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Influence of ultrasonic and mechanical dispersion on the viscosity characteristics of water-oil emulsions: experimental study

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Abstract. In this article, the influence of ultrasonic and mechanical dispersion on the viscosity characteristics of water-oil emulsions was studied. It was found that an increase in the duration of exposure to ultrasound leads to an increase in temperature as a result of intensive dispersed system mixing. Due to this, there is an intensification of the interaction between the particles, dispersion, and coagulation. The analysis of the results allowed to determine the optimal ratio between the time of ultrasonic exposure and the emulsifier concentration to obtain an emulsion with low viscosity and a dispersion range. Ultrasonic dispersion promotes the formation of fine particles and a wider polydispersity, which improves emulsion viscoelastic parameters and density. It was found that ultrasonic treatment for 80-120 seconds enhances the nanoscale effect, reducing the emulsion dynamic viscosity. These results are of significant importance for the control and optimization of the viscosity properties of emulsions in various industrial fields, including the food industry.

1 Introduction

Obtaining stable emulsions is a complex process that is influenced by several factors, such as surface tension, viscosity of the dispersion medium, temperature, and particle dispersion. There are various problems associated with the formation of stable emulsions, including coalescence (merging of the smallest droplets into larger ones), flocculation (formation of clots or aggregates of particles), and sedimentation (settling of particles at the bottom of the vessel) [1, 2].

Currently, there are two emulsification principles: mechanical and acoustic. Usually, homogenizers such as colloidal mills are used to produce standard concentrated emulsions. In rotary dispersers, the emulsion dispersion depends on the rotation speed of the rotor and the size of the gap. With a decrease in the gap, the size of the emulsion droplets decreases, and when working at high rotor speeds and small gaps, highly dispersed emulsions are obtained [3-6].

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Nevertheless, modern emulsification technologies are increasingly based on the use of ultrasonic exposure. Ultrasound in a liquid causes high pressures and tensile stresses, which are measured in many atmospheres. In places where there are impurities or gas bubbles, the liquid cannot withstand tensile forces, which leads to the cavitation phenomenon [7-9].

Mechanical and acoustic dispersion, i.e. the method of obtaining an emulsion are considered the main methods of obtaining a dispersed emulsion. Mechanical dispersers (modern colloidal mills) are widely used standardized laboratory devices and installations in the industry for the production of emulsions. The dimensionality of the phase in emulsions depends on the conditions and characteristics of the hardware devices, for example, when using rotary evaporators, the main criterion of dispersion, in addition to the phase nature, the rotation speed of the rotor and the shape and size of the gap are also considered important. In this process, it is also necessary to control the interphase interaction and the influence of the disperser material. With a decrease in the gap size and an increase in the rotor rotation, an increase in the phase dispersion can be expected [3-6].

In modern technologies, the use of ultrasonic exposure is becoming increasingly popular. Ultrasound in the liquid creates significant pressures and strains that can reach values measured in many atmospheres. In places where there are impurities or gas bubbles, the liquid is not able to withstand these tensile forces, which leads to the phenomenon of cavitation [7-9].

Studies show that ultrasonic exposure to liquid can effectively emulsify systems. It provides intensive mixing of liquids and creates high shear forces, which contributes to the formation and dispersion of droplets in the liquid phase. Moreover, ultrasound promotes the destruction of large droplets into the smallest ones, which increases the dispersion of the emulsion and ensures system stability [10, 11]. Thus, ultrasonic emulsification is a promising method for obtaining stable emulsions with desired textural and functional characteristics.

The study of the viscosity of water-oil suspensions in the food industry is of particular relevance and importance. Viscosity is an important parameter affecting the quality and structure of food products, such as sauces, dressings, creams, mayonnaise, and other emulsion products. The viscosity of water-oil suspensions affects their fluidity, stability, and rheological properties. It determines the ability of the suspension to spread evenly, mix, and penetrate into other ingredients, and also provides the desired consistency and texture of the final product [16].

Understanding the viscosity of water-oil suspensions allows to optimize the production process and control the quality of products. By adjusting the viscosity, it is possible to achieve the desired consistency, improve the structure and stability of emulsions, as well as ensure better interaction with other components and ingredients of food products [17].

Thus, the study of the viscosity of water-oil suspensions in the food industry has practical significance, allows to develop optimal formulations and production technologies, as well as to create products with the desired texture and consistency, which is an important aspect to meet the needs and preferences of consumers.

The purpose of the research is to create emulsions for the food industry using lecithin as an emulsifier through the use of mechanical and ultrasonic dispersion. For this purpose, an indicator was chosen as the main criterion – the emulsion viscosity. The emulsion viscosity depends on various factors, including the content of the dispersed phase, the nature and concentration of the emulsifier, as well as the dispersion conditions are considered to be one of the main factors [13-15]. Nevertheless, it is important to consider the relationship between the viscosity properties of the emulsion and its dispersion. The emulsion dispersion, that is, the size and uniformity of the droplet distribution, can also have a significant impact on its viscosity and stability. Therefore, in this study, the interaction between the viscosity properties and the emulsion dispersion will be investigated to get a complete picture of the quality and structure of the emulsions created.

2 Experimental part

Refined, deodorized cottonseed oils (GOST 816:2015) and drinking water (GOST R 51232-98) were selected for the experiment on the emulsion preparation. Soy lecithin, previously hydrolyzed in accordance with the requirements of GOST 32052-2013, was used as an emulsifier.

One of the key parameters characterizing the emulsifier lecithin is its hydrophilic-lipophilic balance (HLB). In this study, the HLB of lecithin exceeds the value of 7, which indicates its pronounced hydrophilic properties and the ability to form direct emulsions based on sunflower oil and water.

The choice of these components and emulsifier is due to their wide application in the food industry, as well as availability and compliance with the requirements of quality standards. This approach makes it possible to create an emulsion with optimal characteristics, having the necessary stability and functionality for use in food products.

To prepare a water-oil emulsion using lecithin as an emulsifier, the starting materials were first weighed. In a separate container, a certain amount of oil was poured, heated to 50°C, after which an emulsifier heated at a temperature of 45-50°C is added, the mixture is thoroughly mixed until the emulsifier is completely dissolved, and then 40% of the total mass of vegetable oil is added, and water with a temperature of 45-50°C is slowly added. Maintaining this temperature, it is mixed for 15-20 minutes at a speed of 1200-1500 rpm. In this process, it is important to carry out intensive mixing to ensure good mixing and stabilization of the emulsion.

The emulsion viscosity was measured on a glass viscometer VPZH-4m, which is designed for use in conditions standardized for the performance of V3 according to GOST 10028-81, as well as on a rotary viscometer Rheotest -2 at a shear stress of 80-200 Pa and temperatures from 20 to 60°C.

The morphology of the obtained food emulsions was studied microscopically using the BioBlue S/N-EC 2209881 lens brand: SP 40/0.65 and 160/0.17 of the Euromex company (the Netherlands).

3 Results and their discussion

The emulsion viscosity plays an important role in its stability. The emulsion stability is determined by the ability to maintain a uniform distribution of the dispersed phase (for example, water) in a continuous phase (for example, oil). The emulsion viscosity affects its sedimentation stability, stability, and shelf life. A higher viscosity usually improves the emulsion stability. The high viscosity helps to prevent the settling of the dispersed phase, providing a more uniform distribution throughout the emulsion. This is especially important for emulsions intended for long-term storage or use in conditions requiring stability, for example, in the food industry. To analyze the dependence of changes in the viscosity of a water-oil emulsion with different oil content (15%, 20%, and 25%) on the concentration of lecithin (emulsifier), the values of viscosity (X) at different measurement points were considered. Figure 1 shows the results of a study devoted to the study of the emulsifier concentration effect on the viscosity properties of a water-oil emulsion with different oil contents: 15 (VM15), 20 (VM20), and 25% (VM25).

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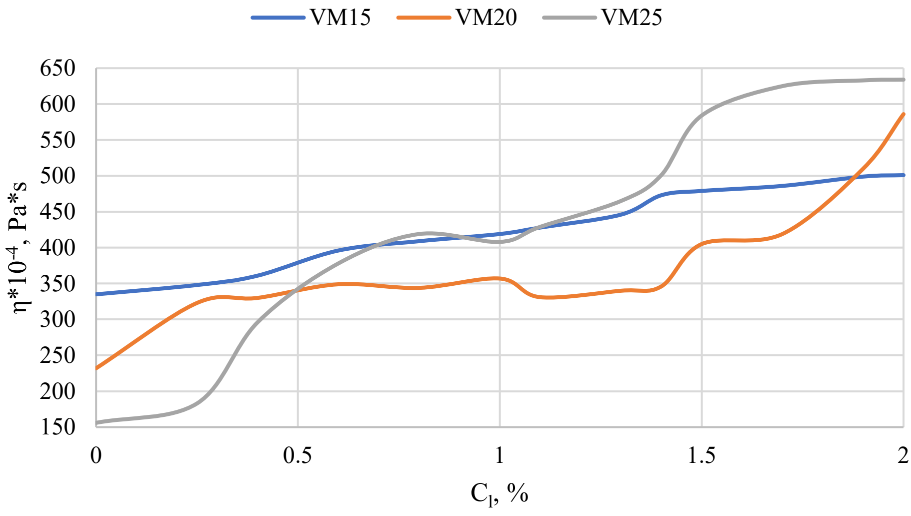


Fig. 1. Change in the emulsion system viscosity depending on the emulsifier concentration (C_l).

Analyzing the results of the study of the emulsifier concentration effect on the viscosity characteristics of the water-oil emulsion, it is possible to draw scientific conclusions about the dependence of the dynamics of changes in the dynamic viscosity of the emulsion, it depends on the content of the emulsifier and the concentration of the dispersed phase (oil). There is a different nature of viscosity changes depending on these factors.

In the absence of ultrasound effect, the stabilization mechanism depends only on the performance of the emulsifier, in our case hydrolyzed lecithin. It is known that with an increase in the emulsifier concentration in the system, the thickness of the adsorption-solvate layer increases. A thicker layer can create more resistance when moving droplets, which affects the increase in the emulsion viscosity. This leads to an increase in viscosity, especially noticeable for emulsions with high oil contents.

At a low concentration of the emulsifier, its interaction with the oil may be limited, which leads to a smaller change in viscosity. Nevertheless, as the concentration of the emulsifier increases, the interaction between it and the oil becomes stronger. At a high concentration of the emulsifier, interactions between the emulsion particles may occur. This can lead to the formation of more complex structural units and changes in rheological properties, including viscosity.

In general, changes in the emulsion viscosity at different concentrations of the emulsifier are associated with interactions at the molecular level and structural changes in the emulsion. These factors may vary depending on the emulsifier type, the dispersed phase, and other conditions for the emulsion preparation.

The different oil content in the emulsion also affects the change in viscosity. Different oil concentrations affect the dispersed phase volume. As the oil concentration increases, the dispersed phase volume increases, which can lead to a decrease in the emulsion viscosity. A larger amount of oil can lead to a denser packing of droplets, which creates an understated resistance to the emulsion flow.

The oil can interact with the emulsifier and affect its stabilizing properties. This can lead to a change in the adsorption-solvate layer structure and, as a consequence, a change in the emulsion viscosity. The physical properties of the oil, such as its viscosity and surface tension, can also affect the emulsion viscosity.

Thus, the oil content in the emulsion can have a significant effect on its viscosity. Nevertheless, the exact mechanisms of this effect may vary depending on the oil chemical composition, interaction with the emulsifier and other factors, so further research is needed to better understand this issue.

As is known, an increase in the dispersion of the dispersed phase leads to an increase in the specific surface area between the phases (water-oil), which reduces the thickness of the adsorption-solvate layer several times. A more significant ultrasound dispersing effect compared to mechanical dispersion contributes to a significant change in the solvate layer at the interface of the phases.

Without exposure to ultrasound, when the lecithin concentration increases to 2% or more, the values of the dynamic viscosity of the emulsion VM15, VM20, and VM25 increase. The stabilization mechanism is due to the increased adsorption of surfactants on the interface of phases. Nevertheless, after ultrasonic treatment, the viscosity decreases, which is explained by a decrease in the thickness of the adsorption-solvate layer and a change in the interactions between the emulsion particles.

A direct water-oil emulsion can achieve a more uniform distribution of the smallest oil particles with an optimal selection of conditions associated with reducing the particle size and considering the isothermal distillation process. This leads to a decrease in the viscosity of the emulsion compared to the initial component. There is a certain limit to the fineness of the adsorption-solvate layer, which limits the possibility of regulating the system viscosity in a certain direction. The study also revealed that an increase in the adsorption-solvate layer thickness leads to an increase in the emulsion viscosity (Fig. 2).

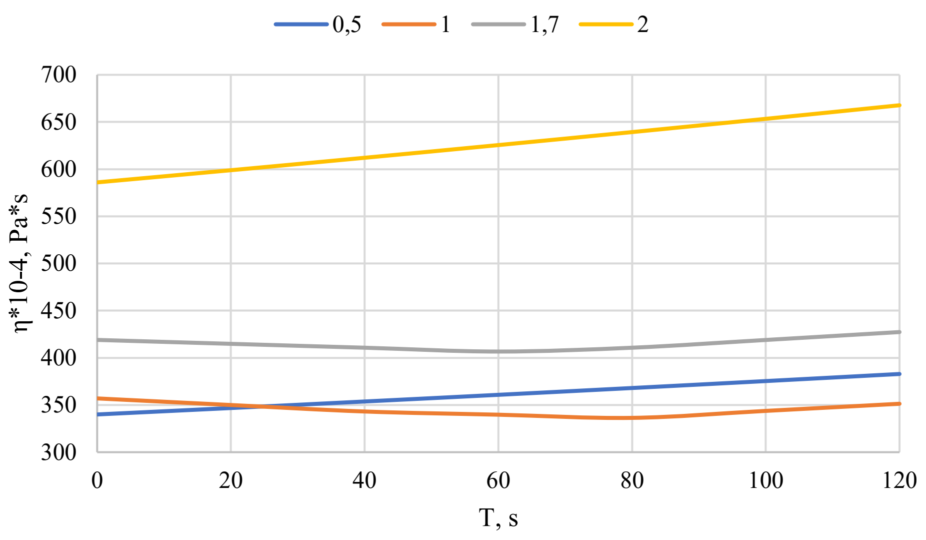


Fig. 2. The dependence of the change in viscosity of the VM20 system on the emulsifier concentration at different times of dispersion under the influence of ultrasound with a frequency of 25 kHz.

It is known that the ultrasound effect on the system can lead to a change in its temperature. When using ultrasound, vibrations of molecules occur in the liquid, which leads to heat release, which is called acoustic heating. At the same time, for an emulsion under the ultrasound effect, both the dispersion process and the aggregation process (coalescence) can occur. Due to the increased phase motion under the effect of ultrasound and heat, the nature of the bond at the phase interface changes, due to which it is possible to observe a decrease in the amount of surfactants in this zone.

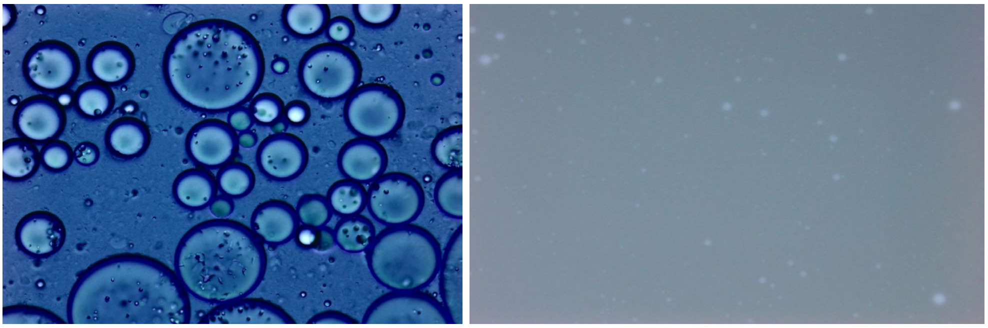
Figure 2 shows graphs of the dependence of changes in the water+oil+lecithin system viscosity on the ultrasonic dispersion duration. The different shapes of the curves prove the different behavior of the emulsion with different emulsifier concentrations under the ultrasound effect and to obtain a more monodisperse emulsion with a lower viscosity, there is an optimal dose of irradiation and emulsifier. When an emulsion with an emulsifier concentration of up to 1% and more than 1.7% is treated with ultrasound, an increase in viscosity is observed due to an increase in the coagulation proportion. At the maximum emulsfier concentration (2% in our case), the viscosity is constantly increasing. By itself, without ultrasonic treatment, the viscosity of this system is higher. This is due to the thickness of the adsorption-solvate layer due to the greater number of surfactants at the phase interface. Perhaps a denser packing of the dispersed phase should also be indicated. With an increase in the ultrasonic exposure duration, the temperature increases, the movement of particles of the dispersed phase increases, which leads to a decrease in the adsorption layer thickness and, as a result, an increase in coagulation. At emulsifier concentrations from 1.0 to 1.7%, a decrease in viscosity is observed during ultrasound treatment during the first 80-100 seconds, which indicates that a more homogeneous water+oil+lecithin system can be obtained due to the observed dispersion. In this process, it is possible to reduce polydispersity. With further exposure to sound up to 120 s, stabilization occurs, a further increase in viscosity due to coagulation processes before the emulsion is divided into phases.

The study of the ultrasonic and mechanical dispersion effect on the characteristics of the emulsion has derived the following data, which are highlighted in Table 1.

Table 1. The ultrasonic and mechanical dispersion effect on the characteristics of an emulsion with an emulsifier in the amount of 2%.

Emulsion	p, kg/dm^3	η, Pa*s	σ, N/m
Mechanical dispersion			
VM15	0.985	501	0.77
VM20	0.975	586	0.75
VM25	0.971	634	0.73
Ultrasonic dispersion			
VM15	0.980	518	0.91
VM20	0.788	667	0.85
VM25	0.770	671	0.77

The stability of emulsions at different temperatures was assessed by the change in their dynamic viscosity. Under these conditions, the viscosity of all emulsions (lecithin content 2%) VM15, VM20, and VM25 varies from 501.3, 586.2, and 634.4 Pa*s*10^{-4} at 20°C to 418.3, 421.2, and 424.5 Pa*s*10^{-4} at 60°C. It is known that non-Newtonian fluids flow practically without changing their viscosity characteristics with increasing shear stress. This stress for the developed emulsion has a value of no more than 200 Pa. Similar changes in viscosity and mechanical characteristics of the emulsion were obtained in [18-21]. The observed synergistic effect, which leads to a significant increase in the dynamic viscosity, and thermomechanical stability of emulsions using lecithin and ultrasonic exposure, differs from emulsions obtained by mechanical dispersion. This effect is explained by the formation of very small particles (droplets) and their wider polydispersity. In addition to the increase in viscoelastic parameters, the emulsions density is also noted as relatively increased. For example, the density of emulsions VM15, VM20, and VM25 containing 2% emulsifier and obtained under the effect of ultrasound and mechanical dispersion at 20°C is 0.980, 0.978, 0.977, and 0.985, 0.975, 0.971 kg/dm^3, respectively. A denser packing of the interphase space in emulsions obtained by ultrasonic exposure is associated with a decrease in particle size, a more pronounced polydispersity and a corresponding particle distribution. The fraction of the surface tension and the free surface energy of the particle increases with an increase in the phase dispersion in the emulsion system. The increase in the dynamic viscosity of emulsions with a 2% emulsifier content is mainly due to a decrease in particle size. Nevertheless, exposure to ultrasound for 80-120 seconds significantly enhances this effect of dispersion and changes in the system viscosity.



(a) (b)

Fig. 3. Microscopic images of food emulsions obtained by (a) mechanical and (b) ultrasonic dispersion (magnified 40 times).

As can be seen from Fig. 3, large sizes of oils are clearly visible in the emulsion obtained by (a) mechanical dispersion, nevertheless, after (b) ultrasonic dispersion, a practical complete dispersion of particles into small ones is observed.

4 Conclusions

The study of emulsions using ultrasonic and mechanical dispersion showed that an increase in the ultrasonic exposure time leads to an increase in temperature due to an increase in the mechanical mixing intensity, which contributes to the dispersion and aggregation (coalescence) processes.

As a result of the study, it was found that when the emulsion with different emulsifier concentrations is treated with ultrasound, changes in its viscosity are observed. The emulsifier concentration affects the proportion of coagulation and the thickness of the adsorption-solvate layer. Under certain ultrasound treatment conditions, a more homogeneous system with reduced viscosity and reduced polydispersity can be achieved. Nevertheless, prolonged exposure to ultrasound can lead to a further increase in viscosity due to coagulation processes and the emulsion separation into phases.

The study also showed that ultrasonic dispersion leads to the formation of small particles (droplets) and their wider polydispersity. This leads to increase in viscoelastic parameters and increased emulsion density. A denser packing of particles in the emulsion obtained by ultrasound is associated with a decrease in particle size, more pronounced polydispersity and a corresponding particle distribution. Ultrasonic treatment for 80-120 seconds enhances the nanoscale effect and improves the dynamic viscosity of the emulsion.

Thus, the use of ultrasonic dispersion in the process of forming emulsions allows to control and optimize their viscosity characteristics, and also provides more monodisperse and stable emulsions. This approach can be useful in various fields, including food industry, where the viscosity of emulsions plays an important role in the quality of their structure and stability.

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