect on emulsion stability. In contrast to work [13], where emulsifiers mono- and diacylglycerols were used to stabilize emulsion systems without focusing on thermal stability, the results obtained demonstrated that the use of Emulgin B2 and Lanett SX provides thermal stability of emulsion systems. In work [17], where the behavior of emulsifiers in whipped cream in aerosol form was studied, it was shown that changes in the composition of emulsifiers can affect the stability and quality of the foam. However, the issues of optimizing the composition of emulsifiers to achieve maximum stability at different temperature regimes remained unresolved. The results obtained demonstrate that Lanett SX and Emulgin B2 provide optimal stability of the emulsion system during storage and temperature effects, which are dependent on (equations (2) and (4)). This becomes possible due to a more detailed analysis of the interactions of emulsifiers and the determination of critical concentrations at which a balance is achieved between the stability of the emulsion and its technological parameters. Compared to the work [18], which investigated the use of plant-animal extracts and biocompatible polymers for the formation of an emulsion, the approach described in this article demonstrated better predictability regarding long-term storage and technological properties of the emulsion. Although the work [18] emphasized the importance of using natural components to ensure stability. The results obtained are focused on the analysis of the combined effect of synthetic emulsifiers in combination with detailed modeling of their effect on the rheological parameters and foaming properties of emulsion systems, which allows to guarantee stability under different conditions of use.

The results of studies on the influence of surfactant concentrations on emulsion stability, viscosity and foaming properties of an aerosol emulsion system can be useful for a number of industries. First of all, these data are valuable for developers of cosmetic products, as they allow optimizing the composition of moisturizers and other emulsions used in aerosol form. In addition, the results obtained can be applied in the pharmaceutical industry when developing preparations with foaming properties, where foam stability can affect the effectiveness and convenience of using drugs. Information on optimal concentrations of sodium laureth sulfate can also be used for the production of cleaning products, where it is important to ensure both sufficient foaming and rapid foam settling without residual traces on the surface.

Limitations of the use of the research results, in particular the relationships (1)–(7), may arise for several reasons. The results obtained for the emulsifiers Emulgin B2 and Lanett SX, as well as wetting agents such as propylene glycol and glyceryl cocoate, and sodium laureth sulfate are based on studies under specific experimental conditions. The choice of the concentration range and types of emulsifiers and wetting agents may limit the applicability of these results to other systems or cosmetic products with different formulations. The rheological properties and stability of emulsion systems depend not only on the specified components, but also on other factors such as storage temperature, changes in environmental conditions, and interaction with other ingredients. Although equations (1)–(4) clearly demonstrate the influence of Emulgin B2 and Lanett SX on the stability and thermal stability of the system, their effectiveness may vary depending on the quality of the raw materials, variations in concentration during production, and other variable factors. Additional studies are needed to study the interaction of these components in the presence of other ingredients that may be part of the commercial formula. Since in real products, wetting agents and emulsifiers can interact with active ingredients or preservatives, which affects stability.

A disadvantage of the studies conducted is the lack of data on the influence of other active ingredients, such as preservatives and antioxidants, on the stability and thermal stability of the emulsion system. Interaction with other components of the formula, in particular preservatives, can affect the overall stability of the system.

Promising directions for further research are to expand the scope of the study to other types of emulsion systems, in particular systems with a higher content of active ingredients or other formulas for cosmetic products. This will increase the universality of the conclusions and recommendations for manufacturers. It is also promising to study the interaction of the components of the developed emulsion system with other active ingredients, such as vitamins, extracts or aromatic substances. This is advisable to optimize their functional and consumer properties, as well as to increase the stability and efficiency of the final product.

7. Conclusions

1. The dependence of the stability of the emulsion system on the ratios of emulsifiers Emulgin B2 and Lanett SX was determined. The rational ratio of emulsifiers (Emulgin B2 at the level of 2.75...3.0 % and Lanett SX 2.0 %) provides maximum stability and thermal stability of the emulsion system during 7 and 30 days of storage. This is explained by the specifics of the chemical structure of emulsifiers, which affect the interaction between phases.

2. The influence of the ratios of wetting agents, such as propylene glycol and glyceryl cocoate, on the rheological parameters of the emulsion system was studied. It was established that the concentration of propylene glycol at the level of 7 % and glyceryl cocoate 1.5 % provides the optimal viscosity of the system within 35...40 mPa·s. The interaction between these components leads to a decrease in viscosity while simultaneously increasing their concentrations, which is explained by the oversaturation of the emulsion system with humectants, which reduces its structural integrity.

3. The effect of the concentration of sodium laureth sulfate on the foaming properties and foam stability of the emulsion system was determined. The concentration of laureth sulfate at the level of 0.20...0.22 % is rational for achieving the desired level of foaming (85...88.5 %) and foam stability (80...83 %), which ensures comfortable application of the product to the skin. The nonlinear nature of the effect of laureth sulfate concentrations is explained by its ability to affect interfacial tension, and at high concentrations – to destabilize the foam.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, that could influence the study and its results presented in this article.

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Data availability

The manuscript has no linked data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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